Investigating the potential income and future water requirements of existing pecan orchards in the Western Cape

By

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: April 2022

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SUMMARY

The peak in pecan production occurs between 12 and 15 years, in traditional densities of 10 x 10 m, resulting in a long period before break even. To address this financial challenge, different approaches can be followed i.e., higher planting densities and earlier production, and cultivar choice for higher productivity, nut quality and adaptability to the environment.

Tree performance under higher densities were evaluated in newly established orchards varying from three to six years, with the objective to assess vegetative and reproductive development of 'Wichita' pecans in the Hermon and Vredendal regions of the Western Cape, South Africa. Additionally, the suitability of three main cultivars, Wichita, Navaho and Choctaw, were evaluated in the Vredendal region. Both studies were conducted during two consecutive seasons. A desktop study on evapotranspiration was conducted using historical data (2009-2020) for both regions, applying the FAO-56 model in conjunction with a locally adapted pecan-specific model, to ascertain the potential water use of pecans under current and future climate scenarios.

In paper 1, phenological development in Hermon commenced approximately two weeks earlier than in Vredendal. Results from both seasons and regions suggested that lower densities resulted in larger trees (volume), with no difference in light interception at this stage, irrespective of tree age. Yields varied according to density, with lower densities showing a higher yield efficiency per tree, but lower yield per ha. Thus, a higher yield is expected at higher densities, providing overcrowding can be managed. Overcrowding occurred in Vredendal, in the 10 x 5 m orchard, (year five), resulting in lower and reduced shoot growth compared to, lower density (10 x 8 m) orchard, with the same age.

In paper 2, there was no significant difference in yield efficiency or nut quality between the cultivars in Vredendal. 'Choctaw' produced bigger nuts in the second season, with significantly bigger trees in both seasons than 'Wichita' and 'Navaho', except for the volume of trees in the first season. Despite the difference in tree volume, no significant difference in light interception between cultivars was observed, indicating that tree shape, rather than volume, influenced light interception. Additionally, 'Navaho' pecans demonstrated an earlier phenological development than

‘Choctaw’ and ‘Wichita’, with an earlier bud break and pollination period, which is critical to serve as cross-pollinator for 'Wichita'. Our data indicate that these three cultivars were suitable for cultivation in the Vredendal region, as the minimum chill units (237.5 CU) was recorded, required for pollination, although additional yield data is required before commercial recommendations can be made.

Evapotranspiration data suggested a higher potential water use for pecans in the Vredendal compared to the Hermon region, with Hermon recording a lower ET than for Cullinan. This trend was also corroborated by actual evapotranspiration, as determined by satellite images. Climate change, with a predicted increase of 2 °C, increased ET and therefore the future water demand for both regions. Although the suitability of the crop, pecan, was confirmed for both regions, the prerequisite for access to irrigation in summer was evident from the ET study and needs to be incorporated in proposed extension of commercial orchards in these regions.

OPSOMMING

Die piek in pekanneutproduksie word tussen 12 en 15 jaar bereik in tradisionele plantdigthede van 10 x 10 m, wat 'n lang tydperk voor gelykbreek tot gevolg het. Om hierdie finansiële uitdaging die hoof te bied, kan verskillende benaderings gevolg word, bv. hoër plantdigthede, vroeër produksie en kultivar keuse, vir hoër produktiwiteit, neutkwaliteit en aanpasbaarheid by die omgewing.

Boomprestasie onder hoër digthede is geëvalueer in nuutgevestigde boorde tussen drie en ses jaar, met die doel om vegetatiewe- en reproduktiewe ontwikkeling van 'Wichita' pekans in die Hermon- en Vredendal-streke van die Weskaap, Suid-Afrika, te evalueer. Daarbenewens is die geskiktheid van drie hoofkultivars, Wichita, Navaho en Choctaw, in die Vredendal-streek geëvalueer. Beide studies is gedurende twee opeenvolgende seisoene uitgevoer. 'n Studie oor evapotranspirasie is uitgevoer met behulp van historiese data (2009-2020) vir beide streke, met die toepassing van die FAO-56-model in samewerking met 'n plaaslik aangepaste pekan-spesifieke model, om die potensiële watergebruik van pekans onder huidige en toekomstige klimaatsenarios te bepaal.

In artikel 1, het fenologiese ontwikkeling in Hermon ongeveer twee weke vroeër as in Vredendal begin. Resultate van beide seisoene en streke het aangedui dat laer digthede groter bome (volume) tot gevolg gehad het, met geen verskil in ligonderskepping op hierdie stadium nie, ongeag boomouderdom. Opbrengste het gewissel volgens plantdigtheid, met laer digthede wat 'n hoër opbrengsdoeltreffendheid per boom toon, maar laer opbrengste per ha. Dus word 'n hoër opbrengs by hoër digthede verwag, mits oorskaduwing bestuur kan word. Oorskaduwing het voorgekom in Vredendal, in die 10 x 5 m boord (jaar vyf), wat gelei het tot laer en verminderde lootgroei in vergelyking met die laer digtheid (10 x 8 m) boord, van dieselfde ouderdom.

In artikel 2, was daar geen betekenisvolle verskil in opbrengsdoeltreffendheid of neutkwaliteit tussen die kultivars in Vredendal nie. 'Choctaw' het groter neute in die tweede seisoen geproduseer, met aansienlik groter bome in beide seisoene as 'Wichita' en 'Navaho', behalwe vir boomvolume in die eerste seisoen. Ten spyte van die verskil in boomvolume, is geen betekenisvolle verskil in ligonderskepping tussen kultivars waargeneem nie, wat aandui dat boomvorm, eerder as volume,

ligonderskepping beïnvloed. Boonop het 'Navaho' 'n vroeër fenologiese ontwikkeling as 'Choctaw' en 'Wichita' getoon, met 'n vroeër knopbreek en bestuiwingsperiode, wat van kritiese belang is om as kruisbestuiwer vir 'Wichita' te dien. Ons data dui daarop dat hierdie drie kultivars geskik was vir verbouing in die Vredendal-streek, aangesien die minimum koue-eenhede (237.5 CU) wat benodig word vir bestuiwing aangeteken is, alhoewel addisionele opbrengsdata benodig word voordat kommersiële aanbevelings gemaak kan word.

Evapotranspirasie data dui op 'n hoër potensiële watergebruik vir pekans in die Vredendal in vergelyking met die Hermon-streek, met Hermon wat 'n laer ET as Cullinan aangeteken het. Hierdie tendens is ook bevestig deur werklike verdamping soos bepaal deur satellietbeelde. Klimaatsverandering, met 'n voorspelde toename van 2 °C, het ET verhoog en dus ook die toekomstige water aanvraag vir beide streke. Alhoewel die geskiktheid van die gewas, pekan, vir beide streke bevestig is, was die voorvereiste toegang tot besproeiing in die somer duidelik uit die ET-studie en moet dit geïnkorporeer word in voorgestelde uitbreidings van kommersiële boorde in hierdie streke.

This thesis is a compilation of four chapters, starting with a literature review, followed by three research papers where each paper is an individual entity and some repetition between papers, therefore, has been unavoidable. Papers were prepared according to the format for scientific publication.

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GENERAL INTRODUCTION

The pecan (*Carya illinoinensis*), native to the United States, has seen a significant increase in production in South Africa, with 4000 ha of new plantings per year, making the country the third largest producer of pecans in the world (Grauke et al., 2016). Pecan cultivation was initially concentrated in the eastern parts of South Africa before expanding westwards to the Northern Cape and Vaalharts, where the majority of the bearing orchards are currently being cultivated. The climate of these regions is similar to the long and warm summer conditions of the native areas in the United States (Reid and Hunt, 2000). In recent years, pecan expansion moved towards the Western Cape to areas such as Citrusdal, Hermon and Vredendal (Pecan South Magazine, 2020; SAPPA, 2017).

For optimal productivity, the planting density of perennial crops is a critical factor to consider. Higher density orchards allow for earlier production and a return on capital investment due to the faster rate of achieving a full canopy cover in the orchard (Hampson et al., 2004; Palmer et al., 1992). In pecan, the typical tree spacing is 10 x 10 m, with higher density orchards being classified as 9 x 9 m and closer (Herrera, 2000). The density of the orchard also influences light interception, which is directly proportional to productivity/yield, with several studies indicating a linear increase in yield with tree density (Palmer et al., 1992). Since pecan trees are large in size, higher density orchards may be difficult to manage due to earlier overcrowding with the closer in row spacing. As appropriate dwarfing rootstocks for pecans are not currently a viable option in controlling the tree vigour, only effective tree training and pruning will assist with vigour control and tree size (Andersen and Crocker, 1969). Previously, pecan cultivation was a secondary income to annual, irrigated crops. However, with the move towards pecan as a primary crop and increasing production costs, the profitability of this enterprise has become a priority. High density plantings proved to be an option in this respect in deciduous orchards, but this model has not been evaluated for pecans and is required before high density plantings can be recommended for financial reasons.

Cultivar choice also influences the productivity of a pecan orchard. In the United States, ‘Wichita’ and ‘Western Schley’ are the primary pecan cultivars in commercial orchards (Grauke et al., 2016). In South Africa, a range of pecan cultivars is available, but they vary according to yield potential and disease susceptibility. Scab resistant cultivars are required for the Western region of South Africa, where high temperatures and less frequent rain is prevalent (Haulik and Holtzhausen, 1988; Clark, 2020). Wichita, Choctaw and Navaho are the main cultivars planted locally (Grauke and Thompson, 1997). 'Wichita' is more prolific, with a high nut quality and visual attractiveness (Pecan Nut Cultivars – Pecans South Africa, 2020). Choctaw, as a secondary main cultivar (for pollination), is known for its large tree structure and nut size. 'Navaho', is the cross-pollinator that is also more adapted to arid regions (Clark, 2020; SAPPA, 2017). Limited information regarding the performance and adaptability of these cultivars in the Western Cape has been documented and therefore baseline information is required for successful future commercial expansion into these regions.

Reliable information on ET in the Western Cape for pecan cultivation in the Hermon and Vredendal regions, is lacking. Irrigation is essential in pecan cultivation in these Mediterranean regions, as pecans are known for their high-water use, with a 30% higher optimum consumptive usage compared to other crops (USA), leading to a higher overall production cost for pecans (Hwang and Bin, 2019; Wang et al. 2007). Therefore, accurate water usage estimates are important if the expansion of pecan is considered in the future, or in non-traditional regions (Sammis et al. 2013). This is especially important under local conditions, in the Western Cape, as water availability is already under severe strain, with climate change most likely to increase the water stress due to increased crop demand, variable rainfall and increased population growth (Talanow et al., 2020).

In paper 1, the effect of different pecan planting densities on the yield potential of young, bearing orchards was determined by quantifying various vegetative and reproductive parameters over two consecutive seasons, in two different climatic regions (Hermon and Vredendal) in the Western Cape, South African. Wichita was the primary cultivar for investigation.

In paper 2, the suitability of three pecan cultivars, Wichita, Navaho and Choctaw were quantified in the Vredendal area. Vegetative and reproductive parameters, as well as climate parameters, were quantified and related to current yields in a medium high density orchard.

In paper 3, a desktop study was performed to quantify current and future ET, using historical climate data and satellite imaging for the sites in Hermon and

Vredendal, to estimate the potential water use of pecans for current and a future climate scenario, should temperatures increase by 2°C.

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LITERATURE REVIEW: Factors influencing the growth, productivity, and quality of pecans for commercial production

Introduction

The pecan (*Carya illinoinensis*) is indigenous to Northern America, where it is growing wild in areas around the Great Lakes and along the Gulf of Mexico (Saaiman, 2014). The eastern pecans extend to Iowa and Clinton, Cincinnati and Ohio in the north, New Orleans and La in the south. The southern native pecans area extends from Texas to the north-eastern side of Mexico (Sparks, 2005).

Native pecan species, such as in Northern America, prefer semi-arid regions, with short cold winters, long hot summers and low rainfall and humidity. South Africa is generally considered a semi-arid country with sub-tropical, Mediterranean, semi-arid and arid climate regions. These climate regions are all suited to produce pecans providing sufficient irrigation is available since South Africa is a very dry country, with less than 500 mm annual precipitation (Olabonji et al., 2020; Otieno and Adeyemo, 2011).

Pecan trees were imported for the first time into South Africa during the late 1800’s and are currently commercially planted in various regions, of which the Vaalharts region in the Northern Cape, is the largest commercial area and contains one of the largest irrigation schemes in the world (Dedekind, 2020; Otieno and Adeyemo, 2011). Pecans are also planted commercially in nine climatic regions in South Africa: Limpopo, Mpumalanga, KwaZulu-Natal, Northern Cape (2), Eastern Cape, North-West (2), Free State, as well as in areas such as Tzaneen, KwaZulu-Natal, Louis Trichardt, around Pretoria and along the Orange River (ARC, 2020; Saaiman, 2014). Most of these regions have either a Mediterranean or semi-arid climate, with one or two sub-tropical climates. However, in the sub-tropical areas, where high rainfall occurs, disease problems are more prominent, leading to the move to more semi-arid regions (Saaiman, 2014).

Planting any fruiting crop requires a high initial investment, unlike annual crops, with a long-term return (Fronza et al., 2018). This is especially true for pecan cultivation, as the production only begins between the 4th and 10th year and only reaches maximum production between year 12th and 15th after planting. Therefore, factors influencing pecan production is very important when considering planting pecans for commercial use, since it has long-term effects that may only be evident afterwards (Fronza et al., 2018)

Documented information regarding the factors influencing pecan production is limited for the Western Cape. Some horticultural information for areas such as Cullinan and the Northern regions, documented primarily in popular publications e.g. SA Pecan and the recently updated local publication, 'Production guidelines for pecan'. Therefore, this literature review investigated the most important factors influencing the growth and yield of pecans for commercial consideration to guide further expansion of pecans into the much different Mediterranean climate in the Western Cape, with different cultivation and management requirements than the predominant summer rainfall regions in South Africa.

Environmental factors

Native pecans occur in a wide range of climatic regions in the United States of America (USA), ranging from mild to extreme harsh winters and very humid to semiarid regions (Table 1) and the region ranges between 30 and 42°N (Sparks 2005). The native pecan range in the USA follows the Mississippi river, as well as the rivers of eastern and central Texas, with different climatic regions and sentimental factors suited for different cultivars (Sparks, 2005). Important environmental factors influencing the commercial potential of pecan trees include climate parameters, soil characteristics, availability of water, pests and diseases native to the area and cultivar choice.

Temperature

The pecan is well adapted to the temperate and subtropical climate regions of the northern hemisphere of the USA. Its native region differs widely in rainfall frequency, the severity of freezing temperatures, heating and chilling and the length of the growing season (Preece and Aradhya, 2019). However, the pecan is adapted to grow in any area with short, cold winters and long hot summers (Taylor and Gush, 2009). Extreme deviations in the climate conditions can influence the productivity of pecans (Sparks, 1996; 2000b) and may lead to alternate bearing.

Suitable climatic conditions range from humid to dry and require temperatures from 24°C - 30°C during the vegetative growth (Sparks, 2005). Pecan trees also require cool winters with temperatures lower or equal to 7.2°C in winter, to satisfy dormancy requirements (Fronza et al., 2018). Pecan trees experiencing temperatures above or below the recommended temperatures can negatively affect growth. Pecans grown in Jammu and Kashmir (India), experienced sunburn and shrivelling of kernels, resulting in black nuts when exposed to temperatures of 38°C, which is higher than the recommended temperatures (Ravindran et al., 2008).

In elevated areas with an early spring, pecan fruit matures early, either because of an early spring or higher springtime temperatures, but no set parameters were given (Reid and Hunt, 2000; Sparks, 2000a). Flowering in pecans is primarily controlled by temperature, with higher temperatures resulting in earlier flowering (Han et al., 2018). Climate conditions, such as long photoperiods, high light intensity and water supply, longer growing seasons, carbon dioxide and warm temperature (no parameters were given) influence the juvenile length of seedlings. These climate conditions can promote growth leading to a shorter juvenile period, leading to earlier fruit production (Sherman and Beckman, 2003).

Climate can also influence pollination of pecans. Temperatures near freezing can damage and kill female flowers and catkins. The degree of impact will depend upon the severity of the damage caused by the duration of the temperature near freezing point or below. These dead flowers will impact pollination and the overall nut production. The rate of flowering is also influenced by temperature. Temperature not only alters the date of pollen shedding, but also disrupts the timing of flower maturity between the male and female flowers (Wood et al., 1997). Pollen dispersal is influenced by the climate and a combination of dry air at relatively high temperatures and wind, which will shorten the release by the anthers, again, no set parameters were mentioned (Wood, 2000). These conditions will also influence the pistil's receptivity period.

Rainfall directly and indirectly determines production, by influencing the soil moisture and pollination directly and indirectly and by causing diseases such as pecan scab (Sparks, 1997). The duration and intensity of the rain will determine the severity of damage. Rain can wash away the pollen from female flowers. Moist and cool conditions can also lead to protracted and delayed dispersal of pollen, with wet conditions and lowered humidity leading to an immense release period of pollen (Wood, 2000). Rainfall, along with relative humidity, play an important role in the occurrence of pest and disease incidence (Taylor and Gush, 2009). Severe pest and disease pressure will limit the viable commercial production of pecans in susceptible areas.

Temperature affects nut volume and kernel development. Optimal nut growth was achieved under higher temperatures with factors such as soil moisture being optimum; no details were available (Sparks, 2000a). Not only is temperature important during kernel development, but rainfall is also paramount (Sparks, 2005). During the four-week period of kernel development, fruit growth is highly dependent on adequate soil moisture (Sparks, 2005). Increasing spring temperatures also stimulates root growth and the absorbance of the water and nutrients. Actively growing roots can be killed at soil temperatures below -2°C, with growth increasing slowly as the temperature increases from 0 - 15°C and rapidly increasing from 15°C - 30°C, whereafter growth slows down until it stops at 38°C (Woodroof and Woodroof, 1934).

Deviations in climate and weather are some of the major reasons for alternative bearing (Sparks, 1983). Climate conditions such as prolonged cloudy days and rainfall events, as well as severe short-term droughts, can induce irregular bearing for the following year, especially during a heavy crop year (Sparks, 1996). Severe conditions can cause premature defoliation that suppresses the return bloom (Sparks, 1996).

Inadequate soil moisture during either fruit elongation, fruit expansion or kernel development, will negatively affect fruit development (Sparks, 1996). When excessive rainfall events occur during this period, nuts will enlarge, but poor filling will occur, when followed by dry soil moisture conditions (Sparks, 1996). Excessive rain can also supress kernel development and quality (Sparks, 1996; Sparks et al, 1995), while inadequate soil moisture can cause fruit abortion.

The previous year's climate has an indirect effect on the current year's growth. Variation in sunlight (sunlight penetration through the tree), temperature and soil moisture influence the photosynthetic activity of the leaves (Arreola-Avila et al, 2006; Sparks, 2000c). Late spring freeze in the current season can indirectly affect the fruit set. Drought in the current season can lead to natural fruit drop and indirectly affect fruit set by inducing fruit abortion (Sparks, 2000c).

Low temperatures

Native pecans have a low chilling requirement (Abou-Taleb et al., 2010) and a wide range of cold tolerance. Hibernation and withstanding very low temperatures are important characteristics of pecan, with Northern American pecan tree genotypes seen to withstand between -34 and -40°C (Sparks, 2005). Kudan et al. (2013) reported that cultivars originating from the southern USA have lower chilling requirements compared to northern cultivars, which can be as high as the requirements of walnuts. These northern pecans are also associated with a higher cold hardiness and early fruit maturity (Reid et al., 2000). The maturity stage of the tree can affect the temperature resistance of the tree in addition to cultivar type, with juvenile trunks being more resistant to freeze injury than non-juvenile trunks. Juvenile trunks of northern origin are also more resistant than southern types. Seedling survival in colder areas is higher in juvenile than non-juvenile trunks (Sparks, 2005).

Another negative effect of low temperatures is cold injury to pecans. This is expressed by symptoms including longitudinal bark splitting, separation of back from wood, sunken areas on limbs and shoots and death and browning (Wood and Reilly, 2001). Freeze injuries are commonly associated with low autumn temperatures before trees are acclimatised for winter, during winter when trees are dormant and, lastly,during spring (Smith, 2002). According to Sparks and Payne (1978), factors that influence the susceptibility of pecan to freeze injury are dormancy, insect and disease injury, air drainage, cultivar and tree death. Late spring freeze is the most common way for freeze injury (Wells, 2008). Therefore, only cultivars that are tolerant to cold injuries and freezing must be selected for cultivation in these environments.

Chilling

The most important factors influencing bud break or release of dormancy are winter chilling and spring warming. Most dormant trees require exposure to cool temperatures under 10°C or less during the preceding winter, before bud break will occur as temperatures increase during spring (Hunter and Lechowicz, 1992). Therefore, pecan yield will be compromised in areas threatened by a reduction in winter chilling predicted by global climate changes (Alae-Carew, 2020).

In general, for most deciduous species in the southern hemisphere, 500 to 1500 chill units (no parameters given) are required during the winter (Taylor and Gush, 2009). Núñez-Moreno et al. (2015) mentioned that the chilling requirement of pecans is 500 to 600 h < 7.2°C and this confirmed studies by Sparks (1993a), who found that early cultivars Desirable and Mahan have a chilling requirement of 500 h, while the later cultivar Stuart, have a requirement of 700 h. In another study, Kudan et al. (2013) reported chilling requirements of ‘Success’, ‘Mahan’, ‘Schley’ and ‘Desirable’ as 300 h to 400 h and 'Stuart', 700 to 1000 h. Dedekind (2020) recorded 322- 453 Daily Positive Chilling Units (DPCU) 117 - 354 Richardson Chilling Units (RCU) for 2018 and 2019 in Prieska, the main pecan production area of South Africa.

In areas where insufficient chilling occurs, yields may be decreased and even lead to alternate bearing. Therefore, some northern cultivars, such as Kanza and Peruque require long summers with sufficient summer heat and minimum of 950 cooling degree days (Thomas et al., 2015).

Heat units

Although pecan trees need a high freeze tolerance when planted in colder areas, the actual limiting factor for growth is the amount of heat it receives during the growing season (Sparks, 2005). Sparks (2005) proposed an average seasonal total above 555 heat units, with a base temperature of 18.3°C, for successful production and 190 to 200 frost free days, with a minimum of 100 chill units according to Fronza et al. (2018) and Thomas et al. (2015). Sparks (1993a) further stated that the date of bud break is less regulated by chilling- and more by heat requirement, but no definite parameters were available for this interaction. Budbreak occurred after heat accumulation of 237-degree days. Results also showed that the standard base temperature of 7.2°C yielded a poor relationship between heat accumulation to bud break and chilling. The best relationship occurred between heat units and chilling hours with a base temperature of 3.9 - 4.4°C. The amount of heat that is required for bud break in the spring decreases as winter chill accumulation increases, but with the lack of an obligate chilling requirement, growth can still commence with little or no chilling (base 3.9 °C). Sparks (1993a) also stated that chilling enhances seed germination but does not prevent germination if a lack of chilling occurs. This less-sensitive response to lower heating temperatures can delay bud break and minimizes the chance of damage from a late spring freeze (Sparks, 2005).

Delayed bud break leads to protracted pollination and causes varying nut maturity resulting in multiple or delayed harvests (Sparks, 2000b). The date of bud break is also important and depends on the growing degree hours (GDH), the hourly temperature above a threshold for each hour of the day, as well as the chilling requirement (Kudan et al., 2013).

Wind

Strong winds can severely damage large trees, and this have long lasting effects, which can influence future growth and production of the tree (Wood et al., 2000). An extreme form of wind damage is uprooting, that is the most noticeable form of damage caused by the strong winds created by hurricanes. Observations after hurricane events showed that central leader trees display less damage than multiple leader trees and recovered more rapidly compared to non-leader trees (Wood et al., 2000). Certain cultivars, including Choctaw, Jackson and Western Schley with dense canopies and large leaflets are more prone to uprooting. Cultivars with open canopies present less wind resistance and are less likely to be uprooted (Wood et al., 2000).

The age of the tree can also influence the resistance against strong winds. Young trees (1~5 years old) have enough flexibility, just as older trees (50~70 years old) have enough bulk and anchorage, to withstand the winds and uprooting (Wood et al., 2000). In contrast, intermediate aged trees are more susceptible to uprooting. Soils wetness contributes to the uprooting of the trees, with more saturated soils increasing the chance of uprooting and increasing the recovery rate if trees are indeed uprooted (Wood et al., 2000).

The most common outcome of extreme winds is limb breakage, which causes major damage to trees that can last for several years, with multiple-stem trees being more susceptible to wind-induced limb breakage then trees with only one or two major shoots (Wood, 1996). Cultivated pecan trees are more vulnerable than native trees, because native trees lack a strong central leader and often have an array of scaffold limbs with narrow crotch angles (Brown, 1974). The short-term effect of limb breakage is the loss of the bearing positions and an additional pruning cost. The long-term effect includes constant corrective pruning due to rotting of heartwood occurring, reduced tree vigour and the occurrence of water sprouts that are even more susceptible to damage (Wood et al., 2000).

Along with limb breakage, defoliation and fruit loss can occur. Strong winds often cause defoliation. If defoliation occurs early during the season, re-foliation may still occur, but at the expense of carbon reserves which may reduce fruit set for the next year (Worley, 1979). Therefore, defoliation may trigger and enhance alternate bearing. Breakage of small branches is less detrimental but will affect tree recovery and may contribute towards a delayed harvest or even no harvest at all (Wood et al., 2000). Wind also influences pollination directly as the pecan is wind pollinated with tree height increases the efficiency of wind pollination, because of the velocity that increases with height (Sparks, 2000b).

Soil

Soil type

Native pecan groves are acidic, with pH levels below 6.0, but can exceed levels above 7.0 (Heerema and Walworth, 2016). Pecans trees are also sensitive to saline soils (Grageda-Grageda et al., 2011). Suitable soil types for pecans in South Africa include Oakleaf, Clovelly, Hutton, Griffin and Inanda forms (Taylor and Gush, 2009). In the USA, pecan orchards require more irrigation water than any other crop to yield maximum yield (Sammis et al., 2004). It has also experimentally been confirmed by Boisen and Newlin (1910) that pecans require up to 1300 mm per annum with a daily water requirement of 600 to 1000 L in Southwest USA (Burner et al., 2013; Othman et al, 2014; Sammis et al., 2004; Sparks, 2002). Therefore, pecans will optimally grow in soils with a low water capacity, such as shallow soils, or drained sandy or gravelly soils and where water limitations can occur (Sparks, 2002). Pecans grown in sandy soils, with less available water, are smaller and less productive than on soils with a higher clay content (Sparks, 2005).

Soil moisture

Pecans are deep-rooted and require a lot of moisture but will not stand poorly drained or waterlogged soils (Rosborough et al., 1950; Sparks, 2005; Wells, 2017a). Poorly drained soils, soils with hardpans, stiff clays or soils with thin soil layers and high-water tables are not suitable. Optimal soil conditions for pecan must be well drained, alluvial, fertile and deep (Putnam et al, 1960; Sherman and Beckman, 2003; Burner et al., 2013). Prolonged flooding during dormancy is not detrimental, but will suppress shoot and root growth at bud break. Prolonged flooding also caused nitrogen deficiency and non-infectious leaf scorch (Reid and Hunt, 2000). Overall, the abundance and productivity of pecan trees diminished as soil drainage decreased.

Soil moisture, which is influenced by soil type and structure, affects all stages as well as the fruit quality characteristics of the pecan nut growth. These characteristics include the nut volume and shape, kernel filling, shell thickness and shuck dehiscence (Sparks, 2000b). The correlation between soil moisture status and the different stages of nut growth are discussed in more detail by Sparks (2000b).

Sparks (2005) noted that the phreatophytic rooting habit and accessibility of roots to the water table are essential adaptations for pecan survival, regardless of the amount of soil moisture that can be stored (Bruner, 2013; Sparks, 2005). Native pecans have deep roots in well-drained loamy soils, as well as shallow roots in semi-arid regions with shallow soils or where shallow soils occur. In Georgia (USA), the productivity and tree height of non-irrigated orchards on moderately well drained soils were higher than trees in orchards on well-drained soils (Middleton et al., 1968) which were characterised by a high-water table and thus trees had access to water.

Drought stress diminishes the ability of the roots to extract water, causing reduced growth and increased fruit split during the watery stage (Othman et al., 2014). Higher yields are achieved in non-stressed conditions and, even moderate water stressed pecan trees, will show a decrease in yield and nut weight and retard growth (Garrot et al., 1993). Low soil moisture can also reduce the stomatal conductance, photosynthetic rate, transpiration, fluorescence, and the chlorophyll content of pecan (Othman et al., 2014). Furthermore, Wells (2016) reported that pecan trees can recover relatively quickly from an early season water stress if they have access to sufficient soil moisture as the nut size begins to increase.

Plant factors

Even though pecan is a high value crop, the time to full production (5 to 10 years) is a major disadvantage compared to other crops (Giuffré et al., 2017). Factors such as the cultivar type and growth habits are determined genetically but can also be influenced by the surrounding environment and management practices, causing changes in the internal factors that leads to the alteration of the growth and production of the plant.

Cultivar

The cultivar choice is the foundation for successful production (Abou-Taleb et al., 2010). Often the marketability of the nut is the primary focus when choosing a cultivar in commercial plantings (Sherman and Beckham, 2003). However, the climatic adaptation requirement must be met for successful growth and production (Sherman and Beckham, 2003). Not all cultivars are suitable for all areas, and yields may not always be sufficient for commercial purposes for all cultivars and all regions. Thus, choosing the correct cultivar for the specific climatic region is paramount in the successful establishment of a viable, commercial pecan orchard (Sparks, 2005).

When it comes to the distribution of a tree/ orchard, temperature at which optimum growth and production occurs not only depends on the variety, but also the stage of development (Taylor and Gush, 2009). The most desired characteristics when choosing a cultivar are disease resistance, good production and market demands (Rosborough et al., 1950). Other factors include yield potential, the nut size and quality, the flower and pollination type, precocity or age of fruit bearing and the time of harvest. Rohla et al. (2007) also stated that early fruit-ripening cultivars having a lower alternate bearing habit than late-ripening cultivars.

Since pecan scab is a high-risk disease, it is important to plant resistant cultivars in areas where the susceptibility is high, and a list of pecan scab resistant cultivars is available from Fronza et al. (2018).

Selection and breeding of precocious cultivars so far resulted in severe problems, including poor nut quality, enhancement of irregular fruiting, tree dieback, premature defoliation and an increase in susceptibility to freeze injury. These problems are accentuated in cultivars producing larger nuts, such as Mohawk, Mahan and Success. Cultivars with smaller producing nuts generally have fever nut quality problems (Wells, 2008).

Cultivars also vary according to climate adaptability, with Wichita not being suitable for elevated climates, as it is susceptible to winter injury (Sparks, 2000c). Some cultivars are more likely to produce abnormal flowers after a spring freeze than others, which may be influenced by the phenology of budbreak. Cultivars where abnormal flowering was observed in Georgia (USA) included Schley, Stuart, Desirable, Farley, Moneymaker, Success, Pabst and Mahan (Wells, 2008) and those where abnormal flowering was not observed included Curtis, Teche, Moor, Van Deman or Frotscher. This abnormal flowering behaviour is temperature dependent, with a critical temperature between -1.7 and -2.2°C (Wells, 2008).

Early maturing cultivars are advantageous as it achieves a premium price in the market. The market generally also demands larger and excellent quality nuts, especially in the earlier markets (Sparks, 2000c).

Some of the most important cultivars planted in South Africa are Choctaw, Wichita, Elliot, Barton, Ukulinga, and Shoshoni, with other cultivars showing potential including Nellis, Cherokee, Caspiana, Mohawk and Western Schley (Taylor and Gush, 2009).

Rootstocks

Rootstocks play an important role as they can cause differences in survival, yield, tree size and precocity (Grauke and Pratt, 1992). Different rootstocks also result in differences in the percentage of nut germination, the earliness of germination and the size of the seedling used. Results from Grauke and Pratt (1992) showed that the scion and rootstock combination could influence bud growth. This interaction between the rootstock and scion can also influence the freeze tolerance and the freeze damage that can be sustained, which will determine the survival ability of the plant. The most common rootstock used in Georgia, United States is 'Elliott' or 'Curtis'. 'Elliott' has good germination and develops a stem calliper relatively quickly, whilst 'Curtis' is similar to 'Elliott' and is more cold tolerant and recommended for the northern parts of the state (Wells, 2017b). The main rootstock and most popular choice in eastern growing region of South Africa is 'Ukulinga', used for its good scab resistance and consistent bearing (SAPPA, 2017).

Pollination

The pecan is a monoecious, dichogamous and a wind pollinated tree (Sparks, 2000b). Pollination is important as it enables fertilization, which enables development of a seed and fruit from the flowers. The timing of pollination is important, as the stigmatic surface of the pistil is only receptive for pollen for a short period of time (Zhang et al., 2015). Pollination is critical and a lack of pollination will result in yield reduction (Conner, 2007). Pollination is the necessary first step to produce nuts and is predominantly facilitated by wind in the case of pecans.

Several factors influence the pollination of pecan trees including tree age, with older trees flowering at different times than younger trees; the duration of pollination and the receptivity window, which also shortens with tree age; flower position, with interior and lower positions maturing more quickly and bud break, which influence flowering (Conner, 2007; Wood, 2000). In addition, Wood (2000) pollination of 'Wichita' is influenced by the distance of the trees from a pollinator, which can lead to reduced kernel quality due to self-pollination if the distance to the pollinator is too far.

Pollen distribution and dispersal of pecan occurs with wind, but differs between cultivars (Wood, 2000). Catkins located in the lower positions of the tree usually shed first and those at the top shed last with the pollen release proceeding from the base to the tip of the tree (Wood, 2000). Lower relative humidity and higher temperatures will ensure moderate turbulence and adequate wind movement, which will increase pollination (Sparks, 2005).

Pecans are unlike most deciduous fruit trees, with the restriction of female flower development in the spring of its anthesis. Stored substrates are decreasingly allocated from the base to the terminus in spring (Sparks, 2005), resulting in weak pistillate flower development on weaker shoots that will lead abortion of the cluster during the first drop (Sparks, 2005). Pistillate flower development is crucial for fruit development and is produced from substrates that accumulated from the previous year's growth. The final number of pistillate flowers is determined at bud break (Sparks, 1996). Thus, the maximum number of pistillate flowers are determined by the previous seasons growing conditions, not only the tree health and growth, but also environmental factors influencing the trees productivity (Sparks, 1996). The production of staminate flowers occur before the development of the pistillate, but this is not advantageous, as pecans are normally cross-pollinated, which is promoted by dichogamy and ensures the availability of sufficient pollen once the pistillate flowers are produced (Sparks, 2005).

However, pecan trees are monoecious, with the male and female flowers developing on different parts of the tree branches (Conner, 2007). The male flowers, catkins, produce the pollen and the female flowers, pistillates, require pollen from the male flowers for pollination. The flowers develop at different times, which causes the pollen production or female flowers to be past maturity when the male flowers are only yet reaching maturity (Ajamgard et al., 2017). This emphasizes the importance of the selection of cross pollinators to reduce chances of inadequate pollination with resulting low nut production or poorly developed nuts (Connor 2007; Zhang et al., 2015). Cross-pollination (dichogamy) is often complete in colder climates and incomplete in warmer climates (Sparks, 2005). When incomplete pollination occurs, it will result in fruit drop. Along with fruit drop, kernel development is also suppressed (Ravindran et al., 2008) and yields can be reduced by up to 75% (Conner, 2007) with reduced nut set and kernel percentage. Results from Ajamgard et al. (2017) showed that the number of nuts per cluster was significantly reduced by self-pollination of different cultivars.

Management practices

The pecan seedling rootstocks grow slowly and require at least two to three years to attain a desirable size for grafting/budding. This time period causes concern, since deep taproot growth occurs, leading to problems with uprooting and transplanting trees in the orchard (Ravindran et al., 2008). Luckily with the advancements made with the application of VAM + *Azotobacter* + GA_3 (5000 ppm), reported by Joolka et al. (2004), grafitability/budding of pecans are reduced to just a year after germination. Another problem, occurring even before grafting, is the germination of the pecan seed and the hardness of the shell with a combination of factors, including the nut size, cultivar, planting depth, and soil moisture, all influencing the seed germination (Ravindran et al., 2008).

Harvesting the nuts from big, mature trees can be challenging. A lot of damage to the tree when hand harvesting, especially using sticks, can cause damage to leaves, shoots and fruiting limbs which will influence the growth of the following year (Ravindran et al., 2008).

Therefore, several general management factors are important for proper pecan production and will be discussed below:

Planting distance and orchard design

Tree spacing influences management practices and decisions, by increasing the difficulty of spraying and harvesting (Andales et al., 2006), pollination, thinning, orchard establishment, future maintenance, and labour costs (Fronza et al., 2018). Tree spacing and orchard design will also influence yield and the breakeven point of the orchard, with closer tree spacings influencing decisions such as tree removal, which might remove the plants potential income before they can pay off their own establishment cost (SAPPA, 2018). Therefore, careful consideration of all factors is required before the orchard design is finalised.

Palmar et al. (1992) showed that yields increased with higher tree densities of apple trees. These higher tree densities resulted in a higher leaf area index (LAI) and light interception, with interceptions up to 84% of the incoming light. However, apple tree size can be manipulated with dwarfing rootstocks, to enable optimization of light interception and distribution (Anthony et al., 2020). This is not currently an option in pecan, primarily grafted on seedling rootstocks and can reach sizes between 45 to 55 m in height (Sparks, 2005).

Another factor that should be considered in implementing higher tree densities is shading of adjacent tree bases with decreased row spacing. The ideal tree height for the selected row spacing should not exceed 80% of the row (Stassen et al., 1995).

Similar to other perennial crops, the pecan tree requires high levels of light for optimal growth, yield and nut quality (Fronza et al., 2018). To increase the light interception, the correct orchard design and tree spacing is required. There are four types of designs used for pecans: square, rectangle, triangle, and quincunx, with the square system being the most common. The standard orchard density is 9 x 9 m, with a density of 9 x 18 m when growing starts to occur, in a rectangular shape (Herrera, 2000). The current standard orchard density in South Africa is 10 x 10 m, with a square design (SAPPA, 2018). The spectral distribution of solar radiation also changes as light penetrates and scatters within the tree. The light interception is therefore influenced by the structure and optical properties of the canopy components, which includes the leaves, fruit/nuts and branches (Bastias and Corelli-Grappadelli, 2012). To manage the interception of sunlight, management practices such as hedge pruning, selective limb pruning and tree thinning are used and described by SAPPA (2018). When tree densities are too high, the crowns of the trees will reach each other, which will cause the lower branches to grow less and lead to lower production (Wood and Stahmann, 2004). This reduction in light interception can result in death of the lower limbs, fruit to be born higher up in the canopy and increased difficulty of tree management (Lombardini, 2006). In extreme cases, reducing the canopy light environment (‘sunlight stress’) can increase alternate bearing (Wells, 2014).

‘Crowding’ is a common phenomenon in mature pecan orchards and occurs when the tree crowns are touching and overshadowing each other, usually after 8 to 12 years depending on the area and soil fertility and tree density, but usually when using a 30 x 30 feet design (Herrera, 2000). Crowding reduces the light interception per unit of leaf area, which decreases the efficiency of carbon assimilation, resulting in a reduced yield, in addition to encroaching canopies that may increase alternate bearing intensity (Wells, 2018). In addition, crowding also decreased air movement and increased the drying time after rain events, leading to a higher probability of pecan scab development (Lombardini, 2006). Black pecan aphids are also more common in the shaded interiors of crowded pecan trees. These shaded areas increase with the increase in overcrowded orchards, with higher risks for pecan scab development (Cottrell et al., 2015).

Canopy density can also increase via management practices like continuous hedging, which stimulates regrowth and potential excessive interior shading, often resulting in reduced yields (Sparks, 2000c). In contrast, Lombardini (2006) reported that mechanical pruning increased light interception in orchards of a 25-year-old pecan orchard, consisting of ‘Kiowa’, ‘Cape Fear’ and ‘Desirable’ pecan cultivars in Texas, USA, with a tree spacing of 11.6 x 11.6 m. The winter hedge pruning took place one time on the west and east side of each tree, 4 m from each side of the tree, which left a 3.6 m opening between the canopies of adjacent rows. Lombardini (2006) also stated that hedge pruning in irrigated desert areas is a common practice but was inconsistent and a short-term solution in more humid areas. These pruning strategies however only increased light interception between trees and not within trees. Overcrowded, unpruned trees can intercept up to 95 % of available sunlight compared to a 65 to 70% light interception by mature, pruned pecan orchards canopies (Wood, 1996 and Lombardini, 2006).

Even though mechanical pruning such as hedging is not advised, is it being considered in newly established orchards of high light intensive areas (Georgia, USA), as it was found to be effective for maintaining tree density, preventing crowding, and partially decreasing alternate bearing (Wells, 2014; Wood and Stahmann, 2004). Results for low-light intensive areas led to poor pecan tree responses (Lombardini, 2006; Wells, 2014; Wood, 2009). The long-term effect of higher tree densities, 9 x 9 m (Andales et al., 2006) to 6 x 6 m after 10 years resulted in overcrowding and shading of branches (Fronza et al., 2018). Shading led to nut production only at the top of the tree (Fronza et al., 2018).

Tree crowding is the phenomenon that pecan producers face during the production cycle and depends primarily on tree spacing. Tree spacing refers to good air circulation, light interception, and exposure for future growth. Other factors such as the soil depth, tree architecture and growth rate also play an important role in selecting the correct orchard design and tree spacing (Lombardini, 2006).

The root growth of bearing pecan trees is about twice the size of the growth of the branches (Lombardini, 2006; Rosborough et al, 1950). Therefore, crowding may impact root growth, which will affect the branch vigour, with 10-year-old pecan trees showing root growth double the size of the tree canopy (Lombardini, 2006). Higher planting density (9.1 x 9.1 m) orchards (no tree-age parameter was given) found in a dry, high elevation climate such as El Paso-Las Cruces area in Texas-New Mexico and the Tuscan area of Arizona, also caused slower growth and a delayed commercial production and potential income (Sparks, 2000c). Competition for nutrients, light and water under higher densities are probably the cause of weakening pecan trees (Lombardini, 2006). Lombardini (2006) also reported that crowding reduced productivity, kernel percentage, induces a reduction in the number of flowers that form and may cause a possible increase in alternative bearing.

Over cropping and carbohydrate reserves

Prolific cultivars, such as Wichita, require crop control, otherwise alternate bearing can occur because of overbearing (Sparks, 2000c). Extreme fruit set causes poor kernel development and quality and is accentuated by shuck decline in excessive fruiting trees (Sparks et al., 1995). This will result in reduced pistillate bloom the following fruit set the following season' (Sparks, 2000c).

Significant depletion of reserves occurs with the presence of fruit on the tree, which creates additional stress in the second half of the growth cycle. With excessive fruiting, pistillate development can be totally inhibited, or suppressed in the following season, resulting in an 'off' year, with weak and absent flowers. This pattern is described as alternate or irregular bearing, because environmental conditions can also affect return bloom, (Sparks, 2005).

Carbohydrate reserves are also affected by heavy cropping and the depletion of nitrogen (N), phosphorus (P) and potassium (K) reserves. The depletion of N, P and K reserves are associated with premature defoliation, caused by the high demand of rapidly growing fruit that cannot be met by uptake from the soil alone and must be supplemented by reserves from the leaves. This will cause a gradual decline in leaf reserves if an 'off' year cannot refill these reserves (Sparks, 2005).

As the fruiting stress increases, shuck decline is induced, premature germination is accelerated and this can lead to potential dieback (Sparks, 2000c). These effects mainly occur in high producing cultivars, selected for, large nut size and a high percentage kernel. In severe cases, tree death can also occur (Sparks, 2000c; Taylor et al., 2020). Heavy cropping can also cause tree breakage, affecting yield and the lifespan of the tree.

Alternate Bearing

Alternate bearing is associated with a lack of return flowering rather than the abortion of fruit or flowers (Smith, 2010). It is the tendency for wide season-to-season fluctuations in cropping intensity, especially for commercial crops such as pecans. Alternate bearing poses a major challenge for pecan trees and is often expressed as an ‘on’ year (heavy bearing) followed by an ‘off’ (light beating) season, or biennial bearing (Thompson et al, 2019). The tendency for alternate bearing increases with tree age increased yields and bearing size (Andales et al., 2006). It can occur at different scales, ranging from only branches to a single tree, orchard or region (Noperi-Mosquada et al., 2020).

Various cultural and management practices including nutrition, light and water management, vegetation control and fruit thinning have been applied to reduce alternate bearing intensity, but none could eliminate alternate bearing completely (Smith, 2010). The main factors responsible for alternate bearing include the level of carbohydrate reserves within the tree, a dual mechanism of carbohydrate balance and phytohormones, and endogenous hormone growth regulators from the fruit and leaves (Wood, 1996).

Pecan productivity, regardless of an ‘on’ or ‘off’ year, is dependent on the success or failure of flowering. The flowering process is complex and involves several environmental and endogenous cues (Thompson et al., 2019). Thompson et al. (2019) investigated the effect of exogenously applied plant growth regulators, such as gibberellic acid, to mitigate alternate bearing in pecan trees. They reported an increase in the number of flowers per shoot (125.3%) after treatment with GA_3 (double rate), compared to to the controlled ‘Western’ trees’ shoots (applied three times between June to July) in a study conducted in Mesilla Valley, USA.

Furthermore, the reduction in return bloom of the subsequent season is dependent on the intensity of the crop load and trees with a moderate crop load had a more pronounced effect compared to trees with a heavy or light crop load (Schmidt et al., 2009). Krezdorn (1955) found a strong relationship between foliar K and P accumulation and depletion and alternate bearing. During large cropping years, trees had a higher concentration of K and P due to higher reserves from the previous year. In addition, the concentrations of K and P increased faster in trees with a low compared to high crop load (Krezdorn, 1955). Smith (2010) found no increase in pecan yield with applied K, but Wells and Wood (2007) showed that a critical N:K ratio of 2:1

reduced alternate bearing. Additionally, increased yields with excessive N, reduced the nut yield and quality and enhanced alternate bearing (Wells and Wood, 2007).

Alternate bearing was also linked to fruit maturation time, fruit growth and the chemical composition of the kernel (Noperi-Mosquada et al., 2020). Pecan is a late season crop that ripens at the end of the season, close to autumn. Thus, a relatively short period remains to store carbohydrates and reserves for the next season's development and a lack of management of this process may further increase the onset of alternate bearing (Noperi-Mosquada et al., 2020).

Fertilization

Fertilizer management in pecan is often overlooked (Weckler et al., 2015). Whilst excessive application of fertilizers promotes pest and disease incidence, a lack of nutrition will result in poor nut development and growth and may induce alternate bearing (Weckler et al., 2015). Fertigation is an effective method of applying fertilizers to pecan orchards, which can reduce the labour cost (Wells, 2015a).

Pecans responded positively to fertilization and increase in stem diameter and tree height, especially during the early years of planting compared to trees in their natural habitat (Burner et al., 2013). However, fertigation with N may cause root damage to newly planted pecan trees during establishment if the irrigation and delivery rates are not properly managed (Wells, 2015a). Excessive levels of zinc (Zn), copper (Cu), calcium (Ca), magnesium (Mg) and manganese (Mn) in the soil can lead to deficiency (Wood et al, 2006).

In most plants, seasonal variation in nutrient concentrations occur in plant tissues, due to differential requirements during the developmental phases (Stassen et al., 1981). Maintaining an adequate nutrient balance during these developmental stages is crucial for optimum tree functioning and can also prevent leaf scorch and premature defoliation (Kim and Wetzstein, 2005).

The timing of fertilizer application is also important. According to Kraimer et al. (2004), a late-season N-fertilizer (NH_4NO_3) application stimulated new growth which can cause serious freeze damage, but this contradicted Sparks et al. (1995) who reported that the cold damage sustained was unaffected by the timing of application.

Mineral imbalances

One of the challenges most growers face is the establishment of orchard trees in regions with calcareous and alkaline soils with high pH levels, in which micronutrients, particularly Zn, are poorly available (Heerema and Walworth, 2016; Walworth and Pond, 2006). In calcareous soils, soil application of zinc (Zn) is challenging (Walworth and Pond, 2006). Walworth and Heerema (2016) recommend the application of ZnEDTA in calcareous and alkaline soils to overcome Zn deficiencies in pecan.

Zn deficiency is the most common and economically important deficiency for pecan trees, especially for more susceptible cultivars, such as Wichita (Heerema and Walworth, 2016). Zn has an extremely low solubility in alkaline conditions and forms complexes with carbonite minerals (Walworth and Heerema, 2016). Zn is an essential trace element required by pecan trees for successful nut production, and generally described as a non-infectious disease of pecans (Reid and Hunt, 2000), with inadequate levels severely limiting crop productivity (Hu and Sparks, 1991).

Zn-deficiency symptoms are usually characterized by the shortened internodes giving the tree branches a “rosette” foliar feature, with a reduced leaf area, wavy leaf margins with interveinal leaf necrosis and chlorosis (Heerema and Walworth, 2016). Zn deficiencies also cause reduced flowering intensity, reduce pistillate flowering and the final number of fruit set, which severely reduces nut production (Hu and Sparks, 1991). Zn deficiencies can also cause impairments in the development of the reproductive structures, decrease carbonic anhydrase and lead to low stomatal conductance (Hu and Sparks, 1991). These impairments reduced the number of fruit produced per branch and drastically decreased the development of fruit and delayed nut maturation (Hounnou et al., 2019; Fronza et al., 2018).

During the pecan growth period, especially of shoot elongation, pecans require relatively high concentrations of Zn (Sparks, 1993b). Zn is required for the regulation of the transfer of photosynthesis from the chloroplast into the cytoplast and therefore photosynthesis can be expected to be affected (Hounnou et al, 2019). When Zn deficiency occurs, it can cause stunted growth and even dieback in extreme cases in pecan trees and can quickly reduce the canopy volume (Heerema and Walworth, 2016). The negative impacts of Zn deficiency on the carbon assimilation (Heerema et al, 2017) can also result in a reduced leaf area and leaf thickness (Hu and Sparks, 1991; Ojeda-Barrios et al., 2012).

The coverage and environmental conditions during foliar Zn applications affect the efficiency of the treatment (Heerema et al, 2017). Furthermore, Zn deficiencies increase the Iron (Fe), Mn, Cu and P concentrations and decrease K and N concentrations (Ojeda-Barrios et al. 2012).

Delayed bud break and dieback on the current year's shoots caused by a Mn imbalance was observed in 'Western Schley', Southeast Arizona. Mn imbalances are not common in pecans, with toxic concentration not showing any symptoms on the tree (Núñez-Moreno et al., 2012). Severely affected trees had a Mn concentration of 13000 ppm and unaffected trees, a concentration of 5900 ppm. The main cause for the high Mn concentrations was the very low soil pH of 4.3.

Along with the delayed bud break, lateral branches produce smaller catkins which later die, leaves turn pale with curled leaflets causing a reduced leaf size and canopy cover and leads to early defoliation and even dieback of branches (Núñez-Moreno et al., 2012). Reproductive characteristics are also affected by Mn toxicity, as well as the growth of the shoots. Affected trees only had an average of 7% fruiting shoots versus 86% of unaffected trees. The annual shoot growth was also affected, with only 2 cm versus 13 cm shoot growth of unaffected trees, with the shorter shoots showing signs of 'rosette' symptoms (Núñez-Moreno, 2012). Most of the symptoms occured early in the season and indicated that the Mn was redistributed from reserves, which could be affected by the previous year's growth (Núñez-Moreno et al., 2012).

With regard to the reproductive biology of pecans, N is the most dominant element. The number of nuts per tree will dramatically increase as N levels in the tree increases over a wide range, above visible deficiency (Sparks, 2000b). This increased N, no details about set were available, resulted in an increase in pistillate formation and less abortion of flowers, indicating the importance of N on the fruit set of the current year's growth.

Four distinct reproductive drops occur in pecans (Wood et al., 2010). Observations indicate that a low K concentration may be the cause of Stage II fruit drop of pecans, since stage II is associated with the absence of zygotes, as well as ovule tissue structural problems, caused by physiological stresses (Wood et al., 2010). This postulate is further supported by evidence demonstrating increased nutmeat yields and quality and reduced fruit drop (Wood et al., 2010). In years with a high crop load, K deficiency is a common problem in pecans and is visible as interveinal chlorosis of the older leaves (Wood et al., 2010).

Smith (2010) showed a relationship between leaf necrosis and defoliation, with P and K concentrations below 1%, because of a high demand for K and P found during fruit development. A concentration of 1% leaf K, according to Smith (2010), should be sufficient to support fruit development. P and K play an important part in leaves and fruit of alternate bearing pecan trees, since a depletion of P and K reserves from a heavy demand, such as fruit development, might be a factor in alternate bearing (Krezdorn, 1955). Years of large crop loads in pecan resulted in leaf necrosis and partial early defoliation on the fruiting shoots (Smith, 2010). These shoots had lower P and K concentrations than the non-fruiting shoots. Necrotic symptoms on leaves would lead to defoliation and reduced nut weight, and therefore kernel quality. This defoliation, specifically premature defoliation, reduces the pistillate development of the following year and can initiate an alternate bearing cycle (Smith, 2010).

Irrigation

Pecans are a high-water use crop and therefore require a large quantity to thrive (Wells, 2018; Kallestad et al., 2006). When pecans are subjected to any kind of water stress, reduced yields, vegetative growth and nut weight are experienced (Ibraimo et al., 2018). Different stress periods exist.

Appropriate irrigation scheduling is very crucial when rainfall does not occur regularly, especially in winter rainfall areas like the Western Cape, or dryer production regions like the Northern Cape of South Africa (Ibraimo et al., 2018). Irrigation is one of the most important management tools to increase nut size, yield, nut quality and precocity and the pecan production as a whole (Wells, 2015b; Wells, 2015c; Wells, 2016; Garrot et al., 1993). When all other nutrients are in sufficient quantities, non-water-stressed evapotranspiration will contribute the most to the tree’s carbohydrate production (Andales et al., 2006).

The amount of irrigation water requirement for the production of pecan crops ranges from 1.9 to 2.5 m per year, with 1.4 m water required in New Mexico, depending on the soil type (Sammis et al., 2004; Kallestad et al., 2006). Weed growth is promoted by irrigation and can reduce the growth of pecan trees by more than 50 % (Grey et al., 2018). Newly planted trees that are sensitive to competition from weeds, with promoted weed-free strips shown to increase the trees survival, growth and water efficiency and reduce the time to nut bearing and produce the first commercially viable yield (Smith, 2011).

Although pecans have a high-water requirement, it is resistant to severe droughts of moderate duration, with shorter shoot growth and smaller leaves in the spring of the second year after a severe drought. Thus, a normal leaf moisture level is maintained, even if the water requirement is reduced (Finch and Van Horn, 1936). If a drought persists, dieback will occur, limited to branches in the treetop, with continuous progression downwards. If the drought stress occurs before the onset of kernel development, it would lead to fruit abortion, but not leaf abscission (Ravindran et al., 2008).

Furthermore, pecan growth, drought resistance and production increases directly with soil depth (Sparks, 2002). However, the ability of pecans to withstand water deficit is low compared to other trees. The pecan's sensitivity to water logging conditions was illustrated with a widespread Fe deficiency in young trees, after excessive irrigation near bud break, of calcareous soils (Sparks, 2000c).

Conclusion

In this review, factors influencing commercial pecan production were discussed in general. The review indicated the lack of local peer reviewed results under local conditions but contains some of the most important factors needed to take in consideration when pecans are chosen as an alternative crop.

The most important factors to consider when choosing to plant pecans is to ensure the location is suited to plant pecans and that the cultivar chosen can adapt to the specific soil and environmental factors, provided that sufficient water is available to produce pecans. Other factors include management factors, which are producer specific and are determined upon the experience and knowledge of set producers.

The Western Cape consists of mostly a Mediterranean-type climate with a wet winter rainfall and hot, dry summers required to produce pecans. The province also experiences cold winters, which lend themselves to produce deciduous fruits including pecan trees in specific areas, but with predicted climate change, an increase in the winter temperatures is still ideal for pecans which has a relatively low chilling requirement.

In most of the deciduous fruit areas, commercial production requires irrigation, as the Western Cape Province lacks access to sustainable rivers in most of these areas. Nevertheless, pecans have been planted commercially since the late 1990's, in a number of larger commercial regions in the Western Cape. However, for the newly identified marginal areas for pecan expansion, growing conditions have not been quantified sufficiently to confirm viable yields and suitable cultivars for commercial consideration. Therefore, further research and investigation into factors that will influence commercial pecan extension to these areas needs to be conducted before this can be recommended.

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Tables and Figures

Table 1: Climate regions of pecans in the United States; region/ area, maximum and minimum temperatures and frost-free days of pecan orchards.

Region/ Area	**Temperature °C**		**Growing season (frost-free days)**	**Reference**
	Maximum	**Minimum**		
North	38	30	155 to 200	Reid and Hunt, (2000)
South	40	1.7	293	Sparks, (2000c)
West	32.2	3.9	312	Sparks, (2000c)

PAPER 1: The influence of planting distance on the development of newly established commercial 'Wichita' pecan orchards in the Western Cape

Abstract

South Africa is the third largest producer of pecans, with pecans first being commercially cultivated in Mpumalanga before expanding to the Vaalharts region of the Northern Cape. Recently, commercial production expanded to the Western Cape areas such as the Hermon and Vredendal. For successful production of any crop, the planting density forms a critical component, influencing productivity and the potential yield as produces are looking for higher and earlier production. Typical pecan tree spacing is 10 x 10 m (100 trees ha^{-1}), with higherdensity orchards 9 x 9 m (123 trees ha^{-1}) and higher. The development of newly established 'Wichita' orchards was investigated by quantifying vegetative and reproductive parameters, at different densities and ages, to provide a baseline for future research. Light interception was not influenced by tree age or density. Smaller trees (volume) were recorded in higher compared to lower density orchards, with a higher biomass production per tree for lower density orchards according to satellite imaging (Fruitlook®). Substantial increases in tree growth followed severe pruning, leading to a significant increase in tree size, especially in lower density orchards in Hermon. Overcrowding was observed in the five-year-old pecan orchard with a tree spacing of 10 x 5 m (200 trees ha^{-1}), leading to a reducing in lateral growth, as well as a decrease in yield in Vredendal. In trees of the same age, the lower density orchards produced more nuts per tree, with a higher yield per tree, but lower yield per ha. Hermon recorded slightly larger and heavier pecans compared to Vredendal, for trees of the same age. Growth and production tended to occur about two weeks earlier in Hermon compared to Vredendal, leading to an earlier harvesting date in Hermon.

Keywords: Biomass production, planting density, light interception, overcrowding

Introduction

The pecan (*Carya illinoinensis*) is a nut crop that thrives in southern United States due to its long, warm growing season (Reid and Hunt, 2000). It has since been planted throughout the world, with a significant increase in pecan plantings in South Africa, from a 2% market share in 1990 to 7% in 2020, rendering South Africa the third largest producer of pecans worldwide (Pecan South Magazine, 2020). In South Africa, it was primarily cultivated in the east, in the Nelspruit area of Mpumalanga, before gradually expanding westwards, to the Northern Cape in Vaalharts, with more arid conditions to reduce scab susceptibility (Pecan South Magazine, 2020). Recently, expansion has occurred even more west, to the Western Cape (Pecan South Magazine, 2020; SAPPA, 2017).

While pecans in South Africa are typically planted at a spacing of 10 x 10 m (SAPPA, 2018), an increasing number of producers are experimenting with higher density plantings, with spacing 9 x 9 m and closer (Herrera, 2000). They aim to achieve earlier productivity, earlier capital returns and faster filling of the allocated space (Hampson et al., 2004), but with no real data to support their findings in South Africa.

The planting density of perennial crops is a critical component of productivity and potential yield (Palmer et al., 1992). A perennial crop's productivity/yield is directly proportional to its planting density and the amount of solar radiation intercepted, with optimal tree spacing allowing optimum solar radiation interception and thereby enhancing yield per ha (Reid and Hunt, 2000). Palmer et al. (1992) found that yield increased linearly with tree density when comparing a single row system at 2000 trees ha^{-1} to 8333 trees ha^{-1} full-field system, for 'Golden Delicious' apple trees. However, this increased tree density has the potential to result in tree crowding, with excessive shadowing reducing production and limiting tree management approaches (Andales et al., 2006). Thus, finding the optimum planting density for each crop, cultivar, training system and region poses a challenge.

Another factor affecting trees' light interception is leaf area distribution, which is quantified by leaf area index (LAI) and fractional interception of photosynthetic active radiation (PAR), to determine vegetative cover and productivity potential of a crop (Othman and Hilaire, 2021). Palmer et al. (1992) found that higher tree densities of 'Golden Delicious' apple trees, compared to lower density orchards, resulted in higher LAI and light interception, with an interception of 83 – 84% of incoming light in a full-field system at 8333 trees.ha^{-1}.

Along with tree spacing and density, the type of canopy development (shape) is critical for seasonal and lifespan development (Robinson et al., 1991). For example, the umbrella-shaped canopy of apple trees showed several problems, including difficulty in hand harvesting, poor light distribution and low light interception early in the live of a tree, which resulted in delayed cropping (Robinson et al.,1991). While numerous strategies, such as rootstock and scion selection, can assist in controlling tree size in apples, only effective tree training and pruning can assist in controlling tree size in pecans, as appropriate dwarfing rootstocks are not currently a viable solution (Andersen and Crocker, 2004).

Yield or yield per input is used to determine the viability and efficiency of agricultural trees (Robinson et al., 1991). In addition, efficiency should also be quantified in terms of orchard management activities, such as spraying and pruning. Once again, these management practices relate to orchard design and tree density, which influence the amount of light intercepted by the tree that will determine the yield potential of the orchard. Jackson and Palmer (1980) also discovered an increase in apple production in relation to total light interception, but this gain was not solely due to increased light interception and pertained to improved light distribution throughout the canopy, resulting in increased light exposure to all fruiting positions in the canopy.

Planting density influences light interception on a per-area basis, with higher density orchards allowing pecan trees to occupy their assigned areas sooner than lower density orchards (SAPPA, 2018). Thus, potentially earlier harvests, higher yields and increased biomass production compared to standard density orchards, per area. However, pecan is sensitive to crowding and therefore the ideal orchard design for maximum solar radiation interception and distribution should be determined to achieve earlier productivity, whilst maintaining a viable yield after a full canopy is established in the absence of vegetative control via dwarfing rootstocks, or any pruning practices in early establishment. Insufficient information on the performance and management of high-density pecan orchards under local conditions initiated this study to determine the feasibility of high-density pecan orchards in the Western Cape.

In this paper, the aim was to i) quantify the development of newly established ‘Wichita’ orchards at higher densities than the traditional, commercial at 100 trees.ha^{-1} in South Africa and ii), evaluate these in two alternative locations in the Western Cape - Vredendal and Hermon. This would serve as a baseline for future research to determine the optimum planting density for pecans under Western Cape growing conditions. Both regions contained higher planting densities (two sites each) than commercially recommended and the four sites were compared to one another during two consecutive seasons, to establish a baseline of tree performance in these regions. Photosynthetic active radiation, vegetative growth parameters and yield were quantified over two consecutive seasons to follow the canopy development of trees at higher densities to the norm. In addition, satellite images were utilized to describe seasonal changes in biomass and evapotranspiration to indicate trends for these production areas (0.5 ha in area) over a number of seasons.

Materials and Methods

Experimental sites and experimental design

Two trails were conducted, one each in Vredendal (Trial 1) and Hermon (Trial 2), with both trials comprising two sites. The experimental sites for Trial 1 were located on two commercial farms, Zandkraal (Fig. 1.1) and Rotsvas (Fig. 1.2) (31° 35’ 22” S; 18° 25’ 6” E and 31° 42’ 52” S; 18° 31’ 49” E) in Vredendal and on one for Trial 2, Kleinplasie (Fig. 1.3), (33° 27’ 19” S; 18° 57’ 11” E) in Hermon, Western Cape, South Africa. The trials were conducted during the 2019/20 and the 2020/21 seasons.

The climate of Vredendal is classified as between Mediterranean and semi-arid and is characterized by short, mild winters with occasional rainy days and long, hot and dry summers. The annual rainfall of this region is 170 mm with a daily mean temperature of 17.8°C. The climate of Hermon is also Mediterranean, characterized by cold and wet winters and long, hot and dry summers. The annual rainfall of this region is 407 mm, with a daily mean temperature of 18.8°C, calculated using data provided by ARC-ISCW Agrometeorology Programme (ARC, 2021).

Vredendal Trial

Site 1 was a six-year-old pecan orchard, planted in 2015, with a tree spacing of 10 x 8 m (125 trees per ha^{-1}) and a total area of 2.6 ha and Site 2, a five-year-old pecan orchard, planted in 2016, with a tree spacing of 10 x 5 m (200 trees per ha^{-}) on 1 ha. Site 1 comprised three cultivars: ‘Wichita’ and ‘Choctaw’, planted as three rows per cultivar, and ‘Navaho’, planted randomly in-between the other cultivars as a cross-pollinator. Site 2 consisted of ‘Wichita’ rows with cross-pollinator ‘Navaho’, planted randomly in-between. All trees were grafted on ‘Ukulinga’ rootstock. Both sites were irrigated with a double drip line per tree, with a wetted diameter of 0.3 m and a delivery rate of 4 $L.h^{-1}$. Irrigation occurred for three to four hours per day. The soil type of Site 1 was a loamy, lime soil – Oakleaf 2120 and Site 2 was a sandy soil – Dundee 1210 (Soil Classification. 1991; Oberholzer and Schloms, 2011). Both sites were fertilized using recommended applications of urea, zinc, boron and nickel, with specification given regarding phosphorus or potassium. For pest management, false codling moth traps were placed in the orchard for monitoring due to the adjacent citrus orchards. The work rows were managed with herbicides for clean cultivation.

Hermon Trial

Site 3 was a four-year-old pecan orchard (2017), with a tree spacing of 8 x 4 m (312 trees ha^{-1}) on 3.73 ha and Site 4, a five-year-old orchard (2016), with a tree spacing of 8 x 6 m (208 trees ha^{-1}) on 1.58 ha. Both sites were planted on ridges, with an average height of 0.6 – 0.8 m and 2.5 m in width for Site 3 and 0.4 – 0.6 m and 2.5 m in width, in Site 4. At both sites, the main pecan cultivar was 'Wichita', with 'Navaho' as cross-pollinator, planted randomly in the orchard, all on 'Ukulinga' rootstocks. A cover crop, consisting of a mixture of a variety of weeds, most of which was Wild radish (*Raphanus raphanistrum*), were planted in both sites during winter. Both sites were irrigated with two micro-sprinklers per tree, with a wetted diameter of 0.45 m and a daily delivery of 30 $L.h^{-1}$ and 70 $L.h^{-1}$, each. Irrigation was scheduled three times a week, two to three hours per day, according to soil moisture readings, using a shovel and determined by the producer. The soil type for both sites 3 and 4 were a sandy clay with shale. Organic fertilizer was applied according to recommendations, with limited Basta® application in the tree row for weed control when required. Sites 3 and 4 were pruned and trained since establishment. Branches were removed from the bottom of the tree trunk at a height of 1 – 1.4 m. Severe pruning, with more than a meter of cutback, was done after harvest, in the 2019/20 season, to allow more sunlight to reach the inside of the tree.

Treatments and Trial Layout

Tree density served as the treatment, with Trial 1 consisting of densities 10 x 8 m and 10 x 5 m and Trial 2, 8 x 6 m and 8 x 4 m. No statistical layout was followed, as established orchards were selected for descriptive evaluation. The experimental design for both locations, and all four sites, consisted of a random selection of 15 representative trees, which served as experimental units.

Data collection

Vegetative parameters

Fractional interception of photosynthetically active radiation by the canopy

The fractional interception of photosynthetically active radiation (PAR) (µmol.m^{-2} s^{-1}) was determined for seven trees at Site 1, nine at Site 2 in Vredendal (Trial 1) and eight trees at both Sites (3 and 4) in Hermon (Trial 2), using a Decagon AccuPAR LP-80 ceptometer, Decagon Devices Inc. USA. This monitored the change in the effective fraction cover (f_{ceff}), as performed by Ayars et al. (2003) and Marsal et al. (2014).

Photosynthetically active radiation measurements were conducted below the canopy (underneath the lowest branches) of the selected trees, at predetermined 1 m intervals in each direction (North, South, East and West), to the edge of the tree canopy. A full sun reading was taken in the work row to represent the above canopy reading, required to calculate the fractional interception of PAR for the tree. All measurements were taken between 12 h and 14 h on clear sunny days, to ensure high PAR values (> 600 µmol.m^{-2} s^{-1}) and consistent readings. The PAR measurements were then used to calculate the fractional PAR (fPAR) as a percentage (%) and modified from the equation described in Zarate-Valdez et al. (2015):

$$\text{fPAR} = (1 - (\frac{PAR_{below}}{PAR_{above}})) \times 100$$

2019/20 season

PAR measurements were recorded at the end of vegetative growth, on 11/05/2020 for both sites in Trial 1 and on 28/04/2020, for both sites in Trial 2, and are presented as an average of all four measurement directions (N, E, S and W).

2020/21 season

Four measurements were conducted, individually per direction (N, E, S and W), during the second season, at specific phenological stages. No PAR measurements were conducted at stages 1 or 6, since bud break and leaf drop had no visually influence on light interception (Table 1.1).

Stem Circumference and Volume

Stem circumference (cm) was determined using a standard measuring tape, at a height of ~1.4 m above the ground on the following dates: Trial 1 (11/05/2020, 21/05/2021) and Trial 2 (23/04/2020, 15/04/2021).

Tree volume (m^3) was determined using a Nedo mEssfix (5 m) telescopic (Nedo, Switzerland) measuring ruler, to quantify height, width, and length of the individual trees. To calculate the volume of the tree, the average height of the orchard canopy was used, instead of the individual tree height, since the bottom ~ 1.4 m of the tree is bare and does not contain any side braces and therefore does not contribute to the actual tree canopy. The volume was taken on the following dates: season 1, Trial 1 (04/06/2020), Trial 2 (02/06/2020) and season 2, Trial 1 (06/07/2021) and Trial 2 (07/07/2021). The volume was calculated based on tree shape (Wood, 1996) described as a semi-ellipsoid (Rechneronline.de, 2021):

Volume = $(\frac{2}{3}\ x\ \pi\ x\ H\ x\ W\ x\ L\ )$

H = height

W = Width

L = Length

Shoot Growth and Vegetative Development

Shoot growth of two representative shoots per tree was measured only during season 2, on 21/05/2021 for Trial 1 and 04/05/2021 for Trial 2, with a Nedo mEssfix (5 m) telescopic (Nedo, Switzerland) measuring ruler. In addition, 20 additional randomly selected 'Wichita' trees were used for shoot measurements, two shoots per tree, at Site 3 to determine the correlation between shoot growth and yield, as the Hermon site was accessible.

Biomass changes were determined on a weekly basis using satellite data from 'Fruitlook®' available from the free website Fruitlook (https://fruitlook.co.za), from establishment of the orchards. Biomass was determined per 0.5 ha and then converted to a per tree biomass, based on the tree number for the area.

Phenological development was monitored, for Vredendal and Hermon, according to the stages described in Wells, (2017) (Fig. 1.4), modified by Ibraimo et al. (2018): 1. Bud-break, 2. Pre-pollination, 3. Pollination to early dough, 4. Dough stage, 5. Shuck or hull split and 6. Leaf drop

Pruning

Pruning mass was quantified per tree with an orchard scale (W22 Series. UWE. South Africa) at the end of winter in 2020 (26/08/2020), for both sites in Trial 2. Selective branches were removed in Trial 1, but this was not quantified due to logistics.

Weather data

Climate data was obtained from automatic weather stations in close proximity to the trial sites, for the stations in Vredendal (31° 41' 2" S; 18° 28' 9" E) and Hermon (33° 34' 60" S; 18° 58' 4" E) (ARC Institute for Soil Climate and Water (ARC-ISCW) Agrometeorology Programme (South Africa). Climate variables were recorded on an hourly basis. Chill unit accumulation, presented as Utah cold units (CU) and calculated according to the model of Richardson et al. (1974) were provided, as well as the daily positive chilling units (DPCU), according to the model presented by Linsley-Noakes et al. (1995).

Yield

Yield (kg.tree^{-1}) was determined via hand harvesting (in-shell, with shuck removed) on an orchard scale, from the 15 selected trees (W22 Series. UWE. South Africa) on the following dates: Trial 1 11/05/2020. Trial 2 23/04/2020. Trial 1 21/05/2021 and Trial 2 04/05/2021. Yield efficiency was then determined as yield per trunk circumference area (kg.cm^{-3}).

Nut quality characteristics, such as average nut fill, nut mass (g) (Kern PLJ series precision balances scale. Merck KGaA. Darmstadt. Germany) and nut size (length (mm) and diameter (mm)) were also determined (Mitutoyo 150 mm Digital Calliper. USA). In season 1, a random sample of 10 nuts from Sites 2 and 3 were selected to quantify nut fill (%), by opening the nut and visually inspecting it. A random sample of 50 nuts from Sites 2 and 3 was used for the other parameters. In season 2, a random sample of 50 nuts from all four sites was collected for these parameters, with again selecting 10 nuts randomly per sample, per site, to evaluate nut fill.

Statistical analysis

Data was analysed using one-way ANOVA using Statistical analysis software (SAS 9.4) Enterprise Guide 7.1 (SAS Institute Inc. Cary. North Carolina. USA). Least significant difference (LSD) was determined using the linear model procedure and the pairwise t-test for $p \leq 0.05$. Significant differences should be interpreted accordingly, where applicable, to reflect the layout of the trials.

Results

Vegetative parameters

Fractional interception of photosynthetically active radiation of the canopy

Trial 1: Fractional PAR of the individual trees for the first season did not differ significantly between the two plant populations (125 and 200 trees ha^{-1}) (Sites 1 and 2) on 11/05/2020 (Table 1.3). In season 2, none of the fPAR differed significantly for the different phenological stages (Table 1.3).

Trial 2: No significant difference was recorded in the first season between 312 and 208 trees ha^{-1} (Sites 3 and 4) on 28/04/2020 (Table 1.3). In season 2, treatments differed significantly for phenological stage 2 – (21/11/2020) (Table 1.4), with a significantly lower fPAR for the higher density, (79.63%) compared to the lower density (86.75%) (Table 1.1). There were no significant differences between treatments for any of the other phenological stages (Table 1.3).

Stem Circumference and Volume

Trial 1: Tree stem circumference differed significantly between Sites 1 and 2 in 2019/20 with lower density (125 trees ha^{-1}) having larger stem circumferences, but not in 2020/21 (Table 1.4). Nevertheless, stem circumference increased for all trees in season two. The average shoot length in season two differed significantly, with the lower density averaging a higher shoot length of 140.03 m compared to 99.67 m for the higher density (Table 1.4).

Tree height and volume differed significantly in season one, with Site 1 having bigger trees (5.85 m; 88.12 m^3) than Site 2 (4.88 m; 60.84 m^3). In contrast, only tree volume differed significantly between Site 1 (86.12 m^3) compared to Site 2 (65. 68 m^3) (Table 1.4) in the second season.

Trial 2: Tree stem circumference differed significantly between Sites 3 and 4 (312 and 208 trees ha^{-1}), with Site 4 recording the larger stem circumferences in both seasons

(Table 1.4). Average shoot length of the trees in the second season was significantly higher in Site 4 (149.97 m) than Site 3 (107.07 m) (Table 1.4).

Tree height and volume differed significantly in both seasons, with Site 4 recording a higher average tree height and volume than Site 3 (Table 1.4). These differences in tree development were observed personally, during the first and second season.

Vegetative development

A six-stage crop growth development timeline for Trial 1 and 2 was captured in Tables 1.1 and 1.2 respectively. Overall development, in Hermon (Trial 2), occurred two to four week earlier compared to Vredendal (Trial 1), whilst development between seasons differed by two weeks for bud-break and leaf drop, with the rest of the development occurring at the same time, with the exception of leaf drop, which differed five weeks when comparing seasons.

The pruned shoot mass collected at Trial 2 (26/08/2020) is shown in Table 1.5. More severe pruning was evident and a higher pruning mass of Site 4 than Site 3 (Table 1.5).

Yield and quality parameters

Trial 1: The lower tree density of 125 trees ha^{-1} recorded a significantly higher yield per tree, number of nuts and yield efficiency than the higher density of 200 trees ha^{-1} Site 2 for both seasons (Table 1.6). Yield expressed on a ha basis did not differ significantly for Site 1 compared to Site 2 in the first season, but a significant difference in the second season occurred, with Site 1 averaging a higher yield.ha^{-1} higher than Site 2 (Table 1.6).

Trial 2: Yield per tree, number of nuts per tree and yield efficiency (23/04/2020) differed significantly between lower density (208 trees ha^{-1}) than 312 trees ha^{-1} in the first season (Table 1.6). However, in the second season, no significant differences between sites were recorded for yield per tree and number of nuts. However, yield efficiency was significantly higher in Site 3 (Table 1.6). Yield expressed per ha did not differ significantly between Sites 3 and 4 in the first season, but Site 3 recorded a significantly higher yield.ha^{-1} in the second season (Table 1.6).

A number of relationships between yield and vegetative parameters (shoot growth, stem diameter, tree volume and fPAR) were investigated for 'Wichita'. Significant correlations were only established between yield and shoot length (R^2 = 0.2462), tree volume and fPAR (R^2 = 0.4686), data not shown, and tree volume and yield efficiency (R^2 = 0.1888).

In 2019/20, quantification of nut quality parameters of 'Wichita' were only measured for Sites 2 and 3. Even though not from the same region, Site 3 (Hermon) obtained a higher nut length, diameter, as well as mass than Site 2 (Vredendal), whilst recording a much higher yield compared to Site 3 (Table 1.7). Nut fill at both sites was 100 % (Table 1.7).

In 2020/21, nut quality parameters for 'Wichita' trees were quantified for all sites (Table 1.8). Nut length declined in the following sequence: 208 > 312 >200 and 125 trees ha^{-1}, with Site 4 recording the longest nut length. Diameter and mass declined in the following sequence: 312 > 208 > 200 >125 trees ha^{-1}, with Site 3 recording the highest nut diameter. Nut fill percentage was still 100% for all sites.

Climate Data

The highest average maximum temperature in season 1, for Vredendal, was recorded in February (32.75°C) and Hermon (33.53°C), whilst April had the highest maximum temperature in season 2 (31.41 C) for Vredendal and March (29.98°C) for Hermon. July recorded the lowest minimum temperatures in season 1 (3.85°C), for Vredendal and August (6.35°C) for Hermon, and season 2 - July (3.74°C) for Vredendal and Hermon (5.86°C) (Tables 1.9 and 1.10). Daily positive chill units (DCPU) and Utah Chill units (CU) are shown on a monthly basis in Table 1.11. Seasonal accumulated chilling presented as DCPU and CU, in Vredendal, was higher in 2019/20 (450.5; 193) than 2020/21 (344; 88) (Table 1.11). Seasonal chilling units for Hermon, again accumulated more chilling units in 2019/20 recorded (574.5; 307.5) than in 2020/21 (438.5; 196.5) (Table 1.12).

Remotely sensed data from satellites

Data for biomass production, for all four sites from establishment, is summarised in Fig. 1.5 to 1.8. As expected, there was an overall increase in seasonal biomass production, in all sites. There was a peak early in the season (August – October), with the onset of new growth, with a decline as the season progressed.

Seasonal biomass production is summarised on a per tree basis and for 0.5 ha, primarily to reflect biomass data for the experimental trees, in the selected area of each site, in Table 1.13. There was an increasing trend for all the sites from 2016 until 2021, except for one or two years. In the 2020/21 season, Site 4 (208 trees ha$^{-1)}$ had the highest biomass production per tree (301.36 kg), followed by Site 2 (200 trees ha^{-1}) (201.43 kg), Site 3 (312 trees ha^{-1}) (113.81 kg) and Site 1 (125 trees ha^{-1}) (79.82 kg). It should be noted that Sites 3 and 4 contained cover crops during winter, which increased the total biomass production in satellite images during this period.

Discussion

During the 2019/20 season, only one PAR reading was taken per site, at harvest time, due to logistics. No significant differences were found between the sites, indicating that a difference in light interception was not observed at this time in three to five-year-old trees, planted at different densities and that tree size/ volume does not influence the light being intercepted, measured by PAR. This contradicts findings on Guavas, where results indicated a clear-cut difference in light interception due to different densities – 3 x 1.5 m, 3 x 3 m, 3 x 6 m and 6 x 6 m (Singh et al., 2007) only from six years onwards, with the proliferation of shoot development leading to this reduction. No relationship was found between fPAR and tree volume or yield efficiency for the first season, indicating that the light interception of the pecan trees was not compromised at this young age, yields were still low and tree density did not influence light interception or yields yet. This indicated that tree volume, for the different planting densities and specific tree ages, was not the only factor influencing fPAR and that tree volume was not necessarily represented by tree shape, as even differences in the tree shapes did not result in differences in light interception. Further investigation using alternative solar radiation techniques should be implemented to confirm whether tree volume of pecans under these orchard designs impact light interception significantly.

During the 2020/21 season PAR was determined at four phenological stages, representing differences in tree growth which may have an influence on the light interception. Significant differences in fPAR were only observed at Stage 2, for trial 2, indicating that tree density influenced light interception, but only in the early stages of the canopy growth of the season. This is possibly due to the varying tree shapes and different tree densities. Later phenological stages did not record any significant differences, confirming that light interception was not yet affected by planting density, at these higher density plantings, in five and six-old trees. Stage 2, where leaf expansion occurred, differed significantly between the two plant densities of 312 and 208 trees ha^{-1} (Sites 3 and 4), with the lowest density intercepting more sunlight compared to the higher density. This difference could be partially attributed to the volume difference at the end of the previous season, as well as a reaction on pruning, which resulted in a denser canopy early in the following season. The significant correlation between tree volume and fPAR indicated the natural increase in volume as trees aged, as well as increased light interception.

Due to differences in tree age, significant differences occurred in stem circumferences and tree volumes between different plant densities, at both locations. The older trees in lower density orchards were bigger than trees of a similar age (five years) in higher density orchards and differences were not solely due to tree density. However, in the second season, stem circumferences of trees at different planting densities at Vredendal, were similar indicating a reduction in shoot growth, which resulted in overall tree growth as the trees are filling their allotted space, for the six-year-old trees. This was not the case in Hermon, where a significant difference in stem circumference was still noticeable in the second season, with trees being younger than those in Vredendal at this stage and being managed differently with respect to tree training. It remains to be seen whether crowding at this site will also be observed during the next season, when trees at Hermon will reach the same age of the current Vredendal trees.

In the second season, tree volume also differed significantly in both trials, with an unexpected decrease in tree volume for the low plant density of 125 trees ha^{-1} (Site 1) from the first season, while the other sites all showed an increase in tree volume. This may be due to the weight of the nuts bending the branches, which may have altered the shape of tree and impacted the formula used to calculate tree volume. In addition, the canopy shape may have changed due to bearing branches bending down, due to the higher yield and number of nuts and thus required an adaptation of the formula used to calculate tree volume thus far, possibly also incorporating a reference to tree density in future. If the change from vegetative to reproductive growth influenced the perceived reduction in tree volume, further investigation is needed as this phenomenon is likely to occur Sites 2 (200 trees ha^{-1}) and 4 (208 trees ha^{-1})in the following season. On the other hand, Site 4 showed a large increase from the previous season, which indicated a positive growth reaction to pruning the previous season, since it recorded a higher volume than recorded at Vredendal, for trees of a similar age (Site 2). Again, this observation was based on the limitations of calculated volume based on tree size and may be biased towards tree height and diameter, disregarding tree density.

In the second season, the trees in Site 2 (200 trees ha^{-1}) filled their allocated space in the tree row, resulting in overcrowding in the tree row, with lateral branching touching adjacent trees. This probably also contributed towards shorter shoot lengths compared to the trees in Site 1 with 125 trees ha^{-1} (99.67 m vs 140.03 m) and an increase in tree height from the previous season (4.88 m to 5.78 m) compared to tree height increases of the lower tree density in Site 1 (5.85 to 6.04 m), where trees could still expand sideways. This is most likely the cause for the reduction in yield, recorded in Site 2, as pecan pistillate flowers are produced on the current year's growth, with the flowers arising from the most apical buds of each shoot (Andersen and Crocker, 2004). Unexpectedly, there was no correlation between tree volume and yield efficiency (Fig. 1.9), but it is probably due to the small range of the various parameters at this stage.

In both seasons, phenological development at Hermon was on average two – four weeks earlier than at Vredendal. Bud-break occurred around week 35/36 at Hermon and week 40, in Vredendal, during the first season and occurred two weeks later in the next season. This is probably due to Vredendal receiving much less chilling compared to Hermon, even though recording lower average maximum and minimum temperatures during the winter period. Pollination occurred around week 44 to 48 at Hermon, while only starting at week 48 in Vredendal, again with a two-week difference in season two. In addition, the two-week delay for most of the phenological stages in the second season might also be due to lower temperatures in September, known to exacerbate a lack of winter chilling (Sparks, 1995). This may indicate an adaptive survival mechanism of pecan, delaying budbreak and minimizing any damage from late spring freeze (Sparks, 1995). According to Campoy et al. (2011) bud position and differences in sensitivity of vegetative and reductive buds to chilling temperatures may lead to delayed bud break, but this was not quantified in the scope of the study.

The trees from Vredendal and Hermon had different shapes, with the Hermon trees trained to a more formal central leader since establishment, which influenced tree volume/canopy calculations. Trees at Vredendal followed a closed to open vase design after initial attempts towards a central leader were abandoned. The vase canopy design rendered the trees more vulnerable towards limb damage, affected by strong winds, with more tree damage recorded at Vredendal than Hermon. This is a common problem in young pecan trees, especially those with an open-canopy design in wind prone areas, resulting in less wind resistance and being more prone to wind damage (Wood et al., 2000). Cultivars such as Choctaw, with its dense canopy, are also more prone to wind damage (Wood et al., 2000), but quantification between cultivars with reference to wind damage was not included in this study.

A significant difference in yield per tree, between treatments, in both regions, were recorded as expected from the age difference, as well with tree densities with the lower density pecan recording higher yields. In the second season, yields only differed significantly at Vredendal (Trial 1), with a decrease in Site 2 (200 trees ha^{-1}) compared to Site 1 (125 trees ha^{-1}). At Vredendal, only Site 1 showed an increase in the yield per hectare, from 699.25 $kg.ha^{-1}$ to 759.91 $kg.ha^{-1}$, but it also exceeded industry norms for six-year-old pecans at traditional densities (10 x10 m). Dedekind (2020), however, recorded a much higher yield of 12.34 $kg.tree^{-1}$ for six-year-old pecans in Prieska at the same, with traditional tree density of 10 x 10 m producing 1200 $kg.ha^{-1}$, compared to the 759.91 $kg.ha^{-1}$ of Site 1 (10 x 8 m), at the same age. In contrast, Site 2 showed a decrease in yield, in spite of an increase in tree size evident in an increase in stem circumference, height and overall volume, leading to the previous conclusion that overcrowding occurred which manifested in a decline in yield. The recorded increase in tree growth (height and volume) resulted in a reduction in shoot length, which could influence the number of bearing units per shoot, alternatively, the increase in tree height could have increased overshadowing in the canopy, and therefore the reproductive potential of the tree.

Hermon (Trial 2) did not record a significant difference in yield between sites (3 and 4) in the second season. The severe pruning at Hermon significantly impacted reproductive growth and masked the age difference, as well as the difference in planting density. Nevertheless, the heavy pruning at Site 4 (208 trees ha^{-1}) still showed a substantial increase in yield from 242.47 $kg.ha^{-1}$ for season one to 549.78 $kg.ha^{-1}$ for season two, caused by longer shoots leading to more pistillate female flowers per shoot (Andersen and Crocker, 2004. This crop load is considerably higher than reported for local five year old trees at traditional tree densities (10 x 10 m) of 100 $trees.ha^{-1}$ (50 $kg.ha^{-1}$), indicating that higher density orchards does lead to higher yields per hectare (SAPPA, 2020). Smith et al. (1993) also reported that yield was positively related to the percentage of fruiting shoots in pecans, which is a possible cause for the higher yield of lower density of 208 trees ha^{-1} (Site 4), caused by longer shoots, leading to more fruiting shoots. Yield was reduced by fruit thinning as well as whole branch removal, allowing for higher light exposure after thinning of older 'Mohawk' trees (Smith et al., 1993). Lombardini (2006) found that thinning results depended on cultivar, with 'Desirable' being positively affected by one-time pruning, where after the effect disappeared after three years, whilst 'Cape fear' having mixed results and 'Kiowa' pecans showing no effect. However, Worley and Mullinix (1997) indicated that a reduction in yield should be expected from pruning young pecans. This is not entirely the case for four year old trees planted at 208 trees ha^{-1} (Site 4) who showed an increase, although little when considering the increase in tree size, but may be the result of a sink:source reaction. At site 3 the 4 year old trees planted at 318 trees ha^{-1} reacted oppositely, despite also being pruned heavily, but recorded a much higher increase from 0.61 kg.tree^{-1} to 2.44 kg.tree^{-1}, which was for four-year-old trees, substantially more than industry yields for four-year- old trees, at densities of 100 trees.ha^{-1}. The yield was higher than recorded for the lower density orchard (Site 4) at the same age (four years), indicating a higher density orchard in Hermon would possibly achieve higher yield.ha^{-1} in future. This result was also recorded in a study on 'Royal Gala' and 'Summerland McIntosh' apples, with results indicating a decrease in yield per tree for higher density orchards, but an increase in the yield per ha (Hampson et al.,2004).

The lower density orchard in Hermon recorded slightly longer nuts than the higher density orchard, with the higher density orchard recording heavier and thicker nuts compared to the lower density orchard. This is also the case in Vredendal with the higher density orchard obtaining larger and heavier nuts compared to the lower density orchard, and possibly due to the higher density orchards recording a smaller number of nuts per tree. With regards to nut quality for both regions, Hermon recorded slightly larger nuts compared to Vredendal, but a true comparison and conclusion can not be made regarding this observation, as factors such as orchard management, including pruning, water allocation and fertigation can all contribute to these differences in addition to yield. Therefore, further investigation is needed to identify the factors contributing to the nut size differences.

Significant differences in yield efficiency were also found in both seasons, for both trials. The Hermon trial (Trial 2) saw an increase in the yield efficiency from the first to the second season, where the five year old trees planted at 312 trees ha showing an increase of almost three times in yield efficiency. In the Vredendal trial, there was a decrease in yield efficiency at both sites, which was more prominent for the five year old trees planted tat 200 trees ha^{-1} (Site 2). The yield efficiency of Site 1 (153.84 g.cm^{-2}) compared favourably with that recorded by Dedekind (2020) of 108.8 g.cm^{-2} for six-year-old pecans in Prieska, with a tree density of 10 x 10 m compared to the tree density of 10 x 8 m in Vredendal. This indicates a higher yield efficiency for higher density pecan orchards with Site 3 (higher density orchard) at age four also recording a higher yield efficiency than the lower density orchard of Site 4 at the same age.

Pecan prefers a climate with long hot summers and short cold winters, which fitted the description of the Hermon and Vredendal regions, with Vredendal more dependent on irrigation during summer, higher average maximum temperatures recorded. Favourable temperatures between 24 and 30°C during its vegetative growth, with little variation between day and night temperatures are required for optimal growth (Fronza et al., 2018). This corresponded with the average temperatures recorded in Vredendal (29.1 and 28.8°C) and Hermon (28.8 and 26.5°C) for both seasons. Temperature extremes, exceeding 38 °C, is a limiting factor and can cause black nut in pecans (Ravindran et al., 2008). Temperatures up to 43°C occurred in Vredendal when looking at absolute temperatures during this period, provided by the ARC-ISCW Agrometeorology Programme, but no visual damage was recorded on the pecans. Late spring and early winter freezes (Kaur et al., 2020; Sparks. 2000) were not experienced, with the lowest recorded temperatures being 3 to 5°C (ARC-ISCW Agrometeorology Programme).

The chill unit requirements for ‘Wichita’ pecans are 250 – 300 Richardson Chill Units (RCU) (Utah model) (Dedekind, 2020), with a minimum requirement of 100 chill units (RCU) (Wells. 2017) and a higher heat requirement for spring bud break (Sparks, 2005) when less chilling occurs. Both areas exceeded the chilling requirement during the recorded years, indicating sufficient chilling was received, with both regions recording a decrease in the second season, possibly leading to the observed two-week delay in budbreak.

The biomass production, using satellite imagery, measured for all four sites showed a clear increase from 2016 until 2021 for most seasons, as expected. The reason for the observed decreases are unclear and partially also reflects the contribution of weeds or cover crops which is typically included in calculations based on satellite imaging. In 2020/21, in Trial 2, Site 4 (5 year old; 208 trees ha^{-1}) recorded the highest biomass production per tree (301.36 kg), with Site 1 (6 year old; 125 trees ha^{-1}), in Trial 1, recording the lowest biomass production (79.82 kg). Results for Site 4 supported the excessive growth observed in the second season, with a significantly higher tree volume, tree height and longer shoot lengths, but it still included the contribution of the cover crop, which was not present at Site 1. Site 1 contained the oldest pecan trees and yet produced the least biomass according to the satellite imaging. This indicated that the density of the orchard influences the calculation of biomass production via imaging significantly, as well as the contribution of cover crops in satellite imaging, which will contribute to biomass differentially based on tree spacing. This is also evident in Site 3 (4 year old; 312 trees ha^{-1}), recording a biomass production of 42.86 kg per tree in its first year, compared to 22.83 kg for Site 1, despite the occurrence of a cover crop. This data therefore indicated calculations for biomass on tree basis is not accurately reflected by satellite imagery, as a smaller tree cannot have a higher biomass production than a larger tree, and that the biomass per area also reflected the impact of tree density in addition to possible contributions of cover crops.

The weekly biomass production for Sites 1 and 2 followed the same trend, with peaks occurring at the same time. Several of the peaks correlated with the phenological stages, but these peaks did not occur each season. In the 2020/21 season, a similar peak was recorded for both sites at stage 1, indicating the onset of bud-break, followed by a higher peak at Stage 3, indicating catkin development. Another subtle peak was observed in Stage 2, when leaf expansion occurred. These differences in peak occurrences, as well as the amount of biomass production are unclear and can be influenced by other factors such as the presence of weeds or the differences in growth between the pollinator cultivar and the main cultivars. The largest peak was recorded during weeks 5 and 6, for both sites, but the cause of the peak is unknown. The weekly biomass production for Sites 3 and 4 followed the same trends as Sites 1 and 2. In the 2020/21 season, a large peak was seen for both Sites 3 and 4 after phenological Stage 2, indicating that the leaf expansion occurred around week 42 – 44.

Conclusion

The limitations of the study with reference to number of sites and descriptive analyses are acknowledged and results were therefore exploratory and preliminary. However, as no information existed, this baseline information was important for future research to provide the industry with guidelines regarding the suitability of higher density plantings of 'Wichita' pecans in these regions of the Western Cape.

Neither tree age, nor planting distance, had a significant effect on the solar radiation interception of the pecan trees at this young age, suggesting that tree shape or pruning practices had the largest impact on light interception, which was primarily influenced by the tree volume and confirmed previous findings for apple. Tree volume was, however, affected by tree density, with higher density sites recording smaller tree volumes compared to the lower density sites, when comparing sites of similar age. Site 4, with a tree density of 8 x 6 m (208 trees ha^{-1}), had a significant increase in tree growth in the second season (five years old), which followed a winter with sufficient winter chilling and severe pruning and the combined effect resulted in a higher tree volume and yield. This further resulted in an increase in shoot length, which may have contributed to an increase in yield, due to an increase in bearing positions (pistillate flowers). However, this must be confirmed, as excessive shoot lengths are also known to result in a reduction in yield in pecan. Site 2 with 200 trees ha^{-1} (10 x 5 m) showed a decrease in tree yield from the previous season, whilst recording an increase in tree height and volume and a decrease in yield efficiency, indicating possible overcrowding as evident by the decrease in lateral growth and touching of adjacent trees in the orchard. As the first signs of overshadowing were observed at the age of five years, where no pruning or training was conducted to reduce tree size, this density may compromise the performance of similar orchards in future. This result is expected in the coming season in Sites 3 (4 year old; 312 trees ha^{-1}) and 4 (5 year old; 208 trees ha^{-1}), with a higher density orchard, if maintenance pruning is performed in time, but requires further investigation.

As expected, tree age affected yield. Medium planting densities recorded higher yields per tree and lower yields per hectare, confirming literature. Overall, yield per ha in these areas was comparable to industry standards of similar tree ages in the main production areas in South Africa, which was partly due to the higher densities.

Both regions recorded temperatures within the desired range for optimal pecan growth, with no signs of freeze or heat damage observed. Overall, tree development occurred about two weeks earlier at Hermon compared to the Vredendal region, due to climate differences i.e. higher chill units at Hermon. However, both regions had sufficient chilling for satisfactory bud break to occur. These results indicated that both regions are suitable for ‘Wichita’ cultivation under the current climate conditions, as long as sufficient water is available for irrigation.

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Tables and Figures

Table 1.1: The effect of planting density of 'Wichita' pecan trees on the fractional photosynthetically active radiation (fPAR) for Trial 1 (Site 1 – 10 x 8 m and Site 2 – 10 x 5 m) and Trial 2 (Site 3 – 8 x 4 m and Site 4 – 8 x 6 m), at specific phenological stages at Hermon and Vredendal, during two consecutive seasons.

			fPAR (%)				
			2019/20 Season	**2020/21 Season**			
Site	**Tree age (years)**	**Planting density (trees ha^{-1})**	**Phenological stage**				
			5	**2**	**3**	**4**	**5**
			11/05/2020	01/12/2020	11/01/2021	16/03/2021	26/04/2021
1	**6**	**125**	89.03 ns	94.84 ns	92.15 ns	94.22 ns	89.74 ns
2	**5**	**200**	85.97	94.45	90.94	87.99	92.12
P			0.1162	0.8037	0.6303	0.1113	0.4809
			28/04/2020	20/11/2020	01/18/2021	17/03/2021	30/04/2021
3	**4**	**312**	55.23 ns	79.63 b[y]	85.64 ns	80.37 ns	70.63 ns
4	**5**	**208**	61.41	86.75 a	89.09	81.19	73.98
P			0.1138	0.0452	0.3974	0.8577	0.3802

[y] Means with a different letter within a column differ significantly at the 5% level.

Table 1.2: Six-stage crop growth of pecan trees at Trial 1 (Zandkraal and Rotsvas) in Vredendal, during the 2019/20 and 2020/21 seasons, described in Wells, (2017) and modified by Ibriamo et al. (2018).

Six stage crop growth			
Stage	**Definition**	**Season 2019/20**	**Season 2020/21**
		Date	
1. Bud-Break	Emergence of leaf primordia	Week 40	Week 42
2. Pre-pollination	Occurrence of leaf expansion	Week 44	Week 44 – Week 47
3. Pollination to early dough	Stigmas of pistallate flower turn from green to red/brown until shell hardening is complete	Week 48/ Week 49	Week 49/ Week 50
4. Dough stage	Kernel is completely formed	Week 18	Week 14
5. Shuck or hull split	Sutures of shuck begin to split apart	Week 19	Week 18 /19
6. Leaf drop	Leaves begin to abscise from the trees	Week 23 - Week 27	Week 27

Table 1.3: Six-stage crop growth of pecan trees at Kleinplasie, Hermon, during the 2019/20 and 2020/21 seasons described in Wells, (2017) and modified by Ibriamo et al. (2018).

Six stage crop growth Stage	**Definition**	**Season 2019/20**	**Season 2020/21**
1. Bud-Break	Emergence of leaf primordia	Week 35/36	Week 38
2. Pre-pollination	Occurrence of leaf expansion	Week 40	Week 42 - 44
3. Pollination to early dough	Stigmas of pistallate flower turn from green to red/brown until shell hardening is complete	Week 44 - 48	Week 47
4. Dough stage	Kernel is completely formed	Week 10	Week 12
5. Shuck or hull split	Sutures of shuck begin to split apart	Week 14 - 18	Week 14
6. Leaf drop	Leaves begin to abscise from the trees	Week 18	Week 23

Table 1.4: Vegetative parameters of 'Wichita' pecan trees for Trial 1 (Site 1 – 10 x 8 m and Site 2 – 10 x 5 m) and Trial 2 (Site 3 – 8 x 4 m and Site 4 – 8 x 6 m) recorded at Hermon and Vredendal, during two consecutive seasons.

Site	**Tree age (years)**	**Planting density (trees ha^{-1})**	**Stem circumference (cm)**		**Tree Height (m)**		**Tree Volume (m^3)**		**Avg. Shoot Length (m)**
			11/05/2020	06/07/2021	04/06/2020	06/07/2021	04/06/2020	06/07/2021	21/05/2021
1	**6**	**125**	35.35 a^y	41.01 ns	5.85 a^y	6.04 ns	88.12 a^y	86.12 a^y	140.03 a^y
2	**5**	**200**	32.49 b	39.62	4.88 b	5.78	60.84 b	65.68 b	99.67 b
P			0.0127	0.1552	< 0.0001	0.1224	0.0008	0.0043	0.0067
			23/04/2020	04/05/2021	02/06/2020	07/07/2021	02/06/2020	07/07/2021	07/07/2021
3	**4**	**312**	22.42 b^y	26.90 b^y	2.9 b^y	4.57 b^y	15.8 b^y	20.92 b^y	107.07 b^y
4	**5**	**208**	32.57 a	39.65 a	4.97 a	6.50 a	40.34 a	73.62 a	149.97 a
P			< 0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^{y} Means with a different letter within a column differ significantly at the 5% level

Table 1.5: Average pruned shoot mass per tree of 'Wichita' pecans in Trial 2 (Hermon), (Site 3 – n = 29) (Site 4 – n = 15) during the 2019/2020 season.

Treatment	**Tree age (years)**	**Plant density (trees ha^{-1})**	**Average pruned shoot mass (kg)** 26/08/2020	**SE**
Site 3	4	312	2.88	0.59
Site 4	5	208	8.50	2.97

Table 1.6: Yield related parameters for 'Wichita' pecan tree for Trial 1 (Site 1 – 10 x 8m and Site 2 – 10 x 5m) and Trial 2 (Site 3 – 8 x 4m and Site 4 – 8 x 6m) from Hermon and Vredendal, for two consecutive seasons.

Site	**Yield**				**No. nuts per tree**		**Yield efficiency (g.cm^2)**	
	(kg.tree^{-1})	**(kg.ha^{-1})**	**(kg.tree^{-1})**	**(kg.ha^{-1})**				
	11/05/2020		**21/05/2021**		**11/05/2020**	**21/05/2021**	**11/05/2020**	**21/05/2021**
1	5.90 a^y	699.25 ns	6.08 a^y	759.91 a^y	712.73 a^y	812.13 a^y	172.98 a^y	153.84 a^y
2	3.19 b	637.544	1.68 b	335.61 b	369.73 b	213.80 b	97.64 b	41.52 b
P	0.0020	0.5568	<0.0001	<0.0001	0.0005	<0.0001	0.0012	<0.0001
	23/04/2020		04/05/2021		23/04/2020	04/05/2021	23/04/2020	04/05/2021
3	0.61 b^y	189.87 ns	2.44 ns	761.45 a^y	69.30 b^y	262.53 ns	26.84 b^y	91.78 a^y
4	1.17 a	242.47	2.64	549.78 b	136.70 a	302.20	47.99 a	66.31 b
P	0.0034	0.2271	0.5167	0.0158	0.0070	0.2628	0.0031	0.0183

[y] Means with a different letter within a column differ significantly at the 5% level.

Table 1.7: Nut quality parameters for a composite sample of 50 nuts for 'Wichita' pecans for Trial 1 (Site 2 – 10 x 5m) and Trial 2 (Site 3 – 8 x 4m) during the 2019/2020 season.

Plant density (trees ha^{-1})	Nut length (mm)	SE	Nut diameter (mm)	SE	Nut mass (g)	SE	Nut fill (%)
200	40.99	0.45	19.57	0.18	7.15	0.18	100
312	41.50	0.53	20.22	0.21	7.54	0.19	100

Table 1.8: Nut quality parameters for a composite sample of 50 nuts for 'Wichita' pecans Trial 1 (Site 1 – 10 x 8m and Site 2 – 10 x 5m) and Trial 2 (Site 3 – 8 x 4 m and Site 4 – 8 x 6 m) during the 2020/21 season.

Plant density	Nut length (mm)	SE	Nut diameter (mm)	SE	Nut mass (g)	SE	Nut fill (%)
125	41.87	3.01	19.40	1.02	7.42	0.99	100
200	43.67	3.67	19.77	1.10	7.55	1.28	100
312	43.67	2.50	21.08	1.28	10.01	1.16	100
208	45.11	2.95	20.25	0.98	9.08	1.16	100

Table 1.9: Monthly average maximum and minimum temperature, from the start (September) until the end of the season (August) for the 2019/20 and 2020/21 seasons in Vredendal (ARC-ISCW automatic weather station).

Month	**Maximum temperature (°C)**		**Minimum Temperature (°C)**	
	2019/2020	**2020/2021**	**2019/2020**	**2020/2021**
September	28.19	24.04	9.54	6.47
October	27.42	26.46	9.81	9.40
November	28.68	27.13	11.75	11.63
December	28.58	28.83	13.32	13.25
January	29.47	31.37	14.84	14.73
February	32.75	31.26	15.94	13.13
March	29.84	29.98	13.65	12.86
April	28.04	31.41	11.46	11.86
May	23.86	24.50	7.40	8.35
June	19.69	22.51	6.79	8.30
July	19.97	19.67	3.85	3.74
August	17.09	18.11	5.19	6.37

Table 1.10: Monthly average maximum and minimum temperature, from the start (September) until the end of the season (August) for the 2019/20 and 2020/21 seasons in Hermon (ARC-ISCW automatic weather station).

Month	**Maximum temperature (°C)**		**Minimum Temperature (°C)**	
	2019/2020	**2020/2021**	**2019/2020**	**2020/2021**
September	25.5	20.95	11.14	8.63
October	25.34	25.48	10.99	11.06
November	28.18	27.00	13.67	14.41
December	29.45	25.17	14.89	15.66
January	31.16	27.3	17.49	16.94
February	33.53	26.35	18.17	17.64
March	30.36	29.98	15.76	15.5
April	27.21	29.45	12.58	13.48
May	24.59	22.40	9.99	9.84
June	20.44	21.17	8.86	9.24
July	20.09	17.68	6.94	5.86
August	17.47	18.09	6.35	7.37

Table 1.11: Monthly total daily positive chilling units (DCPU) and total monthly Utah Chill Units (CU) from May to August for the 2019/20 and 2020/21 seasons, in Vredendal (ARC-ISCW automatic weather station).

Month	**DCPU**		**Utah Model (CU)**	
	2019/20	**2020/21**	**2019/20**	**2020/21**
May	38.00	27.00	-92.50	-96.50
June	105.50	68.50	42.00	-41.50
July	114.50	248.50	69.50	226.00
August	192.50	*	174.00	*
Total	450.50	344.00	193.00	88.00

*Missing data due to broken sensors/ uncollected data

Table 1.12: Monthly total daily positive chilling units (DCPU) and total monthly Utah Chill Units (CU) from May to August for the 2019/20 and 2020/21 seasons, in Hermon (ARC-ISCW automatic weather station).

Month	**DCPU**		**Utah modal (CU)**	
	2019/20	**2020/21**	**2019/20**	**2020/21**
May	37.00	40.00	-160.00	-91.00
June	107.00	91.50	54.00	-7.50
July	158.50	307.00	152.00	295.00
August	272.00		261.50	*
Total	574.50	438.50	307.50	196.50

*Missing data due to broken sensors/ uncollected data

Table 1.13: Seasonal biomass production per tree and per 0.5 ha measured, for all for sites in Vredendal and Hermon, from establishment, estimated from Fruitlook®, using satellite imagery. Site 1 (10 x 8 m), Site 2 (10 x 5 m), Site 3 (8 x 4 m) and Site 4 (8 x 6 m).

Site	**Tree age (year)**	**Plant density (trees.ha^{-1})**	**Biomass production (kg tree^{-1})**				
			2016/17	**2017/18**	**2018/19**	**2019/20**	**2020/21**
1	**6**	**125**	26.63	22. 83	28. 80	58.51	79.82
2	**5**	**200**	30.61	21.37	86.02	156.96	201.43
3*	**4**	**312**		42.86	99.23	88.93	113.81
4*	**5**	**208**	119.02	156.42	238.11	195.33	301.36
			Biomass production (kg 0.5 ha^{-1})				
1	**6**	**125**	1464	1255	1584	3217	4390
2	**5**	**200**	2816	1966	7914	14440	18532
3*	**4**	**312**		4642	10749	9633	12329
4*	**5**	**208**	7855	10324	15715	12892	19890

*Sites 3 and 4 contains a cover crop

Fig. 1.1. Trial 1 (Site 1), planted 2015, spaced 10 x 8 m on the commercial farm Zandkraal, in Vrendendal, containing 'Wichita' pecans as the main cultivar alongside 'Choctaw pecans and 'Navaho' as the cross-pollinator.

Fig. 1.2. Trial 1 (Site 2), planted 2016, spaced 10 x 5 m on the commercial farm Zandkraal, in Vrendendal, containing 'Wichita' pecans as the main cultivar alongside and 'Navaho' as the cross-pollinator.

Fig. 1.3. Trial 2 (Site 3 and 4). Site 3 planted 2017, spaced 8 x 4 m and Site 4 planted in 2016, spaced 8 x 6 m, containing, both sites on the commercial farm Kleinplasie, in Hermon, containing 'Wichita' pecans as the main cultivar alongside and 'Navaho' as the cross-pollinator.

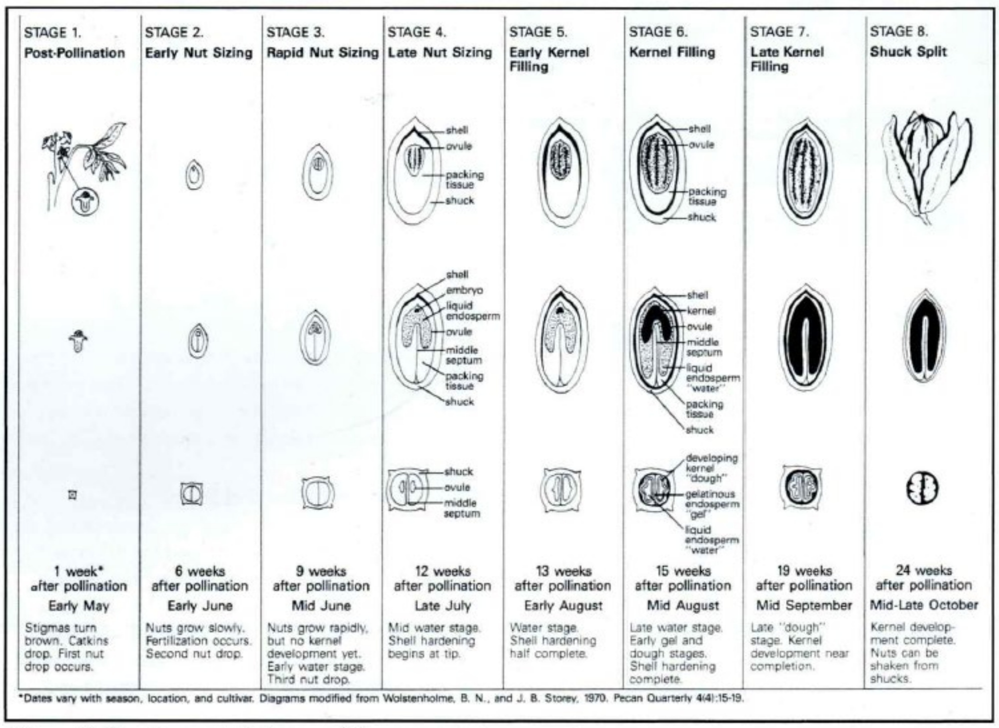

Figure 6. Developmental stages of the pecan nut.

Fig. 1.4. The phenological stages of pecans growth, as described by Wells (2017).

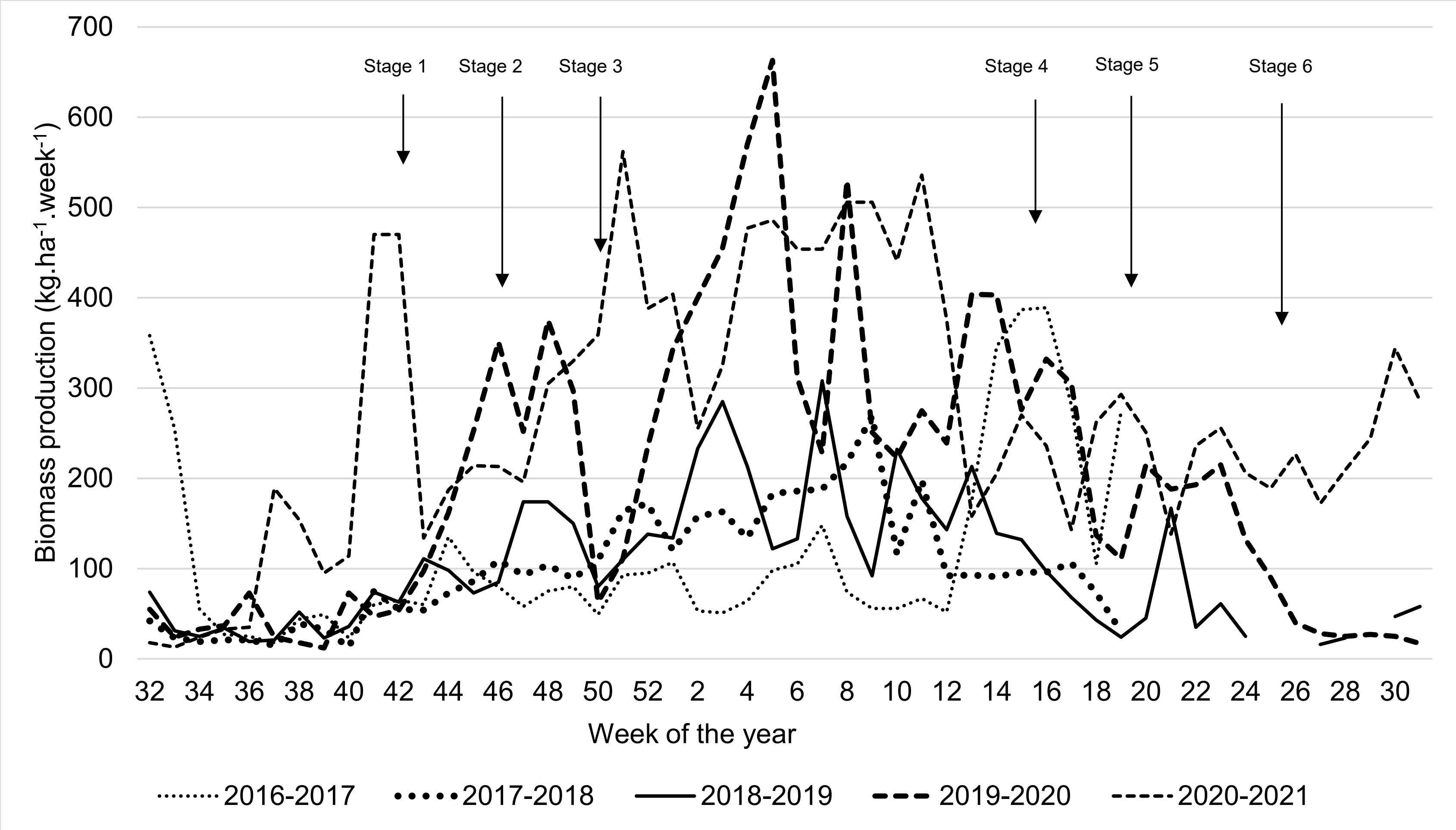

Fig. 1.5: Weekly biomass production (kg.ha^{-1}.week^{-1}) of 'Wichita' pecans, at Site 1 (10 x 8 m) in Vredendal, for five seasons from 2016 to 2021, calculated by Fruitlook® satellite imagery. The stages represent the six different phenological stages of the pecan tree, throughout the growing season.

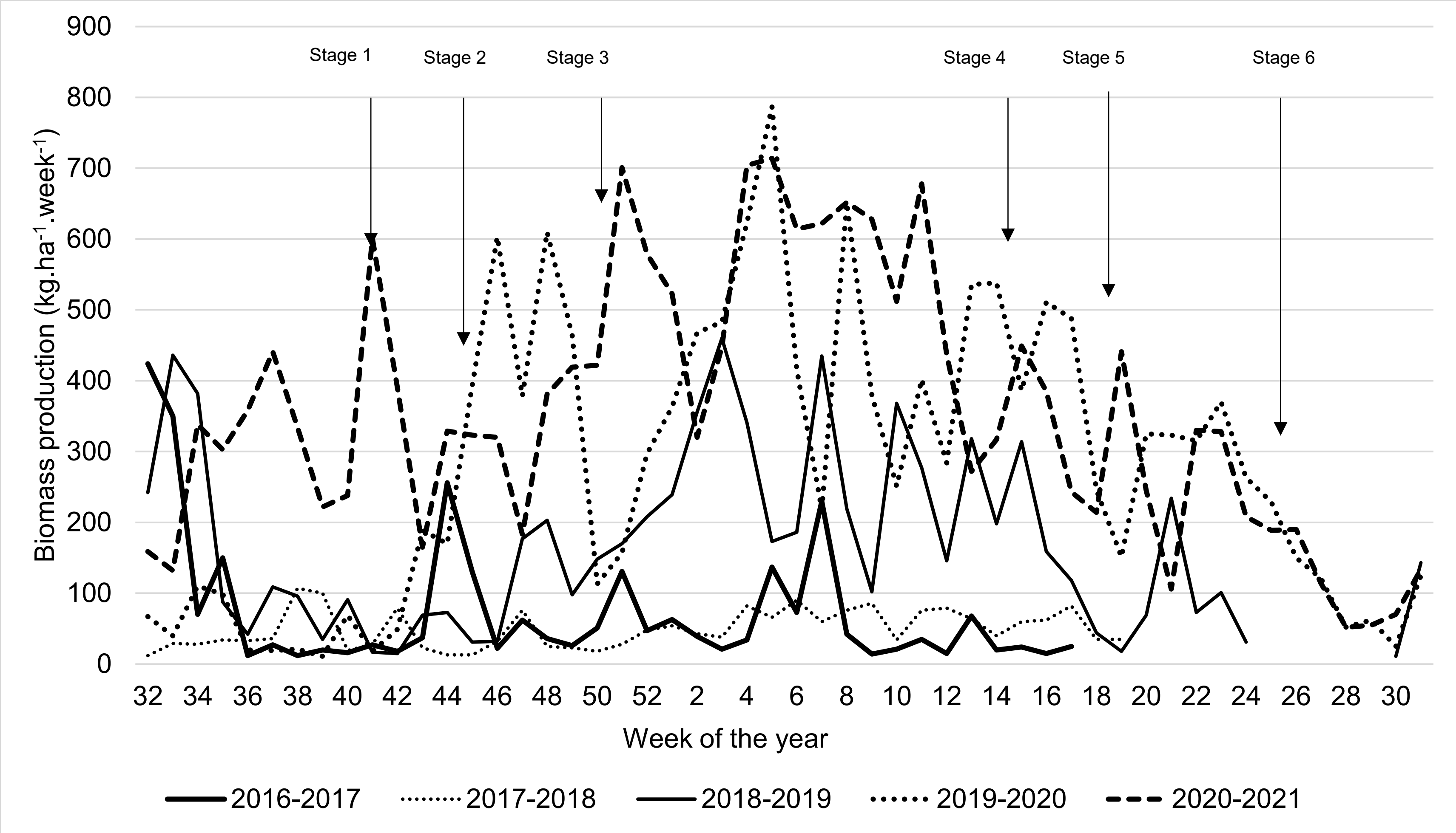

Fig. 1.6: Weekly biomass production (kg.ha^{-1}.week^{-1}) of 'Wichita' pecans, at Site 2 (10 x 5 m) in Vredendal, for five seasons from 2016 to 2021, calculated by Fruitlook® satellite imagery. The stages represent the six different phenological stages of the pecan tree, throughout the growing season.

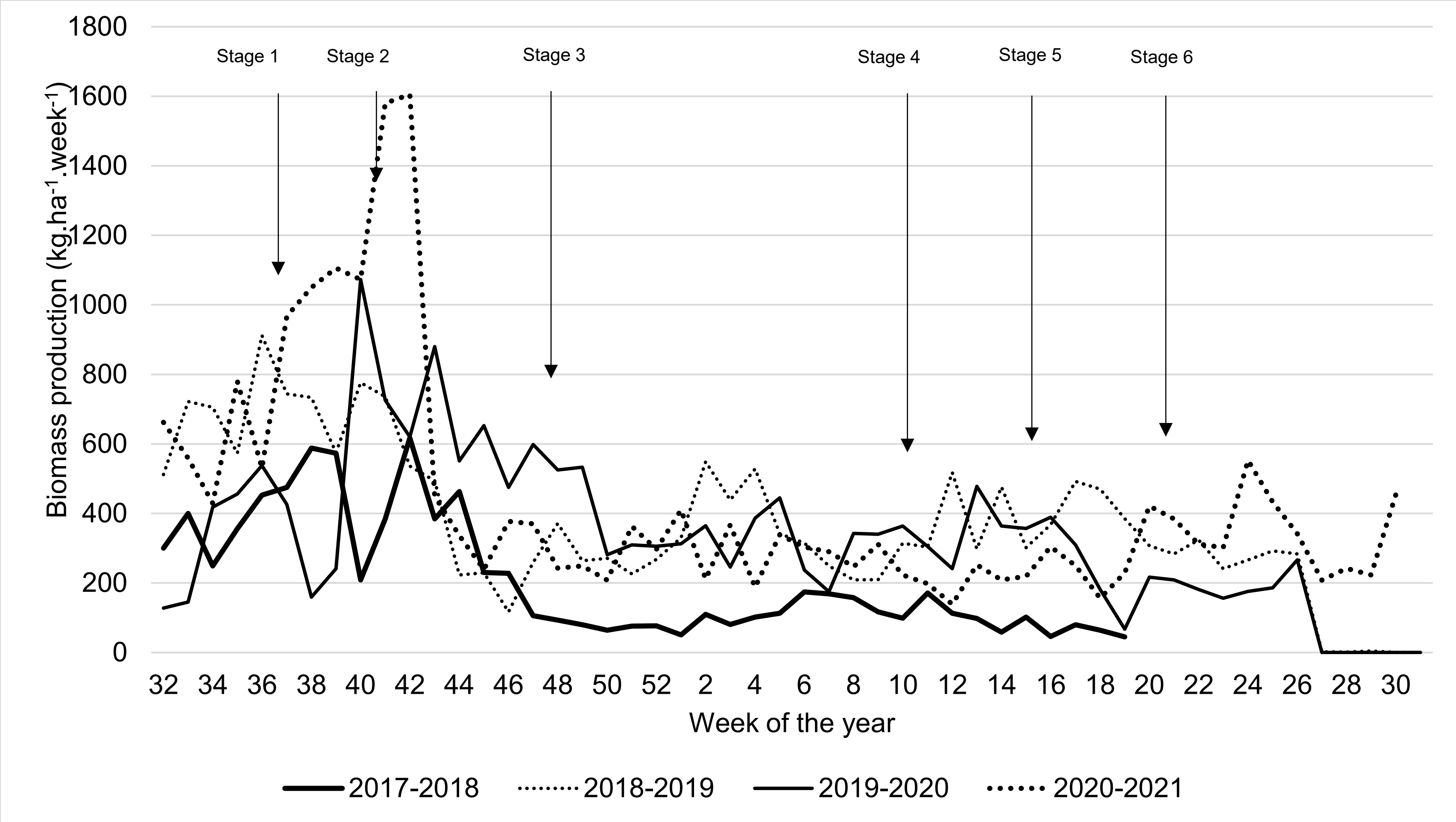

Fig. 1.7: Weekly Biomass Production (kg.ha^{-1}.week^{-1}) of 'Wichita' pecans, at Site 3 (8 x 4 m) in Hermon from 2017 to 2021, calculated by Fruitlook® satellite imagery. The stages represent the six different phenological stages of the pecan tree, throughout the growing season.

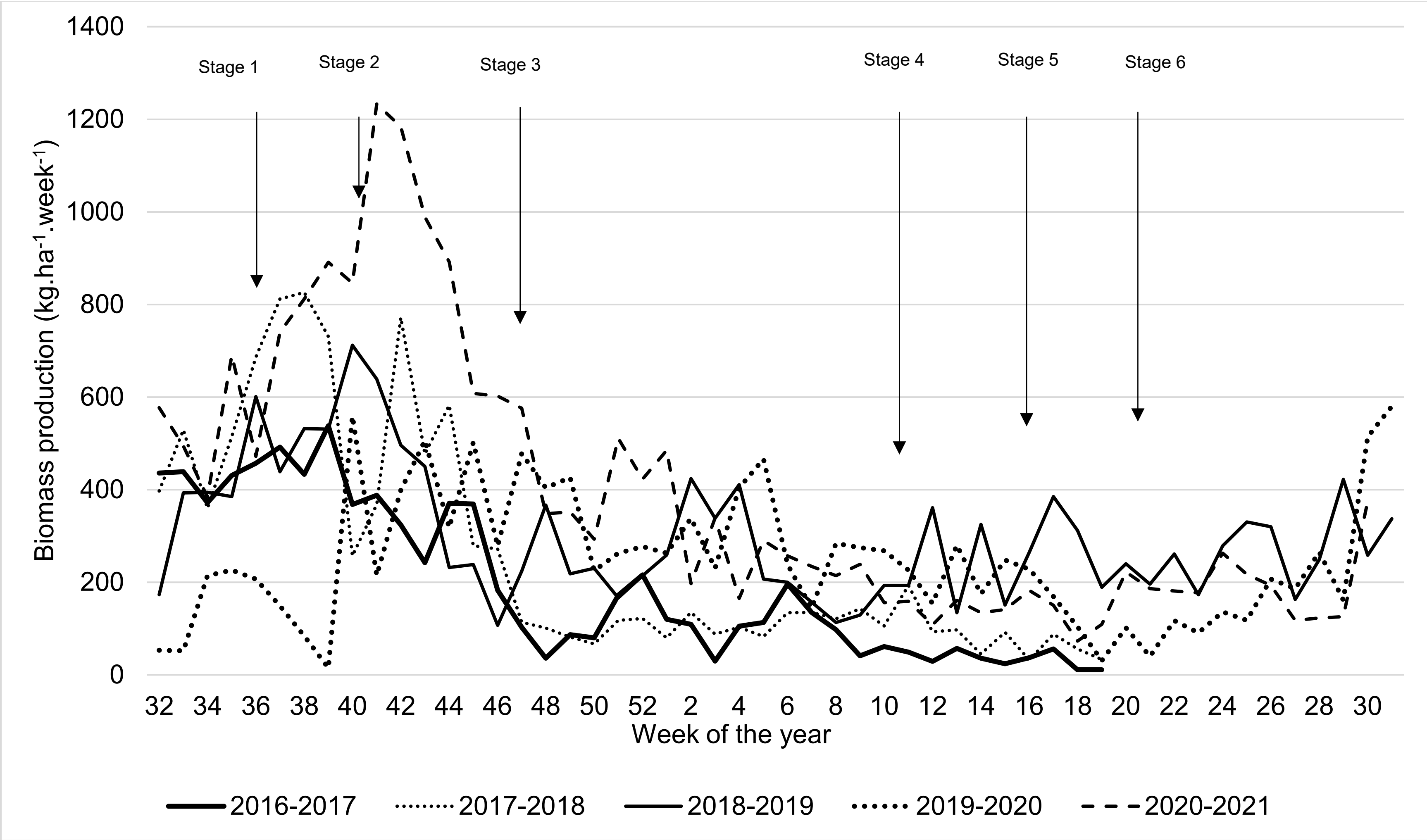

Fig. 1.8: Weekly biomass production (kg.ha^{-1}.week^{-1}) of 'Wichita' pecans, at Site 4 (8 x 6 m) in Hermon, for five seasons from 2016 to 2021, calculated by Fruitlook® satellite imagery. The stages represent the six different phenological stages of the pecan tree, throughout the growing season

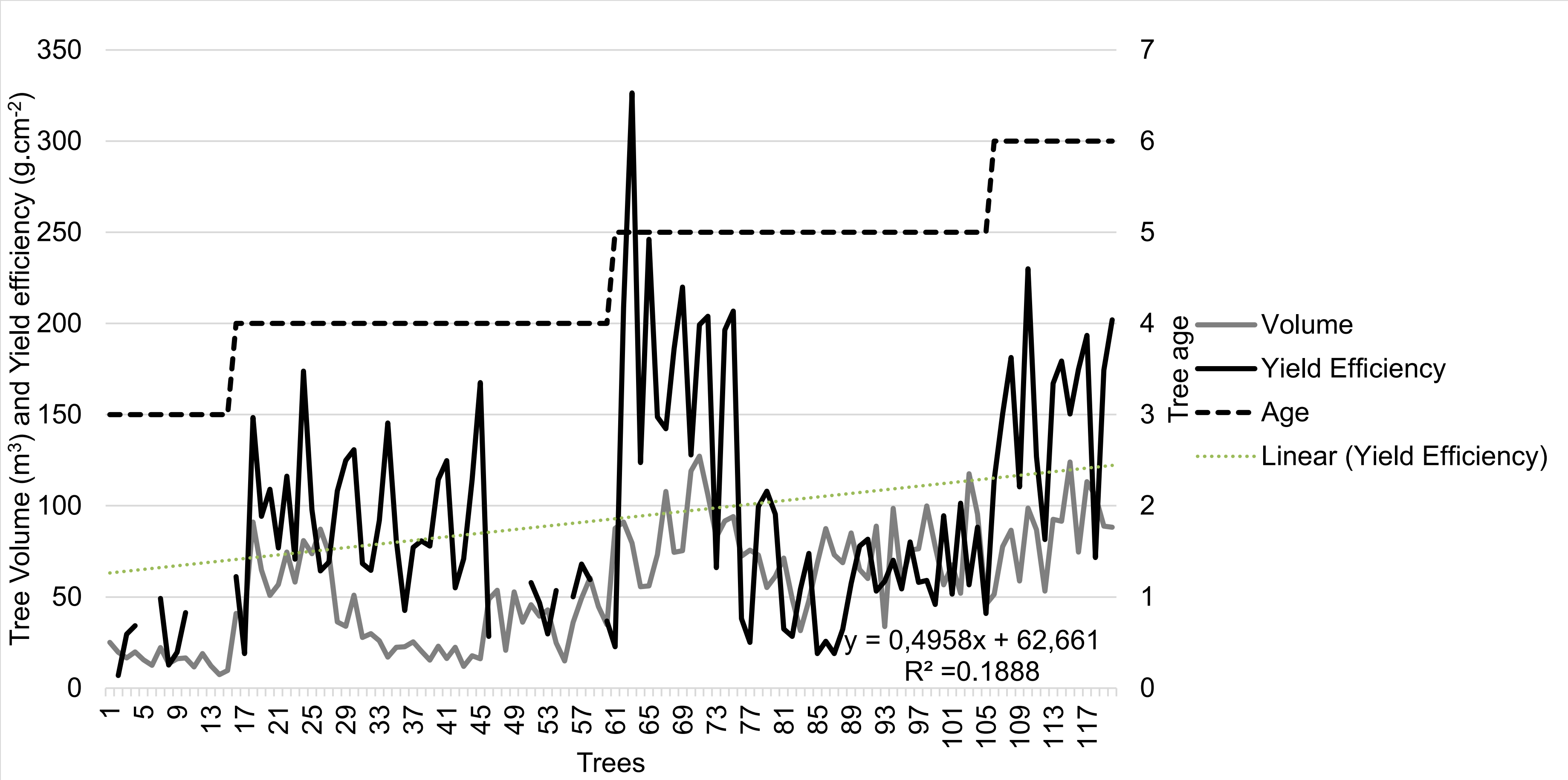

Figure 1.9: The correlation between tree volume (m^3) and yield efficiency ($g.cm^{-2}$) for the Vredendal and Hermon Trials ($P = 2.34941 \times 10^{-6}$).

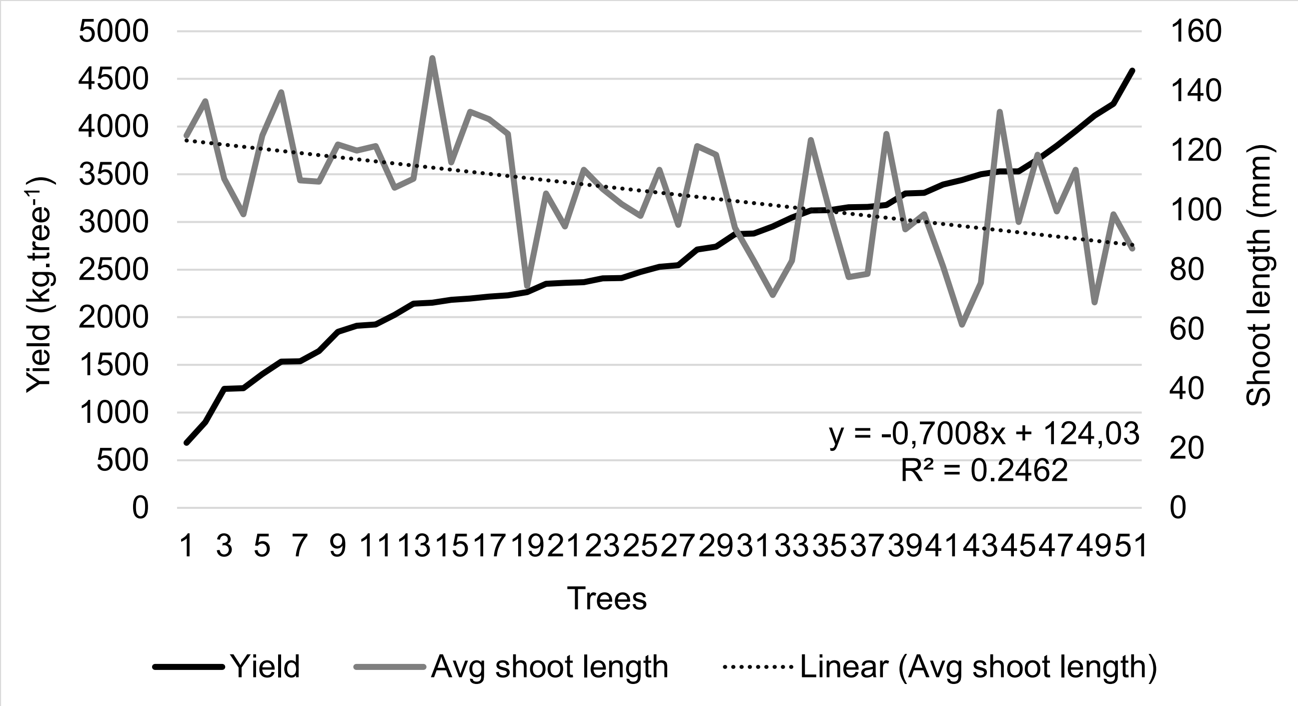

Figure 1.10: The correlation between yield (kg.tree^{-1}) and average shoot length per tree (mm) for 51 trees at the Hermon Trial – Site 3 (8 x 4 m) (P = 0.0002).

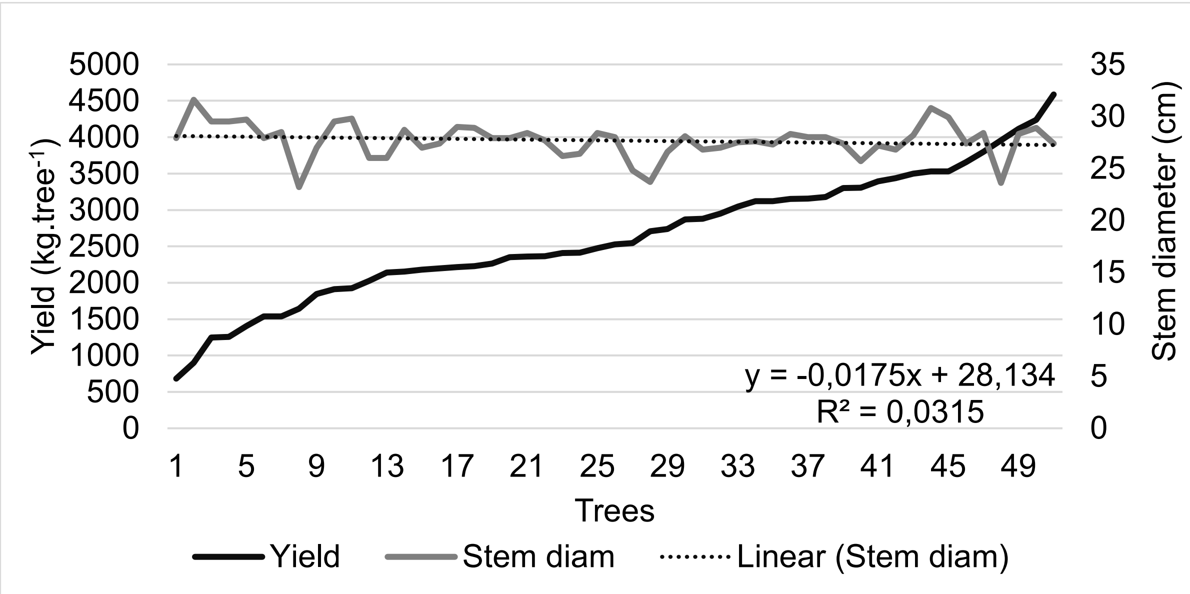

Figure 1.11: The correlation between yield (kg.tree^{-1}) and Stem diameter (cm) for 51 trees at the Hermon Trial – Site 3 (8 x 4 m) (P = 0.2126)

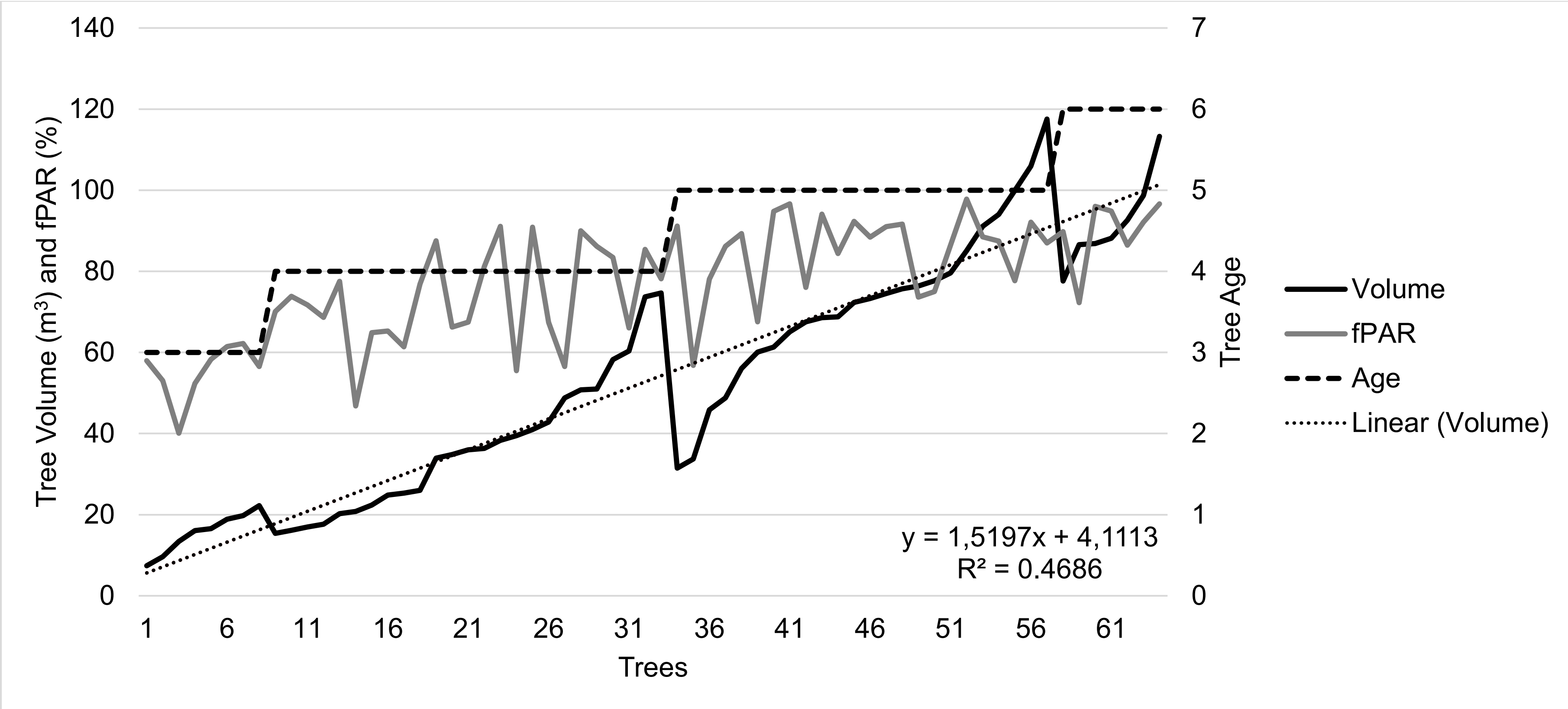

Figure 1.12: The correlation between tree volume (m^3) and fPAR (%) for pecans as it ages from age three until age six, for the Vredendal and Hermon Trials ($P = 8.53793 \times 10^{-10}$).

PAPER 2: Investigating the suitability of three pecan cultivars for commercial production in the Western Cape

Abstract

Cultivar differences are an important factor when considering commercial pecan cultivation and cultivar selection is influenced by the adaptability of a cultivar to its surroundings (climate), precocity, insect and disease resistance, potential yield, nut quality and pollination attributes. In South Africa, the three most common cultivars include Wichita, Navaho and Choctaw. These cultivars (treatments) were evaluated, during two consecutive seasons, to determine their suitability for commercial cultivation in the Vredendal region. The orchard was established in 2015, at a planting density of 10 x 8 m. Several vegetative and reproductive parameters were quantified on the young trees, including fPAR, canopy volume, stem circumference, shoot length and yield. The six-stage crop developmental stages were also monitored. In 2020, stem circumference and tree height were significantly higher in 'Navaho' and 'Choctaw' compared to 'Wichita', with no significant difference regarding tree volume. In 2021, a significant difference was recorded for stem circumference, tree height and tree volume, with the highest values recorded in 'Choctaw', followed by 'Wichita' and 'Navaho', which did not differ significantly with regard to stem circumference or tree volume. No significant difference for yield, number of nuts per tree or yield efficiency was recorded between cultivars, but 'Choctaw' had the longest nuts and biggest diameter, as well as highest nut mass, followed by 'Wichita' and then, 'Navaho'. Vredendal was suitable for pecan production, but historic chill units (237.50 CU) were less than the recommended range of 250 – 300 RCU, although there was no visual impact on bud-break, which was probably due to the spring temperatures. Wind, temperature and relative humidity during the pollination period ranged within the recommended requirements for pecan and it was reflected by crop load. It is recommended that yield still be monitored for in future before final recommendations can be made regarding the suitability of these cultivars for commercial production in this region.

Key words: Adaptability, climate, chill units, pollination, vegetative parameters, yield

Introduction

The United States (US) is the world's largest producer of pecans, with New Mexico as the new leading state for producing the highest percentage of cultivated crop – 34.3% (in the US) in 2019, followed by Georgia – 28.6% (USDA, 2019). Plantings comprise primarily 'Wichita' and 'Western', with later plantings integrating 'Pawnee' (Grauke et al., 2016).

Characteristics like bearing consistency, disease and insect resistance and nut quality are critical aspects in cultivar selection (Grauke et al., 2016). Scab tolerance is a major thread and should receive priority over yield potential. Susceptible cultivars should not be planted in areas with high humidity, i.e. KZN, and tolerant cultivars such as Apalachee, Western, Caddo, Ukulinga and Lakota are considered instead (Botha, 2018). Locally, scab is more prevalent in the north-eastern parts of the country, where high temperatures and frequent rain create ideal conditions for scab development (Clark, 2020; Haulik and Holtzhausen, 1988; Sparks, 1995; 1996).

The primary cultivars utilised commercially in South Africa are Wichita, Choctaw and Navaho, all of which originate from the US Department of Agriculture (USDA) (Grauke and Thompson, 1997). In addition, 'Barton', 'Ukulinga', 'Pawnee', 'Western Schley', 'Mahan' and 'Mohawk' occur in smaller quantities (Clark, 2020). Other important cultivars include Elliot and Shoshoni (de Villiers, 2003). Excluding the cultivar choice, the earliest harvest occurs around year five (50 $kg.ha^{-1}$ for 100 trees ha^{-1}) for most production regions in South Africa with full potential bearing reached around year 13 (1.2 – 2.5 $t.ha^{-1}$ for 100 trees ha^{-1}) (SAPPA, 2020).

‘Wichita’ is the most popular of the three cultivars due to its prolific and precocious nature (Pecanbreeding.uga.edu. 2020). 'Wichita' nuts are medium in size, outstanding in quality and visually attractive. ‘Wichita’ is recommended as the main cultivar in several climate regions in South Africa, ranging from a dry (Western) and moderate (Bushveld) to cold climate (Highveld) according to region descriptions of SAPPA (2021). ‘Navaho’ has a vigorous growth habit with a strong structure, is extremely prolific and precocious, and, as a result, larger, more vigorous trees are predicted (Thompson et al., 1995). Navaho is recommended as the secondary cultivar locally for the Western and Bushveld regions (SAPPA, 2021).

'Choctaw' is very popular in Vaalharts, due to availability and their large nut size, with 20 to 30% of new plantings (Clark, 2020), as well as the Western region (Meier, 2020) and the Bushveld (SAPPA, 2021). Due to its alternate bearing nature, ‘Choctaw’ requires a cross pollinator (Meier, 2020). However, ‘Choctaw’ only starts producing at a later stage that will impact cash flow (Meier, 2020). ‘Choctaw’ requires proper tree management - pruning, such as a proper central leader, since it has weak tree branch angles (Meier, 2020), to ensure optimal growth. It has a potential to produce high yields with bigger nuts than the other two cultivars (Pecanbreeding.uga.edu. 2020).

Local yields vary from 1.5 – 2.5 $t.ha^{-1}$ in Mpumalanga to 3 – 5 $t.ha^{-1}$ in the drier regions of the Northern Cape, with and an expected income for in-shell pecans of R70 – R80 kg^{-1} in 2018 (Botha, 2018). In contrast, Taylor et al. (2020) recorded in-shell yields of 2.8 and 4.55 $t.ha^{-1}$ for 20-year-old (10 x 10 m) ‘Choctaw’ and ‘Wichita’ orchards, respectively, in the Vaalharts region. A maximum yield (50 ~ 22 – 45 $kg.tree^{-1}$) for ‘Choctaw’ (10 x 10 m) was recorded from the 11^{th} – 12^{th} growing seasons in the US (Pecanbreeding.uga.edu. 2020). Thus, environment as well as management practices will influence the maximum yield (Herrera, 2000).

Pollination is critical in cultivar selection, as pecans are dichogamous, with male and female flowers pollinating at distinct periods (Sparks, 2005). Cross-pollination is preferred because it results in heterozygous progeny and promotes seedling survival. To facilitate cultivar selection for commercial orchards, a pollination chart was compiled by Gafford (2021). Wood et al. (1997) compiled a document on bud break and ripening dates for pecans in the US. However, such detailed descriptions with regard to pollination for local conditions and cultivars is not available yet. In addition, in 2019, the South African industry notice severe pollination issues when estimated yields of 21 336.99 – 35 401.17 ton resulted in 17 171.19 ton (Clark, 2020). According to Clark (2020), this was due to insufficient pollination resulting from prolonged cold weather conditions during the flowering stage, as well as high temperatures during the nut fill, in addition to drought and hail. This emphasized the importance of cultivar choice and access to long-term climate data, for sustainable production of commercial pecans in new regions.

Pecan also has a chilling requirement of 400 – 750 h <7°C (Kudan et al., 2013), with cultivars Desirable and Mahan having a chilling requirement of 500 h and Stuart, 600 h <7.2 °C (Sparks, 1993). Dedekind (2020) stated that the female buds of ‘Wichita’ pecans have a chilling requirement of 250-300 Richardson Chill Units (RCU), while Kudan et al. (2013) found that the chill units (RCU) required for ‘Choctaw’ were 333 and 291 for ‘Wichita’ pecans, with hours below 7°C recorded as 550 and 451, respectively, from 2001 to 2004, in Turkey.

In South Africa, 'Navaho' is frequently recommended as cross-pollinator when Wichita is the primary cultivar. 'Navaho' male flowers shed concurrently with the opening of 'Wichita' female flowers (Clark, 2020; SAPPA, 2017). However, 'Navaho' male flowers can shed their pollen prematurely, resulting in unsatisfactory pollination. This can be remedied by including additional cultivars in the orchard, as well as a higher percentage of a cross-pollinator >20% (Clark, 2020). 'Navaho' is also more likely to survive more arid regions (Thompson et al., 1995).

Bilharva et al. (2018) also stated that at least four cultivars should be planted together, of which three should be pollinators representing at least 15%. In a study by Wood (2000) on 'Wichita' and 'Western Schley', yield losses occurred when the pollinators were planted two rows away from the main cultivar, with losses occurring from weak kernel formation due to self-pollination.

Cultivars vary in terms of productivity and production, as well as effective fractional cover ($f_{c\text{-}eff}$), which is affected by the shape of the tree canopy (Bastias and Corelli-Grappadelli, 2012). Production is closely proportionate to the amount of light intercepted by the tree, which has an effect on the tree's character and profitability (Wood, 1996). The shape of the tree canopy has a significant effect on this light interception, with common shapes of pecans being a full ellipsoid, prolate spheroid, cylindrical and semi-ellipse (Wood, 1996). These morphological traits also affect management practices assessed by Wood (1996) for 83 pecan cultivars. In this study, 10-year-old 'Choctaw' trees had a tree shape of a full ellipsoid, with a height of 10.6 m and a diameter of 9.0 m, whilst 'Wichita' pecans had a semi-ellipsoid shape, with a tree height of 10.4 m and a diameter of 9.3 m.

Existing information on the yield performance of different cultivars were primarily derived from research conducted in Cullinan and Prieska, on Choctaw, Wichita and Navaho (Dedekind, 2020; Ibraimo et al., 2016; Taylor et al., 2017). These results may differ substantially for the same cultivars in the Western Cape, with its predominantly Mediterranean climate. Chilling accumulation and weather conditions during bloom will also impact the pollination period and thus, suitability of these cultivars for commercial production in new climatic regions. Therefore, the aim was to investigate the compatibility and adaptability of 'Wichita', 'Navaho' and 'Choctaw' for commercial production in Vredendal, with all three cultivars expected to be suitable under local conditions, since the regions climate similarity to commercial regions and 'Navaho' pecans is also expected to be a suitable cross-pollinator. A descriptive study was undertaken to quantify tree development (tree size and yield) during early establishment in a semi-high density commercial orchard during two consecutive seasons.

Materials and Methods

Experimental site and experimental design

The experiment was performed on a commercial farm, Zandkraal, in Vredendal, Western Cape (31° 35’ 22” S; 18° 25’ 6” E), South Africa. The trial was conducted during the 2019/20 and 2020/21 seasons, in a six-year-old pecan orchard planted in 2015, spaced 10 x 8 m (125 trees ha^{-1}) on 2.6 ha. The orchard comprised three cultivars: Wichita and Choctaw, planted as three rows per cultivar, with Navaho planted in-between, as the cross-pollinator, every 10^{th} tree within the main cultivar row – Wichita, and planted randomly in-between, every 8^{th} – 10^{th} tree, within the Choctaw rows. All trees were grafted on ‘Ukulinga’ rootstock.

The orchard was irrigated with a double drip line, with a diameter of 0.6 m and a daily delivery of 4 $L.h^{-1}$. Irrigation occurred for three to four $h.d^{-1}$ depending on soil moisture, determined by the producer. The orchard soil was classified as an Oakleaf 2120 – loamy, lime soil (Soil classification, 1991; Oberholzer and Schloms, 2011). Standard commercial fertilization recommendations were followed according to foliar and soil analyses for applications of urea, zinc, boron and nickel. False codling moth traps were used for management since the orchard is adjacent to citrus orchards and with false codling moth were observed in the shucks. Clean cultivation was practised in the work rows with application of commercial herbicides.

Treatments and Trial Layout

No statistical layout was followed as an established orchard was selected for the descriptive study. The trial comprised a random selection of 15 representative trees, which served as experimental units. Different cultivars – Wichita, Navaho and Choctaw served as the treatments.

Data Collection

Vegetative parameters

Fractional interception of photosynthetically active radiation by the canopy

The fractional interception of photosynthetically active radiation (PAR) (µmol.m^{-2}.s^{-1}) was determined with a ceptometer (Decagon AccuPAR LP-80 ceptometer, Decagon Devices Inc, USA) for seven trees per cultivar, according to Ayars et al. (2003) and Marsal et al. (2014).

PAR measurements were conducted below the canopy cover of the trees. Measurements were performed in four different directions – north, west, south and east, from the stem towards the outer canopy. All measurements were taken on a clear sunny day, between 12 and 14 h. PAR measurements were then used to calculate fractional PAR (fPAR) (%), as discussed in Paper 1, using the following equation (Zarate-Valdez et al., 2015):

$$\text{fPAR} = \left(1 - \left(\frac{PAR_{below}}{PAR_{above}}\right)\right) \text{ x } 100$$

2019/20 season

PAR measurements were only performed on seven ‘Wichita’ trees, at harvest on 11/05/2020, due to COVID 19, in 2019/20.

In 2020/21, PAR measurements were performed on five dates, according to the phenological stages of the pecan tree. No measurements were performed at stage 1, since bud break did not visually influence the light interception.

Stem Circumference, Tree Volume and Shoot Length

Stem circumference was measured using a standard measuring tape, at a height of ~1.4 m above the ground, on 11/05/2020 and 06/07/2021.

Tree volume was calculated from tree height and width (within and between rows) recorded with a measuring ruler (Nedo mEssfix (5 m) telescopic Nedo, Switzerland). Tree height, from the soil to top branches, was used to represent the canopy, since the lower branches reached the ground. The volume was calculated according to the standard formula of a Semi-ellipsoid (Rechneronline.de, 2021):

$$\text{Volume} = \left(\frac{2}{3} \; x \; \pi \; x \; H \; x \; W \; x \; L\right)$$

H = height

W = Width

L = Length

Shoot growth was measured for two representative shoots per tree using a measuring ruler [Nedo mEssfix (5 m) telescopic Nedo, Switzerland] for the second season only, due to logistics.

Phenological development was monitored, for Vredendal, according to the stages described in Wells (2017) (Fig. 1.4), modified by Ibraimo et al. (2018): 1. Bud-break, 2. Pre-pollination, 3. Pollination to early dough, 4. Dough stage, 5. Shuck or hull split and 6. Leaf drop.

Climate data

Climate data was obtained from a regional automatic weather station from the ARC-ISCW, in the Vredendal area (31° 41' 2" S; 18° 28' 9" E), for the last 11 years, from 2011 to 2021. Climate variables were recorded on an hourly basis. Chill unit accumulation, presented as Utah cold units (CU) and calculated according to the model of Richardson et al. (1974) were provided, as well as the daily positive chilling units (DPCU), according to the model presented by Linsley-Noakes et al. (1995).

Yield

During 2019/20, only 'Wichita' was harvested (11/05/2020), because of Covid regulations and travel restrictions. The yield was determined per tree via hand harvesting (in-shell) of the 15 selected trees.

In 2020/21, all three cultivars were harvested (21/05/2021), 15 trees per cultivar. In addition, number of nuts per tree were recorded and yield related characteristics such as nut fill, nut mass (Kern PLJ series precision balances scale, Merck KGaA, Darmstadt, Germany) and nut size (length and diameter) were also determined (Mitutoyo 150 mm Digital Calliper, USA) for a random sample size of 50 nuts per cultivar. In addition, 10 nuts were used to evaluate nut fill (%).

Statistical analysis

Data was analysed using a one-way ANOVA using Statistical analysis software (SAS 9,4), Enterprise Guide 7.1 (SAS Institute Inc., Cary, North Carolina, USA) to compare means. Least significant difference (LSD) was determined using the linear model procedure and the pairwise t-test for p ≤0.05. Results should be interpreted accordingly, where applicable, to reflect the layout of the trial.

Results

Vegetative parameters

Fractional interception of photosynthetically active radiation or the canopy

In 2019/20, fPAR for 'Wichita' on 11/05/2020 was 89.03% (Table 2.1). In 2020/21, fPAR only differed significantly between cultivars for the second phenological stage (01/12/2020), where Navaho and Choctaw differed significantly from each other, while Wichita (94.45%) did not differ significantly from either Navaho (96.97%) or Choctaw (93.57%) (Table 2.1).

Stem Circumference, Tree Volume and Shoot Length

Stem circumference differed significantly between 'Wichita' (32.09 cm), 'Navaho' (35.75 cm) and 'Choctaw' (38.17 cm) in 2019/20, whilst 'Navaho' and 'Choctaw' did not differ from one another (Table 2.2). In 2020/21, stem circumference of 'Wichita' (39.62 cm) and 'Navaho' (41.57 cm) did not differ significantly but differed significantly compared to 'Choctaw' (46.13 cm), with the highest stem circumference (Table 2.2). The average shoot length did not differ significantly between cultivars in 2020/21 (Table 2.2).

Tree height differed significantly between 'Wichita' (5.58 m) and 'Choctaw' (6.11 m), but neither differed significantly from 'Navaho' (5.87 m) (Table 2.2). In 2020/21, tree height did not differ significantly between 'Navaho' (6.78 m) and 'Choctaw' (7.17 m), but both differed significantly from 'Wichita' (6.04 m) (Table 2.2).

Tree volume did not differ significantly between cultivars for 2019/20, but in 2020/21 Wichita (86.12 m^3) and Navaho (95.71 m^3) differ significantly from Choctaw, with the biggest tree volume (129.85 m^3) (Table 2.2).

Phenological development

The six-stage crop growth development was captured in Table 2.3. Both seasons followed the same pattern, with the 'Navaho' vegetative development generally progressing first, followed by 'Wichita' and 'Choctaw'. During season one, 'Navaho' and 'Wichita' started bud-break approximately two weeks before 'Choctaw' and in season two, the difference between 'Navaho' and 'Choctaw' was four weeks, with

‘Wichita’ in between. Pre-pollination for ‘Wichita’ and ‘Navaho’ occurred one week before ‘Choctaw’ for the first and the second season. The pollination to early dough stage occurred at the same time for each of the three cultivars, as the exact occurrence could not be monitored, and continued for approximately two weeks, for the first season (week 48-50). For the second season, the third stage for ‘Navaho’ and ‘Wichita’ occurred two to three weeks before ‘Choctaw’. The dough stage occurred at the same week for all three cultivars in the first season (week 18-19) and the second season (week 14). Shuck split also occurred at the same time for all three pecans in the first (week 19) and second season (week 18-19). Leaf drop, for the first season, occurred first in ‘Navaho’ (week 23), followed by ‘Wichita’ (week 25) and then by ‘Choctaw’ (week 27), but for the first season leaf drop seemed to occur at the same time for all three pecans, between week 26 -28.

Yield

Yield for ‘Wichita’ in 2019/20 was 5.9 $kg.tree^{-1}$ with a yield efficiency of 172.98 $g.cm^{-1}$ (Table 2.4). Neither yield per tree, yield per ha nor yield efficiency differed significantly between cultivars in 2020/21 (Table 2.4). The number of nuts per tree for ‘Wichita’ was 712 in 2019/20 (Table 2.4). In the second season, no significant differences were recorded between cultivars (Table 2.4).

Relationships between yield efficiency and vegetative parameters (tree volume and fPAR) were investigated for all cultivars, with the only significant correlations for tree volume in ‘Navaho’ (R^2 = 0,1177) (Fig. 2.1) and fPAR, in ‘Choctaw’ (R^2 = 0,2936) (Fig. 2.2).

Nut quality parameters

In 2020/21, nut quality parameters were quantified for all three cultivars and are summarized in Table 2.5. Nut length, diameter and mass declined as follows: ‘Choctaw’ (45.37 mm; 23.68 mm; 11.37 g), ‘Wichita’ (41.86 mm; 19.40 mm; 7.42 g) and ‘Navaho’ (38.05 mm; 19.42 mm; 6.27 g). Nut fill percentage was still 100% for all cultivars (Table 2.5).

Climate Data

Monthly chilling (Table 2.6) was monitored for the 2019/20 and 2020/21 season, as well as average maximum and minimum temperatures (Tables 2.7 and 2.8), for the past 10 seasons from 2011/12 to 2020/21. The maximum average temperature for the 2019/20 and 2020/21 seasons was recorded in February (32.8°C) for the first season and April (31.4°C) for the second season. The minimum average temperature was measured in July for both seasons, 3.85°C and 3.7°C, respectively. Long term temperature data recorded for Vredendal indicated an average maximum temperature of 26.3°C and a minimum temperature of 10.3°C (Tables 2.7 and 2.8), with the average maximum relative humidity recorded as 88.8% and the average minimum relative humidity of 33.6 % (Tables 2.9 and 2.10). The average wind speed recorded in Vredendal – 2.41 $m.s^{-1}$ (Table 2.11), provided by ARC- ISCW (ARC, 2021). The monthly average total rainfall recorded for Vredendal?? was 176.69 mm (Table 2.12)

During the pollination period, Vredendal experienced a average maximum and minimum temperature of 28.1°C and 10.8°C, respectively, for the first season, 26.8°C and 10.5°C in the second season. The average maximum and minimum relative humidity were 86% and 24.3% during season one and 83.9% and 35.4%, during the second season.

Total chilling was recorded as 450.50 DCPU or 193 CU in the 2019/20 season, with less recorded in the 2020/21 season – 344 DCPU or 88 CU, due to missing data (Table 2.6). However, long term data indicated that this region averaged 500.35 DCPU or 237.50 CU, for the past 10 years (20012 – 2021) (ARC, 2021).

Discussion

Fractional interception of photosynthetically active radiation of the canopy

In the first season (2019/20), only one measurement was conducted, which was similar to that recorded at Stage 5, in the following season, for 'Wichita' (89.03%; 89.74%). This reflected similarly for tree volume of 'Wichita' for both seasons (88.12 m^3; 86.12 m^3).

In the second season (2020/21), no significant differences were found between cultivars for any of the five stages, except for stage 2, when 'Navaho' and 'Wichita' intercepted significantly more light than 'Choctaw'. This is partly due to the earlier development of 'Navaho' and 'Wichita' at Stage 2 (Table 2.3). However, despite the significantly higher tree volume of 'Choctaw' at the end of the season, in 2020/21, fPAR did not reflect this change in canopy development in the rest of the stages (3-6). This was also supported by the lack of correlation between tree volume and fPAR (Fig 2.1 and 2.2).

The lowest fPAR was recorded in Stage 6, at leaf drop, as expected, with no significant differences between the three cultivars. The higher fPAR recorded in 'Wichita' was due to the later completion of leaf drop in the remaining cultivars and not a reflection of tree volume differences *per se*.

Stem Circumference, Tree Volume and Shoot Length

In the 2019/20 season significant differences were recorded for stem circumference, as well as tree height, with 'Choctaw' recording a significantly thicker stem and higher trees compared to 'Wichita'. 'Navaho' also recorded a significantly thicker stem than 'Wichita', but the tree height was similar to both cultivars. No significance difference found between cultivars for tree volume, despite a difference in tree height, indicating that tree height is not the primary factor influencing tree volume calculations.

In the second season (2020/21), a significant difference was found between cultivars for stem circumference, tree height and tree volume. 'Choctaw' developed into significantly bigger trees than 'Navaho' and 'Wichita', calculated according to a full ellipse tree shape. This was also bigger than the results from Wood (1996), who recorded a much smaller volume of 45 m^3 for a 10-year-old tree with a semi- ellipsoid shape. In both cases, drip irrigation was used.

Although shoot lengths did not differ significantly, 'Wichita' produced the longest and 'Navaho', the shortest shoots. However, this could not be related to tree size only, as cultivar characteristics, tree training and pruning, and yield could have also influenced shoot growth. 'Navaho' recorded longer shoots (110.13 cm) than recorded by Dedekind (2020) (64.15 cm), for six-year-old trees, in Prieska. 'Wichita' shoots were also longer (140.03 cm) than reported by Dedekind (2020) for five-year-old trees (64.15 cm), in Prieska.

Phenological development

The differences in the timing of the phenological stages experienced in Vredendal are cultivar and climate related and are important, as pecans are dichogamous and the timing of the development of male and female flowers are essential for successful pollination. This is especially evident in the selection of Wichita as main cultivar, as it is protogynous and requires pollination from protandrous cultivars such as Navaho (Thompson et al., 1995 Thompson and Conner, 2012). Thus, it was essential to confirm that 'Navaho' developed earlier than 'Wichita' at this site. The synchronization of cultivars is also climate related as was evident in a narrower window of Stage 2, in Prieska, on similar aged trees, where Dedekind (2020) reported only a week between bud-break of these cultivars in 2019.

Yield

In the first season, yield, nuts per tree, as well as yield efficiency, were only recorded for 'Wichita' and served as a baseline for the second season.

In the second season, no significant difference between cultivars were recorded for yield. The yield for 'Navaho' (5.54 $kg.tree^{-1}$) was less than recorded by Dedekind (2020) (13.32 $kg.tree^{-1}$) in Prieska, or Thompson et al. (1995) (7.43 $kg.tree^{-1}$), in Texas, USA. No significant difference was recorded for number of nuts per tree or yield efficiency. Even though Dedekind (2020) recorded much higher yields for 'Navaho', his yield efficiency was lower (94.5 $g.cm^{-1}$), compared to the current data/ results (134.74 $g.cm^{-1}$).

Yield and number of nuts per tree in 'Wichita' only increased modestly form the first to the second season, from 5.90 $kg.tree^{-1}$ to 6.08 $kg.tree^{-1}$ and from 712.73 to 812.13 nuts per tree, with a decline in yield efficiency, from 172.98 $g.cm^{-1}$ to 153.84 $g.cm^{-1}$. This may partly be ascribed to the relative high average shoot length, in 2020/21. Excessive shoot length may result in a lower precocity due to more resources being located to vegetative than reproductive growth. The ideal shoot length for maximum precocity is known to differ between cultivars.

Nut quality parameters

Nut quality parameters were only recorded for the second, when 'Choctaw' recorded the longest nuts, followed by 'Wichita' and then, 'Navaho'. This was also the case with nut mass, with 'Choctaw' recording the heaviest nuts, followed by 'Wichita' and 'Navaho'. 'Choctaw' also recorded the largest nuts in diameter, followed by 'Navaho' and then 'Wichita'. This confirmed local results by Meier (2020), which stated that 'Choctaw' pecans produce very large nuts. Similarly, 'Navaho' produced smaller nuts than the other cultivars (Thompson et al., 1995). The percentage nut fill for all three different cultivars were 100%, indicating that there was sufficient fertilization at present in all cultivars.

Climate Data

None of the pecan cultivars showed visual damage caused by temperature extremes, such as hot or cold weather extremes. Even though Vredendal has a very dry climate, sufficient water was available for irrigation, with no visual signs of wilting on evaluation dates. Suitable temperatures for vegetative growth are between 24 and 30°C (Spars, 2005), with Vredendals historical data recording an average maximum temperature of 26.3°C.

For pollination and successful flowering, a chilling requirement of 300 – 500 CU is recommended, and 250 – 300 for 'Wichita', with a minimum of 100 CU if sufficient heat is available, but suboptimal chilling will lead to pollination problems (Dedekind, 2020; Wells, 2015; 2017). Historic data indicated an average of 236.32 CU for the Vredendal region, which did not meet the recommended requirement, but did fulfil the minimum requirement. However, cold units recorded in 2019/20 (193) and 2020/21 (88 with the missing data in August), met the lower requirement for 'Wichita' (193), but not for 'Choctow' (333) according to data from Turkey (Kudan et al., 2013). Nevertheless, it did not seem to negatively influence the pecan trees as far as phenological development or yield was concerned. Although the timing of bud-break for the cultivars differed, bud-break was not delayed sufficiently to impact yields and/or growth at this time.

Pollination is also influenced by temperatures near freezing point, causing damage to the female flower (Wood et al., 1997). Luckily Vredendal experiences a warm climate with historical average minimum climate during pollination recording 10.94°C, for October and November. Pollination is also negatively influenced by rainfall, directly influencing soil moisture and causing diseases such as scab, indirectly influencing pollination (Sparks, 1997), but Vredendal is a very dry region, only receiving an historical annual average rainfall of 176.69 mm and is not likely to cause scab development. Rain can also influence pollination, by washing away pollen from female flowers and delaying pollination with wet and lowered humidity (Wood, 2000). During the pollination period, Vredendal receives an average total rainfall of 13.71 mm for October and November, which is not to cause any influence on pollen distribution. Vredendal also receives an average maximum and minimum relative humidity of 88.8 and 33.6%, which is not likely to influence pollen distribution indirectly by leading to scab development. Strong wind shortens the release of pollen by the tree, which will influences pollen distribution (Wood, 2000), but even though strong wind do occur in

Vredendal, with an average windspeed recorded at 3.08 $m.s^{-1}$, pollen shedding did not seem to be negatively influenced.

For chilling to occur, optimal temperatures between 0 and 7°C, is needed, with temperatures below 0°C and above 13°C, not effective for dormancy (Arora et al., 2003; Erez, 1995). Fronza et al. (2018) suggested temperatures lower or equal to 7.2°C. Historical data indicated an average minimum temperature of 6.6°C, for the winter month of May to August.

Pecan nut production is also preferred in areas with a humidity of less than 55% (Terreblance, 2019), with Vredendal meeting this requirement, with an average of 55.11%, over the past 10 years. The region also did not exceed the maximum relative humidity of 90%, indicating scab susceptibility (Payne and Smith, 2012). Since pecans are wind-pollinated, adequate wind is required during pollination and although Sparks (2005) did not quantify the wind parameters, historical data indicated average wind speeds of 2.42 $m.s^{-1}$ during this period in Vredendal.

Conclusion

Again, the approach towards this research was descriptive and therefor results are exploratory. Results did not show any significant differences between cultivars with regard to light interception for the five phenological stages recorded, with the exception of phenological stage 2. This was due to 'Navaho' development that started much earlier than 'Wichita' or 'Choctaw' and therefore resulted in a higher light interception in stage 2. Higher light interception was expected with increasing tree sizes, such as with 'Choctaw', but this was not the case and tree volume did not influence light interception, therefore indicating that despite tree size and cultivar differences, light intercepting differences did not occur at this early stage of the tree development.

'Choctaw' trees were bigger than 'Navaho' and 'Wichita' trees, but had a similar yield and number of nuts per tree. The bigger nuts recorded for 'Choctaw' are in agreement with cultivar characteristics, but could also be partially related to a higher photosynthetic potential due to the bigger tree canopy of this cultivar. The higher increase in stem circumference, tree height and tree volume of 'Choctaw' between the seasons also confirmed that this cultivar will fill its allocated space in the orchard sooner than the other two cultivars and may experience crowding sooner.

Long-term climate data indicated that Vredendal is suitable for the cultivation of 'Wichita', 'Navaho' and 'Choctaw', provided sufficient irrigation water is available. At present, the cultivars indicated adaptation to the extreme summer temperatures (32.8°C) and less optimal chilling accumulation, as a viable yield was recorded in 2020/21 and no visual signs of delayed foliation were observed in either of the seasons.

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Table and Figure

Table 2.1: The effect of three different cultivars on the fractional light interception (fPAR) at Zandkraal during the 2019/20 and 2020/21 season, recorded at five different times throughout the phonological stage of the pecan tree.

Cultivar	**fPAR (%)**					
	2019/20 Season	**2020/21 Season**				
	Phenological stage 5	**Phenological stage 2**	**Phenological stage 3**	**Phenological stage 4**	**Phenological stage 5**	**Phenological Stage 6**
	11/05/2020	01/12/2020	11/01/2021	16/03/2021	26/04/2021	15/07/2021
Wichita	89.03	94.45 ab	92.15 ns	94.22 ns	89.74 ns	29.61 ns
Navaho		96.97 a	91.31	92.12	87.41	23.95
Choctaw		93.57 b	87.76	92.41	90.70	22.09
P		0.0186	0.2873	0.6872	0.6435	0.5626

[y] Means with a different letter within a column differ significantly at the 5% level.

Table 2.2: Stem circumference (cm) and shoot length (m) of three pecans cultivars at Zandkraal during the 2019/20 and 2020/21 season.

Cultivar	**Stem circumference (cm)**		**Tree Height (m)**		**Tree Volume (m^3)**		**Avg. Shoot Length (cm)**
	11/05/2020	06/07/2021	04/06/2020	06/07/2021	04/06/2020	06/07/2021	21/05/2021
Wichita	32.09 b	39.62 b	5.58 b	6.04 b	88.12 ns	86.12 b	140.03 ns
Navaho	35.78 a	41.57 b	5.87 ab	6.78 a	76.23	95.71 b	110.13
Choctaw	38.17 a	46.127 a	6.11 a	7.17 a	85.58	129.85 a	122.93
P	<0.0001	<0.0001	0.0020	<0.0001	0.3334	0.0015	0.1118

[y] Means with a different letter within a column differ significantly at the 5% level.

Table 2.3: Six stage crop growth of three different pecan cultivars at Zandkraal in Vredendal during the 2019/20 season (Ibriamo et al. 2018).

Stage	Definition	Season 2019/20	Season 2020/21
		Date (week)	Date (week)
1. Bud-Break	Emergence of leaf primordial	Navaho, Wichita – 40 Choctaw – 42	Navaho – 40 Wichita – 42 Choctaw – 44
2. Pre-pollination	Occurrence of leaf expansion	Navaho, Wichita – 44 Choctaw – 45	Navaho, Wichita - 44 Choctaw – 45
3. Pollination to early dough	Stigmas of pistalle flower turn from green to red/brown until shell hardening is complete	48 – 50	Navaho, Wichita - 47 Choctaw – 49/50
4. Dough stage	Kernel is completely formed	18-19	14
5. Shuck or hull split	Sutures of shuck begin to split apart	19	18 – 19
6. Leaf drop	Leaves begin to dehisce from the trees	Navaho - 23 Wichita – 25 Choctaw – 27	26 - 28

Table 2.4: Yield, yield efficiency and average number of nuts per tree for three pecan cultivars at Zandkraal during the 2019/20 and 2020/21 season.

Cultivar	**Yield**				**Nuts tree^{-1}**		**Yield efficiency**	
	(kg.tree^{-1})	**(kg.ha^{-1})**	**(kg.tree^{-1})**	**(kg.ha^{-1})**			**(g.cm^{-2})**	
	11/05/2020		21/05/2021		11/05/2020	21/05/2021	11/05/2020	21/05/2021
Wichita	5.90	699.25	6.08 ns	759.91 ns	712.73	812.13 ns	172.98	153.84 ns
Navaho			5.54	692.91		715.73		134.74
Choctaw			6.63	828.81		801.00		145.03
P			0.0812	0.0812		0.2310		0.3254

Table 2.5: Nut quality parameters for a composite sample of 50 nuts for three different pecan cultivars at Zandkraal in the 2020/2021 season. Nut fill was determined on n=10 per cultivar.

Cultivar	**Nut length (mm)**	**SE**	**Nut diameter (mm)**	**SE**	**Nut mass (g)**	**SE**	**Nut fill (%)**
Wichita	41.86	0.42	19.40	0.14	7.42	0.14	100
Navaho	38.05	0.54	19.42	0.15	6.27	0.16	100
Choctaw	45.37	0.39	23.68	0.22	11.37	0.25	100

Table 2.6: Monthly total daily positive chilling units (DCPU) and total monthly Utah Chill Units (CU) from May to August for the past 10 years from 2012 to 2021, in Vredendal (ARC-ISCW automatic weather station).

Utah Model (CU)											
Month	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	**Average**
May	51.50	-118.00	-99.00	-65.00	-124.50	-170.00	-183.00	-156.50	-92.50	-96.50	
June	146.50	147.00	141.00	185.50	115.00	99.00	8.00	95.00	42.00	-41.50	
July	235.50	137.00	205.50	253.00	150.00	150.50	-7.50	173.00	69.50	226.00	
August*	261.50	193.50	57.50	86.50	44.50	121.00	213.00	120.00	174.00		
Total	695.00	359.50	305.00	460.00	185.00	200.50	30.50	231.50	193.00	88.00	237.50
DCPU											
Month	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	**Average**
May	95.00	21.00	27.50	21.50	9.00	10.00	11.50	27.50	38.00	27.00	
June	197.50	180.00	158.00	187.50	163.50	136.50	69.00	124.00	105.50	68.50	
July	239.50	175.00	223.00	274.00	165.50	183.50	130.00	180.50	114.50	248.50	
August*	262.50	229.50	105.00	126.00	89.50	149.50	242.00	145.50	192.50		
Total	794.50	605.50	513.50	609.00	427.50	479.50	452.50	477.50	450.50	344.00	500.35

*Missing data due to broken sensors

Table 2.7: Monthly average maximum temperatures (°C), for the past 10 years from 2011 to 2020, in Vredendal (ARC-ISCW automatic weather station).

Month	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	average
September	24.4	22.3	21.1	24.9	24.4	23.5	25.4	21.5	28.2	24.0	24.0
October	25.5	24.8	25.3	27.4	28.2	26.7	26.1	30.3	27.4	26.5	26.6
November	26.5	28.0	28.5	27.5	27.6	29.5	28.2	27.9	28.7	27.1	27.9
December	27.8	29.8	30.9	28.4	30.5	30.9	30.7	27.4	28.6	28.8	29.4
January	31.5	30.9	30.4	31.3	33.9	31.3	30.3	29.3	29.5	31.4	31.0
February	29.8	30.4	32.0	29.4	31.5	31.8	31.2	31.3	32.8	31.3	31.3
March	29.3	30.8	28.3	30.7	28.2	32.1	27.6	27.9	29.8	30.0	29.6
April	26.9	27.5	29.7	28.0	28.2	31.1	26.7	26.6	28.0	31.4	28.4
May	22.4	24.7	24.1	24.3	26.2	27.4	24.2	25.7	23.9	24.5	24.5
June	20.5	19.4	20.7	19.4	21.3	21.8	20.9	22.9	19.7	22.5	20.8
July	19.6	20.4	20.1	18.5	21.0	22.8	22.8	20.2	20.0	19.7	20.6
August*	18.5	19.5	21.8	21.4	24.8	21.4	19.1	22.8	17.1		20.8
Average	25.2	25.7	26.1	25.9	27.1	27.5	26.1	26.2	26.1	27.0	26.3

*Missing data due to broken sensors

Table 2.8: Monthly average minimum temperatures (°C), for the past 10 years from 2011 to 2020, in Vredendal (ARC-ISCW automatic weather station).

Month	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	Average
September	7.5	7.5	6.4	8.0	9.0	7.7	7.8	6.5	9.5	6.5	7.8
October	9.7	10.4	8.8	10.9	9.9	8.8	9.4	13.2	9.8	9.4	10.0
November	10.3	11.7	12.0	12.3	11.4	11.5	11.5	11.3	11.8	11.6	11.6
December	12.4	16.3	14.4	12.9	14.1	12.5	13.7	13.4	13.3	13.3	13.8
January	15.7	13.8	14.7	14.9	16.9	13.5	15.5	13.7	14.8	14.7	14.9
February	13.6	14.6	15.9	13.0	14.8	13.5	14.7	15.3	15.9	13.1	14.6
March	13.1	12.8	12.4	13.0	12.0	12.6	12.5	13.7	13.7	12.9	13.0
April	11.4	9.8	11.9	11.2	12.2	12.1	11.5	11.1	11.5	11.9	11.5
May	6.6	9.1	8.8	8.2	8.6	8.6	10.0	9.1	7.4	8.4	8.6
June	6.5	6.7	5.8	6.3	6.1	5.9	8.3	5.8	6.8	8.3	6.7
July	5.1	6.0	5.0	5.8	5.6	4.1	7.2	6.2	3.9	3.7	5.3
August*	4.8	5.8	6.5	6.8	6.0	5.0	4.7	4.9	5.2		5.6
Average	9.7	10.4	10.2	10.3	10.6	9.7	10.6	10.4	10.3	10.3	10.3

*Missing data due to broken sensors

Table 2.9: Monthly average maximum relative humidity (%), for the past 10 years from 2011 to 2020, in Vredendal (ARC-ISCW automatic weather station).

Month	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	Average
September	93.5	94.1	94.9	9316.0	89.6	88.6	85.2	91.2	80.9	90.8	90.2
October	89.0	88.0	92.8	86.0	91.1	85.6	80.7	72.6	87.0	86.7	86.5
November	89.3	87.3	90.2	90.6	85.3	82.5	83.1	81.2	84.9	83.7	86.1
December	89.0	90.0	89.4	90.7	88.6	85.8	80.1	87.0	82.3	87.5	87.2
January	90.0	87.8	91.2	89.4	88.8	82.3	84.6	86.1	87.0	84.7	87.4
February	89.5	89.0	88.2	89.7	88.5	83.7	82.3	85.6	84.2	85.2	87.1
March	90.6	90.8	92.1	91.8	92.9	82.2	87.4	88.7	86.5	87.7	89.2
April	87.8	89.6	83.1	83.7	85.2	73.8	88.6	86.9	85.9	82.6	84.9
May	94.1	86.9	92.8	94.3	91.0	82.4	86.3	88.4	93.4	89.4	90.0
June	93.0	94.4	93.6	95.7	92.3	90.4	88.0	87.8	94.8	88.5	92.2
July	93.7	95.4	95.6	95.8	93.3	89.3	83.2	92.3	95.4	90.5	92.2
August*	95.2	94.6	94.5	94.8	92.6	87.9	92.5	90.1	93.0		92.6
Average	91.2	90.6	91.5	91.3	89.9	84.5	85.2	86.5	88.0	87.0	88.8

*Missing data due to broken sensors

Table 2.10: Monthly average minimum relative humidity (%), for the past 10 years from 2011 to 2020, in Vredendal (ARC-ISCW automatic weather station).

Month	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	Average
September	33.1	38.1	36.4	32.4	33.9	30.6	27.4	36.8	24.1	28.4	32.0
October	30.8	34.0	34.9	32.5	31.2	26.5	25.2	22.5	23.3	29.3	29.6
November	29.8	31.3	31.5	35.9	28.5	25.1	26.1	25.4	25.2	31.2	29.4
December	33.5	39.1	31.4	35.4	30.3	25.3	24.8	34.8	27.9	30.1	31.8
January	33.6	31.0	35.8	31.4	31.9	25.6	31.2	30.3	34.4	29.2	31.7
February	32.6	34.5	31.9	32.0	30.9	25.3	26.8	31.5	27.8	26.8	30.3
March	35.7	31.2	36.4	34.0	35.5	21.9	32.7	38.8	30.7	30.6	32.6
April	33.0	28.8	28.2	30.9	32.7	22.9	33.1	31.1	27.9	24.4	29.2
May	38.3	35.9	39.8	39.9	34.2	25.7	35.3	31.0	36.6	35.5	36.1
June	43.6	48.6	40.2	50.4	39.9	34.1	43.0	31.3	51.1	39.4	42.9
July	40.7	44.0	44.2	47.2	40.2	27.5	32.3	44.0	40.9	37.8	39.4
August*	45.0	45.1	41.2	45.3	31.2	31.6	36.3	30.5	49.1		39.3
Average	35.8	36.8	36.0	37.3	33.3	26.8	31.2	32.3	33.3	31.1	33.6

*Missing data due to broken sensors

Table 2.11: Monthly average windspeed (m.s^{-1}), for the past 10 years from 2011 to 2020, in Vredendal (ARC-ISCW automatic weather station).

Month	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	Average
September	2.6	2.4	2.4	2.4	2.2	2.4	2.4	2.1	2.3	1.9	2.3
October	2.8	3.3	3.1	3.0	2.5	2.8	3.1	3.2	2.8	2.2	2.9
November	3.7	3.4	3.3	3.1	3.5	3.3	3.4	3.3	3.1	3.0	3.3
December	3.6	3.1	3.4	3.5	3.1	3.3	3.5	3.1	3.4	3.0	3.3
January	3.5	3.5	3.1	3.2	2.8	3.4	3.6	3.4	3.2	3.1	3.3
February	3.2	3.2	3.0	3.1	2.8	3.3	3.3	2.9	2.8	3.0	3.0
March	2.9	2.6	2.7	2.6	2.6	2.5	2.7	2.6	2.3	2.2	2.6
April	2.4	2.1	2.1	2.5	2.2	2.0	2.1	2.2	1.6	1.6	2.1
May	1.6	1.8	1.8	1.6	1.5	1.6	1.6	1.5	0.3	1.3	1.5
June	1.8	1.8	1.7	1.7	1.5	1.7	1.6	1.5	0.2	1.3	1.5
July	1.7	1.6	1.6	1.5	1.5	1.5	1.9	1.6	0.2	1.2	1.5
August*	2.3	2.0	2.0	1.6	1.6	2.0	1.9	1.5	0.7		1.8
Total	2.7	2.6	2.5	2.5	2.3	2.5	2.6	2.4	1.9	2.2	2.4

*Missing data due to broken sensors

Table 2.12: Monthly total rainfall (mm), for the past 10 years from 2011 to 2020, in Vredendal (ARC-ISCW automatic weather station).

Month	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20	2020/21	Average
September	7.4	7.1	13.5	9.7	1.0	9.1	0.0	0.0	6.1	4.3	6.8
October	8.1	9.7	6.6	0.8	0.5	1.8	9.9	3.6	2.0	22.9	7.4
November	14.2	15.5	2.5	26.2	1.3	0.3	3.3	1.0	0.0	0.8	6.3
December	1.5	58.2	107.7	0.0	0.0	0.0	0.0	1.8	0.8	1.0	23.6
January	0.3	0.5	12.2	1.0	15.0	1.5	5.1	0.0	0.0	0.5	7.2
February	70.1	4.6	1.5	0.5	0.3	0.0	0.0	0.0	0.0	0.0	7.0
March	47.5	7.1	11.4	2.0	1.8	0.0	0.0	0.0	0.0	1.5	7.5
April	91.2	6.6	3.3	0.3	7.6	1.5	0.0	0.0	12.7	0.3	11.3
May	216.9	10.9	17.8	3.6	12.5	0.5	1.3	0.0	5.8	12.5	28.4
June	16.8	50.6	14.7	47.0	34.0	16.5	71.1	9.1	14.2	33.8	30.6
July	26.9	13.7	27.4	17.3	18.0	2.3	71.4	22.1	34.8	29.2	24.4
August*	40.4	44.5	15.0	5.1	13.0	6.6	23.6	1.5	14.5		17.8
Average	541.3	228.9	233.7	113.3	104.9	40.1	185.7	39.1	90.9	106.7	176.7

*Missing data due to broken sensors

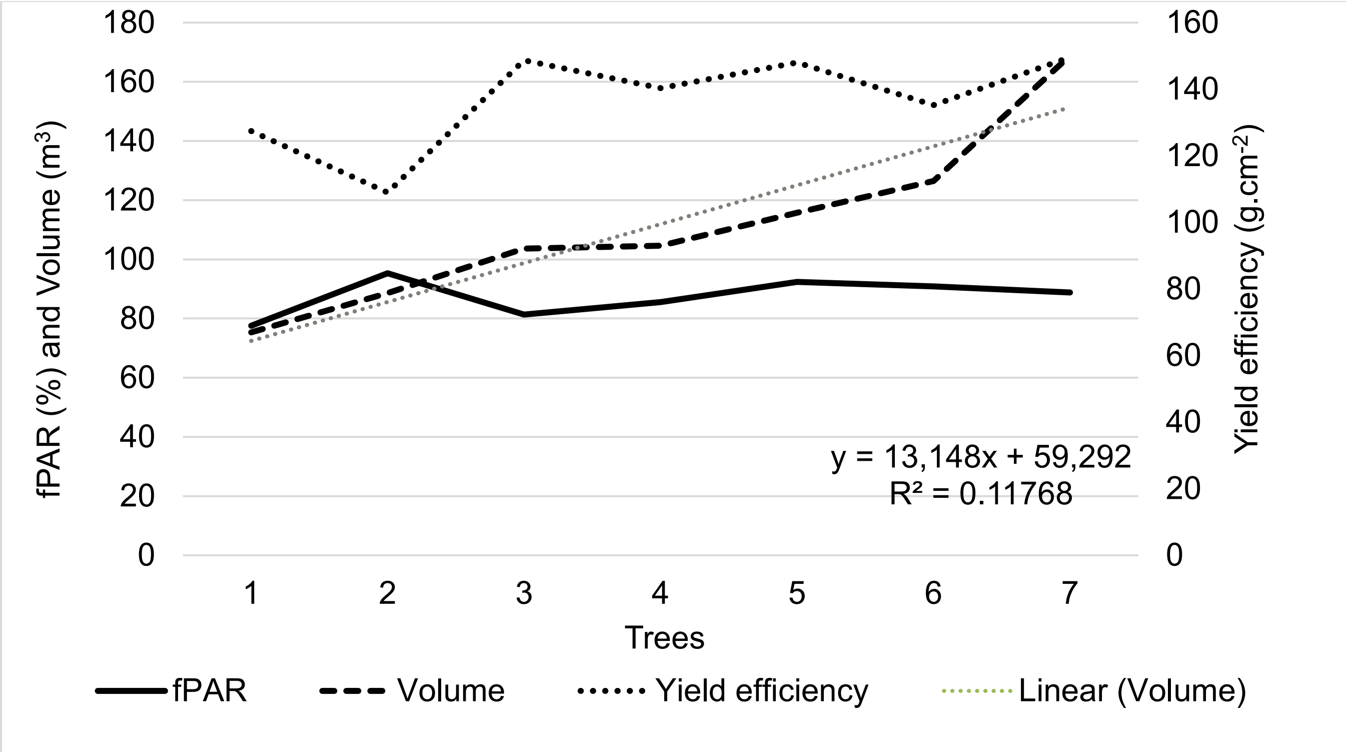

Figure 2.1: Relationship between fPAR (%), volume (m^3) and yield efficiency ($g.cm^{-2}$) for individual 'Navaho' pecan trees at Zandkraal, in Vredendal for the 2020/21 season (P = 0.4512).

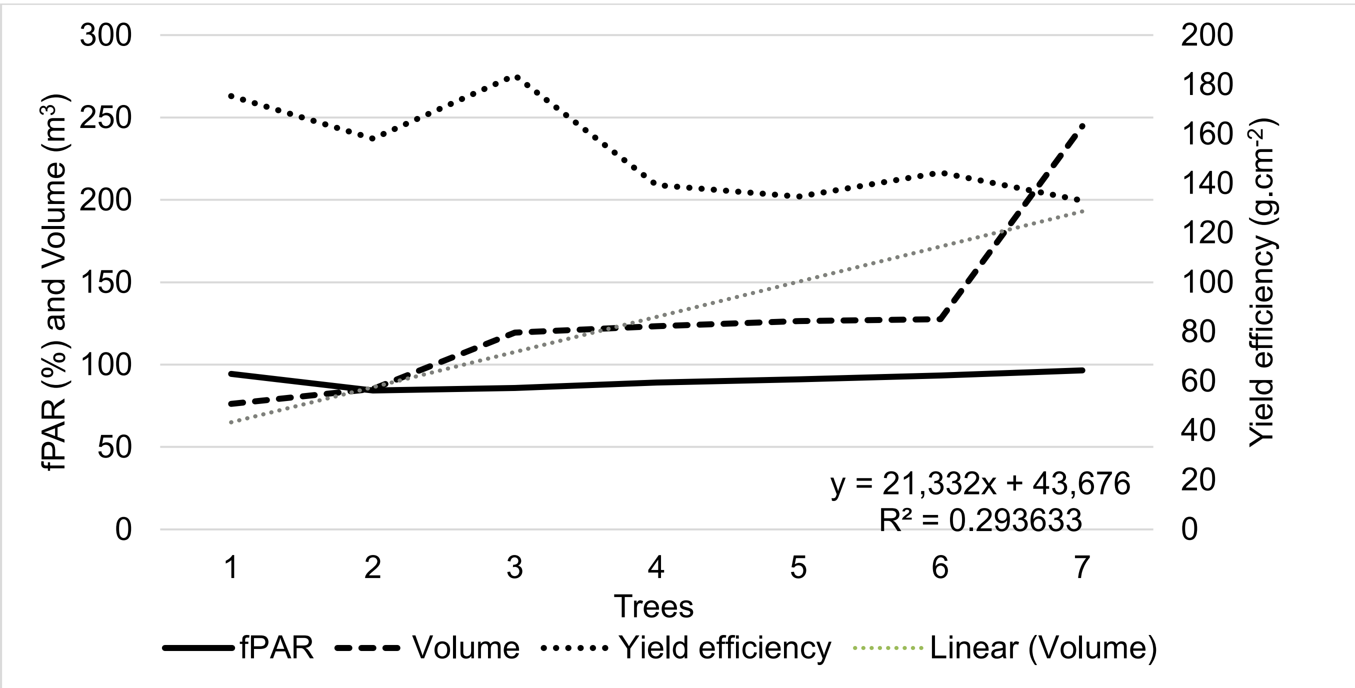

Figure 2.2: Relationship between fPAR (%), volume (m^3) and yield efficiency ($g.cm^{-2}$) for individual 'Choctaw' pecan trees at Zandkraal, in Vredendal for the 2020/21 season (P = 0.2089).

PAPER 3: The potential sustainability of commercial pecan production in the Western Cape: a desktop study

Abstract

This paper was a desktop study on the evapotranspiration (ET) estimates of pecan orchards in the Hermon and Vredendal regions, using historical data. Pecans have a high-water use and require reliable estimates of ET in a new area when considering the sustainability of commercial production. This paper introduced the calculation of ET, using estimates of reference evapotranspiration (ET_o) from the generic FAO-56 method and a pecan specific crop model for determining the K_c of pecans, modified for local conditions from Ibraimo et al. (2016). Results indicated a higher annual ET for Vredendal (1399.9 and 1342.8 mm) compared to Hermon (918.5 and 954.3 mm) primarily caused by climatic differences. Historical data indicated a higher average temperature, annual total rainfall, average relative humidity, wind speed and ET_o for Vredendal than Hermon. Evapotranspiration from satellite imagery (Fruitlook®), confirmed the higher ET for Vredendal of 525.4 (Site 1) and 500.1 mm (Site 2), compared to Hermon, with 450.1 (Site 3) and 390.4 mm (Site 4) in (2020/21). Based on a predicted temperature increase of 2°C for these regions in future, the predicted ET will increase in both regions. This indicated the potential water requirement in both regions, as well as the potential water requirement if climate change results in the predicted temperature increase. The calculated ET realised much higher values compared to satellite data, as calculated ET represents the upper limit of ET, where evaporation is calculated as a maximum value. In reality, evaporation was likely to be much lower in these orchards. Crop coefficients were derived from mature orchards and the adjustment for canopy cover of young orchards has not been validated. For future predictions and to fully understand the sustainability of pecan production in this region, the estimation and measurement of the water use of mature orchards must be conducted accurately. This will be key for determining actual water allocations to pecan producers in these regions.

Key words: Climate change, evaporation, crop coefficients, satellite data, transpiration

Introduction

A lack of information regarding irrigation and nutrition often prevents producers from achieving management objectives, with planning and irrigation water management becoming vital for maximizing orchard profitability (Sammis et al., 2013). In pecan, irrigation is a critical factor for optimal fruit production (Wells, 2015). Wang et al. (2007) reported that pecans had a 30% higher optimum consumptive water usage than any other crop in the New Mexico region of the United States of America (USA). It was also found that due to pecans' relatively high upfront cost for production, farmers tended to reduce the water use of other crops in favour of pecan orchards during drought conditions, which leads to an overall increase in the cost for pecan productions (Hwang and Bin, 2019). Therefore, sufficient water resources must be available in future, if extension of pecan is envisaged in any area (Sammis et al. 2013).

Under local conditions, in the Western Cape, water availability is already under severe strain due to population growth and climate change, which may result in a decrease in water availability towards agriculture in future. Climate change is most likely to increase the water stress due to increasing evapotranspiration, as well as increasing crop demand and variable rainfall (Greenagri, 2006). The Western Cape has already been identified as being highly vulnerable, in terms of the projected climate change, with temperatures predicted to rise by a further 1 – 2°C within the next 30 years (Wand, 2007). In a study by Erasmus et al. (2000), a decline in the Western-Cape precipitation was predicted, which could result in less water for agriculture. They also anticipated a 1.2°C temperature increase by 2020, 2.4°C by 2050 and 4.2°C by the year 2080, with a 5 – 10% decrease in rainfall in the next 50 years (Durand, 2006). The agricultural sector is very sensitive to inter-annual climate variability and to any risk causing extremes in rainfall and temperature (Wand, 2007). This climate variability impact can lead to reduced crop yields, resulting in increased food insecurity (Olabanji et al., 2020). In addition, most perennial crops require irrigation due to the predominant winter rainfall climate and producers are investigating alternative crops like pecan to diversify their risks. Thus, quantifying the water requirement of pecan under local conditions will be critical to indicate future water allocations and availability for the expansion of this crop.

Several studies, cited by Olabonji et al. (2020), surrounding climate change and the impact of climate change on agricultural production in South Africa, have already been assessed and all concluded that a decrease in crop yields will be a result of the changing climate. This impact on crop yields is more significant in areas classified as arid and semi-arid (Durand, 2006). South Africa is classified as a semi-arid country, with the Western Cape containing many semi-arid regions where the land is used for agriculture (Olabonji et al., 2020).

Studies assessing the impact of climate change on future crop production depend on the prediction of the climate and using mathematical models, which can relate to climate change scenarios (Franke, 2021). Therefore, the uncertainty surrounding the future availability of water for pecan expansion in the Western Cape prompted the investigation regarding the prediction of future ET_o, based on a simple temperature increase, which could then be used as reference for the possible future water requirements and to assess the sustainability of pecan expansion. The model will be based on an assessment of pecans' future consumptive water demand, which is a combination of soil evaporation and transpiration, which together constitutes evapotranspiration (ET) of orchards. Evapotranspiration and precipitation are key factors involved in the regulation of the water balance of any region (Nastos et al., 2015). The ET can be estimated by multiplying the reference evapotranspiration (ET_o) by the crop coefficient (K_c) of the crop in question (Wang et al., 2007). However, factors including cultivar, irrigation systems, soil type, crop cover and climate are known to influence ET (Pereira et al., 2015) and therefore local estimations are required for accurate ET values.

Quantifying ET is costly and time consuming and thus development of a model for determining ET, is preferable. Ibraimo et al. (2016) cited several generic and crop specific models for calculating pecan water use that ranged in complexity and intricacy. For our desktop study, a simplified FAO-56 model (Allen et al., 1998) using a dual crop coefficient (which was the combination of transpiration crop coefficient (K_t) and evaporation coefficient (K_e)), for pecans was used to compute the ET. Data from locations suitable for pecan establishment, located throughout the Western Cape, were used. This will indicate the possible future water requirements for pecan expansion in these areas, using ET measurements based on the current size of the trees, with transpiration increasing with tree size and evaporation from the soil decreasing as result of increased shading of the soil by the trees.

Therefore, the aim was to assist current producers in determining the potential water for pecans, by investigating the current ET for two different regions, Vredendal and Hermon, each containing two different sites with different tree densities. These different sites will represent the current ET for pecans planted at higher and lower densities, at both regions, with the lower density orchards, being older and expected to have a higher water requirement.

Materials and Methods

Study area and meteorological measurements

Two regions, that represent existing pecan orchards in the Western Cape, were selected to serve as a baseline for future extension: Hermon and Vredendal. The climate of these regions ranges from arid, semi-arid to Mediterranean, with both regions having short cold winters and long hot summers, ideal for pecan production.

The data was collected from commercial farms, Zandkraal and Rotsvas, in Vredendal, Western Cape (31° 35’ 22” S; 18° 25’ 6” E and 31° 42’ 52” S; 18° 31’ 49” E), as well as at Kleinplasie (33° 27’ 19” S; 18° 57’ 11” E), in Hermon. The site at Zandkraal (Site 1) contained a six-year-old orchard, planted in in 2015, spaced 10 x 8 m (2.6 ha) (125 $trees.ha^{-1}$) and comprised three cultivars: Wichita and Choctaw, planted as three rows per cultivar, with Navaho planted in-between, as cross-pollinator. All trees were grafted on ‘Ukulinga’ rootstock. Rotsvas (Site 2) included a five-year-old orchard, planted in 2016, spaced 10 x 5 m (1 ha) (200 $trees.ha^{-1}$) , with ‘Wichita’ as the main cultivar and ‘Navaho’ as the cross-pollinator.

Kleinplasie contained two sites, with Site 3 a four-year-old orchard, planted in 2017, spaced at 8 x 4 m (3.73 ha) and Site 4, a five-year-old orchard, planted in 2016, spaced 8 x 6 m (1.58 ha). Both sites contained ‘Wichita’ as the main cultivar with ‘Navaho’ as the cross-pollinator.

For each location, historical climate data was collected from local automatic weather stations (AWS) in close proximity to the trial sites, for the stations in Vredendal (31° 41’ 2” S; 18° 28’ 9” E) and Hermon (33° 34’ 60” S; 18° 58’ 4” E) for the last 10 years, form 2009 until 2020, which was provided by the ARC- ISCW (ARC, 2021). The weather parameters recorded were daily maximum and minimum temperatures (°C), rainfall (mm), maximum and minimum relative humidity (%), average wind speed ($m\ s^{-1}$) and solar radiation ($MJ.m^{-2}.d^{-1}$). This data was used to estimate reference evapotranspiration (ET_o) according to FAO-56 procedure (Allen et al., 1998).

Future ET prediction

To determine possible future water use or change in the seasonal crop evapotranspiration (ET), (for a mature pecan orchard by using currently established orchards), a crop coefficient model, based on that of Ibraimo et al. (2016) was used. The local climate data was used to estimate biweekly ET_o values using the standardized Penman Monteith equation, as outlined in FAO-56 (Allen et al., 1998), for a hypothetical short reference grass surface, with a height of 0.34 m as follows:

$$ET_0 = \frac{0.408\Delta\,(R_n - G) + \gamma\,(C_n/T) + 273)u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

where ET_o reference evapotranspiration (mm.day^{-1}), R_n net radiation at the crop surface (MJ m^{-2}.day^{-1}), G soil heat flux density (MJ m^{-2}.day^{-1}, which for daily intervals may be ignored, thus G ≈0, T mean daily temperature at 2 m height (°C), u_2 wind speed at 2 m height (m s^{-1}), e_s saturation vapour pressure (kPa), e_a actual vapour pressure (kPa), e_s-e_a saturation vapour pressure deficit (kPa), Δ slope saturation vapour pressure curve at temperature T (kPa.°C^{-1}]) and γ, a psychrometric constant (kPa.°C^{-1}]). All the variables mentioned were estimated from past conditions for both locations, from which a simplistic approach was followed to estimate future water use of pecans by determining the ET_o for the near future by adjusting the temperature with the desired amount to simulate future temperature conditions.

Crop coefficient modelling

In the study by Ibraimo et al. (2016), two different single modelling approaches, the generic FAO-56 model (Allen et al., 1998) and the pecan-specific crop coefficient model (Samani et al., 2010) were followed, which used single K_c values and ET_o for estimating the monthly ET of pecans. In this study, only the pecan-specific crop coefficient model was used. The evaluation was conducted using data sets, which were obtained from measurements of younger pecan orchards, ranging from three – six years old, for Sites 1 – 4 in Hermon and Vredendal, alongside the past 10-year climate data collected. Modification, suggested by Samani et al. (2010) for the length of the season, as well as the 6-month offset, to account for the growing season in the southern hemisphere, were accounted for. The pecan-specific model from New Mexico estimates ET by empirically relating a crop coefficient of a well-managed, mature reference orchard ($K_{c\text{-}ref}$; $f_{c\text{-}eff}$ = 80%) to canopy cover of a study orchard as follows:

$K_c = (0.6035\ f_{c\text{-}eff} + 0.4808)\ K_{c\text{-}ref}$

Where, K_c is the crop coefficient (ET/ET_o) of the specific orchard, $f_{c\text{-}eff}$ is the effective fractional cover and $K_{c\text{-}ref}$ is the reference crop coefficient. While this approach works well for mature orchards, Ibraimo et al. (2016) suggested that it would not work well for young orchards and that for young orchards a dual crop coefficient approach should be used. Since the current study focussed on young pecan orchards with an effective fractional cover of less than 80%, a references transpiration crop coefficient $K_{t\text{-}ref}$ was used, which was based on transpiration of a mature orchard in Cullinan for a canopy cover of approximately 90%. The above equation was still used but the K_c was replaced by a K_t. This approach is currently being assessed in a current study on pecan water use (personal communication NJ Taylor).

Fortnightly $K_{t\text{-}ref}$ values for a mature, reference orchard in Cullinan, adjusted for the longer season in the Western Cape are given in Table 3.1. Effective fractional cover ($f_{c\text{-}eff}$) for the orchards in Vredendal and in Hermon was calculated using the following equation:

$$f_{c-eff} = \frac{fc}{sin\ (\beta)} \leq 1$$

Where f_c is the fraction cover and β is the angle of the sun to the ground, calculated using δ, and φ, where δ is the solar declination and φ is the latitude (radians). $f_{c\text{-}eff}$ is generally calculated at solar noon (12:00), and therefore β is calculated using:

$$\beta = arcsin\ [sin\ (\varphi)\ \ sin\ \ (\delta)\ \ +cos\ \ (\varphi)\ cos\ (\delta)$$

The fractional cover is based on the general shape of the tree, from which the area of the tree canopy is then calculated:

$$Area = \ \pi\ x\ (\frac{(\frac{W + B}{2})}{2})^2$$

Where, Area is the area of the tree (m^2), or the area of the shadow cast by the tree on the ground when the sun is located directly overhead (i.e. solar noon), π is pi, W is the width of the tree and B is the breadth of the tree. Fractional cover is then calculated by the following equation:

$$f_c = \frac{Area}{Area\ per\ tree}$$

Where, Area is the area of the tree (m^2) and Area per tree, is the spacing of the specific orchard (m^2) in question. An illustration showing the extent of f_c, $f_{c\ eff}$ and β, can be seen in Fig 3.1 (Allen and Pereira, 2009).

The following equation was used to determine ET: ET = K_c x ET_o, where ET is the evapotranspiration of the specific crop, ET_o the reference evapotranspiration for a well water grass and K_c is the crop-coefficient (ET/ET_o), of the pecan tree. K_c was calculated using: $K_c = K_t + K_e$, where K_e is the evaporation coefficient (E/ET_o). By determining a K_e, an adjustment was made for the different irrigation systems used in the study orchards, which affects the wetted area and therefore the potential evaporation rates. This is particular important for young orchards, where the wetted area from irrigation is often exposed to solar radiation.

In order to calculate K_e, the following equation was used, $K_e = f_{ew}$ x $K_{c\ max}$, where f_{ew} is the fraction of the soil that is both exposed and wetted, i.e., the fraction of the soil surface from which most evaporation occurs. $K_{c\ max}$ is the maximum value of K_c following rain or irrigation for a mature orchard, for drip irrigation. This data therefore represent the upper limit for evaporation and assumes that evaporation is never limited by the availability of water in the top soil layer. These maximum evaporation rates are therefore likely to be higher than reality, where soil water can become limiting. These evaporation rates are also for younger orchards where a fairly, large, wetted area will be exposed to radiation. Evaporation rates are expected to be lower for mature orchards where a larger proportion of the soil surface is shaded for a large part of th season. If micro-sprinkler irrigation is used (Hermon), f_{ew} is calculated using: f_{ew} = min $(1 – f_c, f_w)$, where f_w is the average fraction of soil surface wetted by the irrigation or precipitation and f_c is the exposed soil fraction not covered by the vegetation.

In the case where drip irrigation is used (Vredendal), most of the wetted soil is beneath the canopy and may therefore be shaded and the value of f_w may need to be reduced by one-third, to account for the effect of shading. Therefore, f_{ew} is calculated using:

$$f_{ew} = f_w \, x \, [1 - (\frac{2}{3}) f_c]$$

Fruitlook® Model

The actual evapotranspiration (ET), which is the amount of water used to produce a crop, and the ET deficit, which is the difference between the actual ET and potential ET, represented the amount of water that could be evaporated and transpired under local meteorological conditions and ample water supply, which is known as the absolute evapotranspiration deficit (ET def). Both the actual ET and ET deficit were determined, for the four sites in Vredendal and Hermon, using satellite images from Fruitlook®, from 2016 to 2020. The Fruitlook® service uses the Sentinel-2 and Landsat 8, for weekly measurements with a special resolution of 20 x 20 m.

Results

Future ET prediction

Seasonal ET_o prediction (September to August) was 1703 mm for Hermon and 2386 mm for Vredendal, whilst future ET_o, with a predicted temperature increase of 2°C, increased to 1779 mm (4.4% increase) for Hermon and 2511 (5.2% increase) for Vredendal (Table 3.2). Seasonal average rainfall, averaged over the past 10 years, for Hermon was 413 mm and 199 mm, for Vredendal (Table 3.2).

Crop coefficient modelling approach

$K_{t\text{-}ref}$ values are summarised in Table 3.1, with the reference crop coefficient illustrated in Fig. 3.2. Effective fractional cover values, measured for Sites 1 and 2 decreased for the first season to the second season (0.13 to 0.12 and 0.17 to 0.15), whilst Sites 3 and 4 saw an increase from season one to season 2 (0.12 to 0.13 and 0.13 to 0.26) (Table 3.3).

Seasonal total ET based on this approach was 1399 mm (Site 1), 1342 mm (Site 2), 918. mm (Site 3) and 954.3 mm (Site 4) (Table 3.4). When a possible increase in temperature of 2°C was taken into account in the ET_o estimation, the seasonal total ET increased to 1472 mm (5.2% increase) (Site 1), 1412 mm (5.2% increase) (Site 2), 958 mm (4.4% increase) (Site 3) and 995 mm (4.4% increase) (Site 4) (Table 3.4). The monthly ET for both sites is illustrated for the season in Fig 3.3 and 3.4.

Fruitlook® Model

Total actual ET was calculated with data from the satellite service provided by Fruitlook®, on a weekly basis and combined to a seasonal total. ET decreased in Sites 1, 2 and 3 from 540.26 to 525.42 mm, 544.06 to 500.13 and from 544.09 to 450.05 mm, but increased in Sites 4 from 377.97 to 390.42 mm, from the first to the second season (Table 3.5)

Total evapotranspiration deficit, calculated using Fruitlook® for a seasonal total, decreased for Sites 1 and 4, from 281.1 to 184.0 mm and from 198.1 to 158.1 mm. Sites 2 and 3 saw an increase from 164.6 to 251.8 mm and from 155.3 to 159.2 mm, from season one to season two (Table 3.5).

The trends in actual ET and evapotranspiration deficit were similar between the two sites, in each region. Sites 1 and 2 recorded the highest actual ET at the beginning of the year (February - March) with > 25 $mm.week^{-1}$, whilst declining towards 5 $mm.week^{-1}$ at the beginning and end of the season (August/ September).

Evapotranspiration deficit for Sites 1 and 2 peaked in November, January and April and were associated with phenological stages of pre-pollination, pollination to early dough and the dough stage (Paper 1). The highest peak occurred in April, which corresponded with phenological Stage 4, with an average of 12 - 14 $mm.week^{-1}$. Similar peaks were recorded for Sites 3 and 4, with a very large peak in October, which coincided with the onset of bud-break (phenological Stage 1), with March/ April coinciding with the dough stage, with the canopy at a maximum size.

Discussion

Reference evapotranspiration measurements were calculated based on climate data collected for the past 10 years (2009 – 2020), for the Hermon and Vredendal regions. Excluding irrigation, the amount of rainfall, (stored during the winter months and during the leaf bearing season), did not exceed the current ET_o, ET or actual ET estimate (using Fruitlook®), for either Hermon or Vredendal. This data gives an estimate of the amount of water that is required to satisfy the estimated reference evapotranspiration, for Hermon (1703 mm) and Vredendal (2386 mm), under current conditions. Assuming the K_c of the pecans is 1 for the current regions, for a K_c less than 1, it could be expected that the ET would be less than current ET_o. Similarly, an ET higher than the ET_o is expected if the K_c is more than 1. With a predicted future temperature increase of 2°C, the estimated reference evapotranspiration will increase to 1779 mm for Hermon and 2511 mm, for Vredendal. This is caused by the increase in potential atmospheric evaporative demand, especially during the months from October to June, when the tree canopy is at a maximum size, resulting in maximum transpiration.

ET_o for Vredendal was noticeably higher than for Hermon and was directly linked to the climatic differences between regions, with Vredendal being a more semi-arid region than Hermon, more Mediterranean. The historically limited annual precipitation in Vredendal already necessitated access to a substantial irrigation volume for current agricultural production, excluding potential expansion to pecans. If climate change results in a temperature increase of 2°C, this demand for additional irrigation water would increase for all crops, including for pecans, but should be sustainable as enough water is available for the near future (personal communication – Willem van Zyl, producer).

Ibraimo et al. (2016) recorded ET_o values for Cullinan of 1020, 944 and 1034 mm for three consecutive seasons (2009 – 2012). These are much lower than the ET_o recorded for either Hermon or Vredendal. They also recorded that irrigation and rainfall (summer) exceeded the ET_o under those conditions and therefore it would be highly unlikely for stress to occur, since the pecans have an extensive root volume and will have a sufficient water supply. However, these conditions were opposite to what will be experienced in the experimental sites, as the annual rainfall is much lower, especially in Vredendal. Threfore, this region will be more reliant on irrigation to meet pecan orchard waterdemands, at the traditional 10 x 10 m density, if the current annual rainfall is expected to be the same for the years to come.

Previous $K_{c\ ref}$ values, provided by Samani et al. (2010) for New Mexico, were offset by six months to adjust to the Southern hemisphere, but gave poor results in the study by Ibraimo et al. (2016). Initial monthly K_c values gave poor predictions (R^2 = 0.01 to 0.15), with underestimates at the beginning and the end of the season, which resulted in poor ET estimates. This was due to different rates of canopy development and canopy senescence in the two regions. Therefore, $K_{c\text{-}ref}$ were adjusted for the specific climate conditions of the study site, as suggested by Sammis et al. (2004). Both Samani et al. (2011) and Allen et al. (1988) advocate the adjustment of crop coefficient curves for local conditions. These adjusted $K_{c\text{-}ref}$ values subsequently provide good estimates of ET in Cullinan when canopy cover was taken into account. However, Ibraimo et al. (2016) suggested that this adjustment would only work well for orchards where canopy cover exceeded 80% and evaporation made up a fairly low proportion of ET. These authors suggested that for younger orchards a dual crop coefficient approach should be used. Since the canopy cover of the orchards in Hermon and Vredendal was less than 80%, a dual crop coefficient approach was followed and K_t values were determined from the $K_{t\text{-}ref}$ curve for a mature orchard in Cullinan which were adjusted for local conditions in the Western Cape

The effective fractional cover for the pecan trees at all four sites were determined to quantify solar radiation absorption for the different tree canopies that provides the energy for transpiration. Both Sites 1 and 2 (125 and 200 trees.ha^{-1}) recorded a decrease in the $f_{c\ eff}$ from the first season (2019/20) to the second season (2020/21): Site 1 – 0.13 to 0.21 and Site 2 – 0.17 to 0.15. In contrast, at Hermon, Site 3 increased from 0.12 to 0.13 and Site 4, drastically increased from 0.13 to 0.26. This substantial increase in Site 4 was primarily due to the noticeable increase in tree volume from 40.34 m^3 to 73. 62 m^3 from the first to the second season (Paper 1).

The recorded ET values of Ibraimo et al. (2016) (1035, 985 and 1050 mm) for 2009 – 2012 in Cullinan (annual rainfall – 673 mm), were exceeded in Vredendal (using historical data) and clearly indicated the major influence of the much drier conditions, and much longer production season, of Vredendal on ET as compared to the Cullinan area. ET values of Hermon were similar to those of Ibraimo et al. (2016) and indicated less harsh conditions, with historically a higher average rainfall (of 413.3 mm), lower average windspeeds and a lower relative humidity, compared to Vredendal. It should also be noted that these measurements were done on younger pecan orchards, with a smaller canopy cover than used by Ibraimo et al. (2016). It is thus expected that the recorded ET would be much higher in mature orchards, with a bigger canopy cover, in these regions in future, since a much higher leaf area/biomass. would increase the evaporation significantly.

In the first season (2019/20), higher density orchards recorded higher actual evapotranspiration compared to the lower density orchards and was most likely due to the denser biomass area created by the higher density, leading to a higher measured ET form satellite data. In the second season, the same trend was seen in Hermon, but not in Vredendal, indicating that the lower density orchard (Site 1 – 10 x 8 m), containing trees with a bigger canopy size, created a denser area/orchard and lead to a higher ET, in spite of the lower density. With the absence of a cover crop in Vredendal, the difference can only be due to differences in the vegetative growth of the pecan trees, with possibility that the vegetative growth of the pecans in the higher density orchard decreased, resulting into a lower canopy cover overall. Despite the canopy size and density differences, the two sites in Vredendal experienced the same peaks for the measured actual ET, indicating regional/site differences. Thus, phenological development occurred at the same time, but due to the difference in canopy size, ET differed accordingly. This was also evident with the actual ET peaking in January for Sites 3 and 4 in Hermon, which was earlier than Vredendal, indicating a clear climate difference between Hermon and Vredendal. Maximum ET was recorded at the beginning of the year, when canopy size was at a maximum and lower ET occurred, when the canopy size was at a minimum, either at bud-break or leaf drop. This also indicated the impact of leaves and canopy cover on evaporation and transpiration.

Phenological development also commenced earlier in Hermon (Paper 1), with an earlier canopy cover development leading to the difference in timing of peaks and actual ET. The early peak in October in Site 3, which is not so evident in Site 4, may be the influence of a denser orchard design, leading to a denser canopy cover. The occurrence of a cover crop will increase the potential ET, as the cover crop will transpire, and therefore the occurrence of a cover crop needs to be accounted for when ET is determined with satellite imagery. The presence of the cover crop would have also influenced the intensity and timing of the ET peaks in Sites 3 and 4 in Hermon.

ET deficit followed the opposite trend, with the lower density orchards recording higher ET deficits than the higher density orchards, in both regions. This indicated that the lower density orchards experienced more crop stress, possibly due to insufficient irrigation allocation, as both sites were irrigated at the same dates, while being under the same climatic conditions.

In the second season, the higher density orchards recorded higher ET deficits, indicating that higher stress was observed in the higher density orchards, with Site 2 far exceeding the other sites. As the two sites were managed the same, (same irrigation scheduling) and same climate, orchards differed in age and orchard density and thus tree size/canopy and this again illustrated the difference in water requirement of the different tree densities and ages at these sites. Evapotranspiration deficit peaks corresponded with phenological stages. Canopy size was related to maximum ET deficit between January and April, for all four sites in both regions. These hot and dry climatic conditions resulted in maximum stress during full canopy development with a crop load. ET deficit peaks also indicated possible stress periods due to a lack of sufficient water during nut filling and maximum canopy size that should be addressed in future for optimum quality and yield.

Conclusion

Evapotranspiration values recorded in Hermon and Vredendal were substantially smaller than ET_o, due to the fairly low canopy cover recorded at all four sites, and resulted in a K_c value of less than 1, in the middle of the season. A higher ET would thus be expected when the trees mature, leading to a higher canopy cover and higher K_c values (above 1).

The recorded ET confirmed the much higher water requirement in Vredendal compared to Hermon, with Vredendal being hotter and drier, resulting in higher evaporation and transpiration. In both regions, the lower density orchards recorded much higher ET values compared to the higher density orchards, which was also confirmed by the actual ET calculated from satellite data. Since sufficient available water is a primary requirement for pecan cultivation, these estimates will be important if commercial expansion in the Western Cape is considered in future, as pecans will have to be irrigated in summer and the requirement will increase further as trees mature.

As expected, a scenario with an increase in temperatures by 2°C, increased ET by 5.2% for Vredendal and 4.3% for Hermon (averaged for both sites). This will further increase the demand for irrigation volumes in future.

The actual ET, determined via satellite imaging, recorded lower values for Sites 1-4 compared to the ET estimated using an a dual crop coefficient approach, for current conditions, as these ET values likely represented an upper limit for evaporation and transpiration. In reality, lower evaporation and transpiration rates are expected, due to transient water stress in the orchards, as indicated by the ET deficit. Bansouleh et al. (2015) reported a reasonable match between calculated (SEBAL and SEBS algorithms using LANDSAT TM images) and measured ET (Lysimeter), indicating that satellite imagery is reliable and should give an accurate estimate of ET. Nevertheless, for the scope of the study, the estimated current and future ET was sufficient in determining the potential water requirement for young orchards, but further investigation for mature orchards is needed if the suitability of future pecan production in these two regions in the Western Cape is to be determined.

Acknowledgments

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Table and Figures

Table 3.1: Biweekly crop transpiration coefficient ($K_{t\text{-}ref}$) used in the current study, for both the Hermon and Vredendal region, provided from a current project on pecan water use on a bi-weekly basis, in Cullinan for a mature canopy cover of approximately 90 %.

Month	$K_{t\text{-}ref}$
September	0.11
	0.26
October	0.41
	0.56
November	0.71
	0.83
December	0.84
	0.84
January	0.84
	0.84
February	0.84
	0.84
March	0.84
	0.84
April	0.84
	0.89
May	1.06
	1.23
June	1.30
	1.29
July	0.93
	0.39
August	0.01
	0

Table 3.2: Monthly and seasonal total reference evapotranspiration (ET_o) and future ET_o, with predicted 2°C increase in temperature, as well as the average rainfall for Hermon and Vredendal, based on the ET_o by Allen et al. (1998), from historical data from 2009 – 2020.

Month	Hermon			Vredendal		
	Rainfall (mm)	ET_o (mm)	ET_o + 2°C (mm)	Rainfall (mm)	ET_o (mm)	ET_o + 2°C (mm)
September	31.2	118.1	124.1	6.8	183.3	193.5
October	19.4	167.6	175.7	7.4	256.1	269.7
November	29.4	195.7	204.7	8.5	278.2	292.7
December	9.9	210.0	219.4	26.9	284.1	298.7
January	11.4	224.2	233.6	11.7	293.8	308.2
February	6.3	195.9	204.1	7.1	260.1	272.5
March	10.8	172.8	179.9	7.1	230.8	242.2
April	20.0	124.7	129.7	12.7	175.2	183.9
May	50.9	81.5	84.9	30.8	115.4	121.9
June	97.6	65.4	68.2	34.4	89.0	94.6
July	69.3	66.9	69.8	29.5	97.8	103.8
August	57.1	80.9	85.0	16.8	122.4	129.8
Total	413.3	1703.7	1779.1	199.7	2386.3	2511.5

Table 3.3: The effective fractional cover ($f_{c\text{-}eff}$) for four orchards located in Vredendal (Site 1 – 10 x 8 m and Site 2 – 10 x 5 m) and Hermon (Site 3 – 8 x 4 m and Site 4 – 8 x 6 m), for the 2019/20 and 2020/21 seasons.

Area	Experimental Site	Tree age (years)	Plant population (trees ha^{-1})	$f_{c\text{-}eff}$	
				2019/20	2020/21
Vredendal	1	6	125	0.13	0.12
	2	5	200	0.17	0.15
Hermon	3	4	312	0.12	0.13
	4	5	208	0.13	0.26

Table 3.4: Seasonal total evapotranspiration (ET) for current and future conditions with a predicted 2°C increase in temperature for Hermon and Vredendal, based on the ET_o by Allen et al. (1998), from historical climate data from 2009 – 2020.

Area	**Experimental Site**	**Tree age (years)**	**Plant population (trees ha^{-1})**	**ET (mm)**	**ET + 2°C (mm)**
Vredendal	1	6	125	1399.9	1472.7
	2	5	200	1342.8	1412.7
Hermon	3	4	312	918.5	958.1
	4	5	208	954.3	995.5

Table 3.5: Total actual evapotranspiration (ET) and evapotranspiration deficit, for Sites 1 and 2, in Vredendal, and Sites 3 and 4, in Hermon, for the 2019/20 and 2020/21 seasons, provided by satellite images using Fruitlook®.

Site	**Tree age (years)**	**Plan Population (trees.ha^{-1})**	**ET (mm)**		**Evapotranspiration deficit (mm)**	
			2019/20	**2020/21**	**2019/20**	**2020/21**
1	6	125	540.3	525.4	281.1	184.0
2	5	200	544.1	500.1	164.6	251.8
3	4	312	544.1	450.1	155.3	159.2
4	5	208	378.0	390.4	198.1	158.1

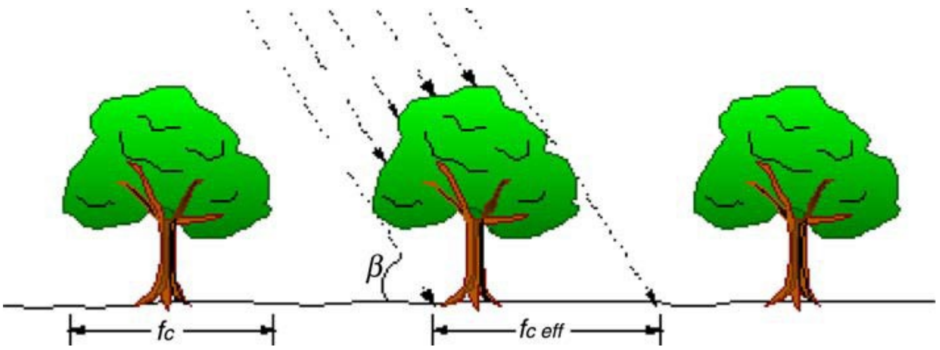

Figure 3.1: Schematic representation showing the extent of f_c, $f_{c\ eff}$ and β. Where f_c is the faction of the soil surface covered by the tree canopy and measured directly overhead (Allen and Pereira, 2009).

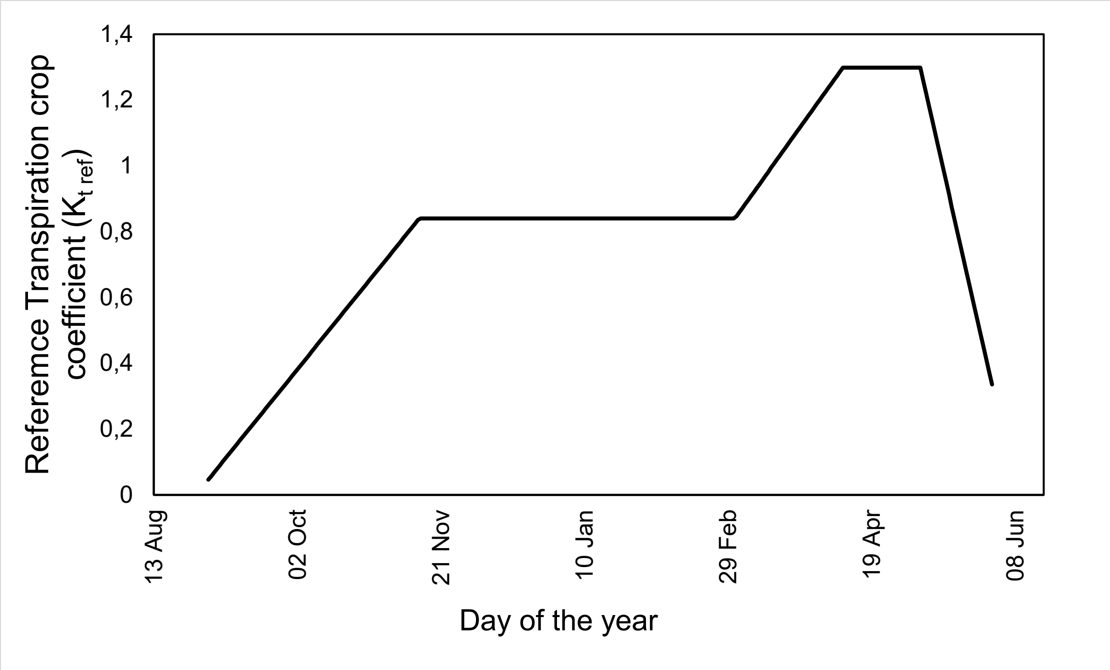

Figure 3.2: Reference transpiration crop coefficient ($K_{t\text{-}ref}$) curve for a mature pecan orchard in Cullinan, based on data from Ibraimo et al. (2016).

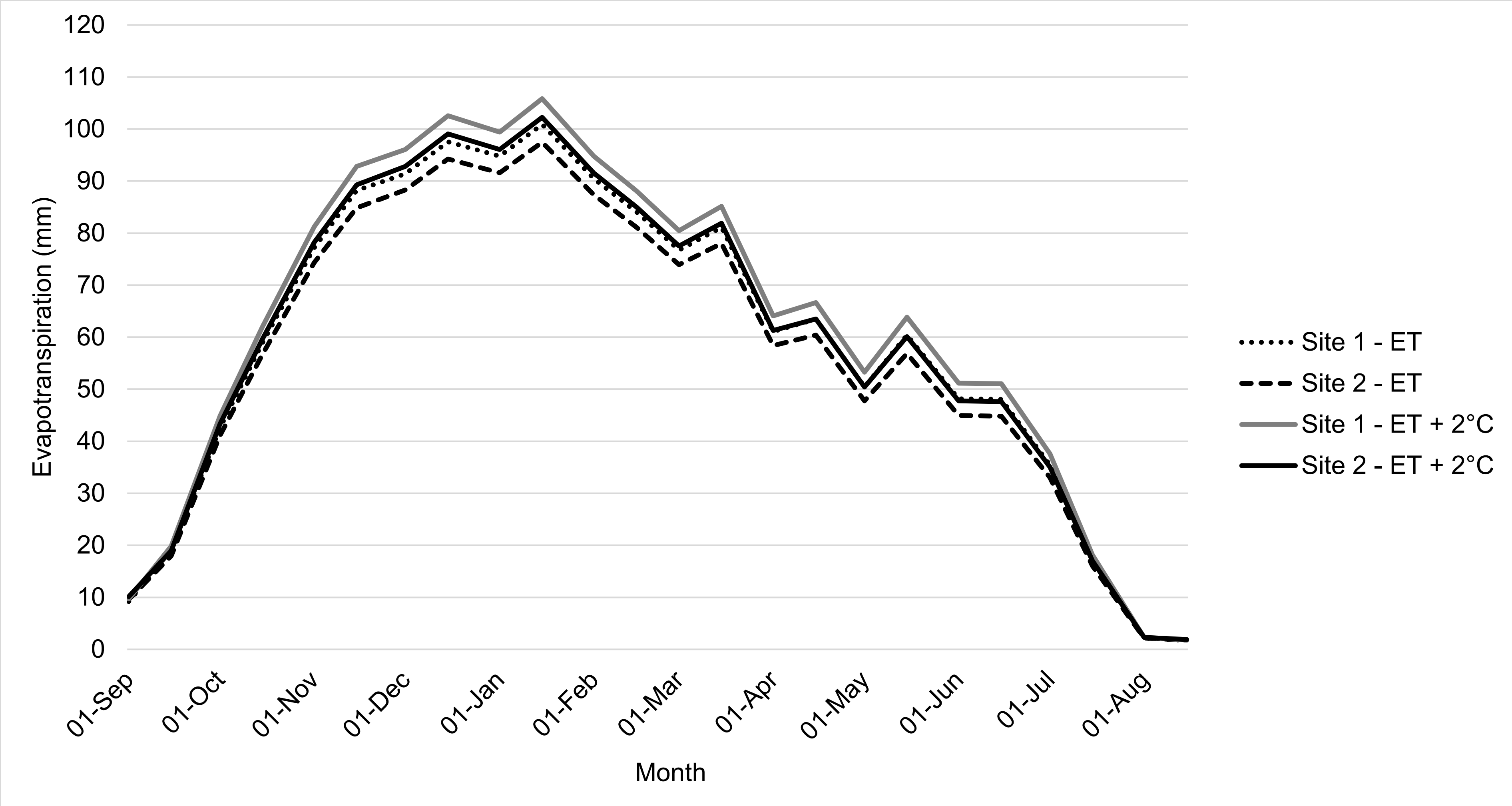

Figure 3.3: Current and future evapotranspiration (mm) prediction, with an adjusted increase in temperature by 2°C for pecans at Vredendal, Sites 1 and 2, from the start of the season (September) until the end (August) using historical data from 2009-2020.

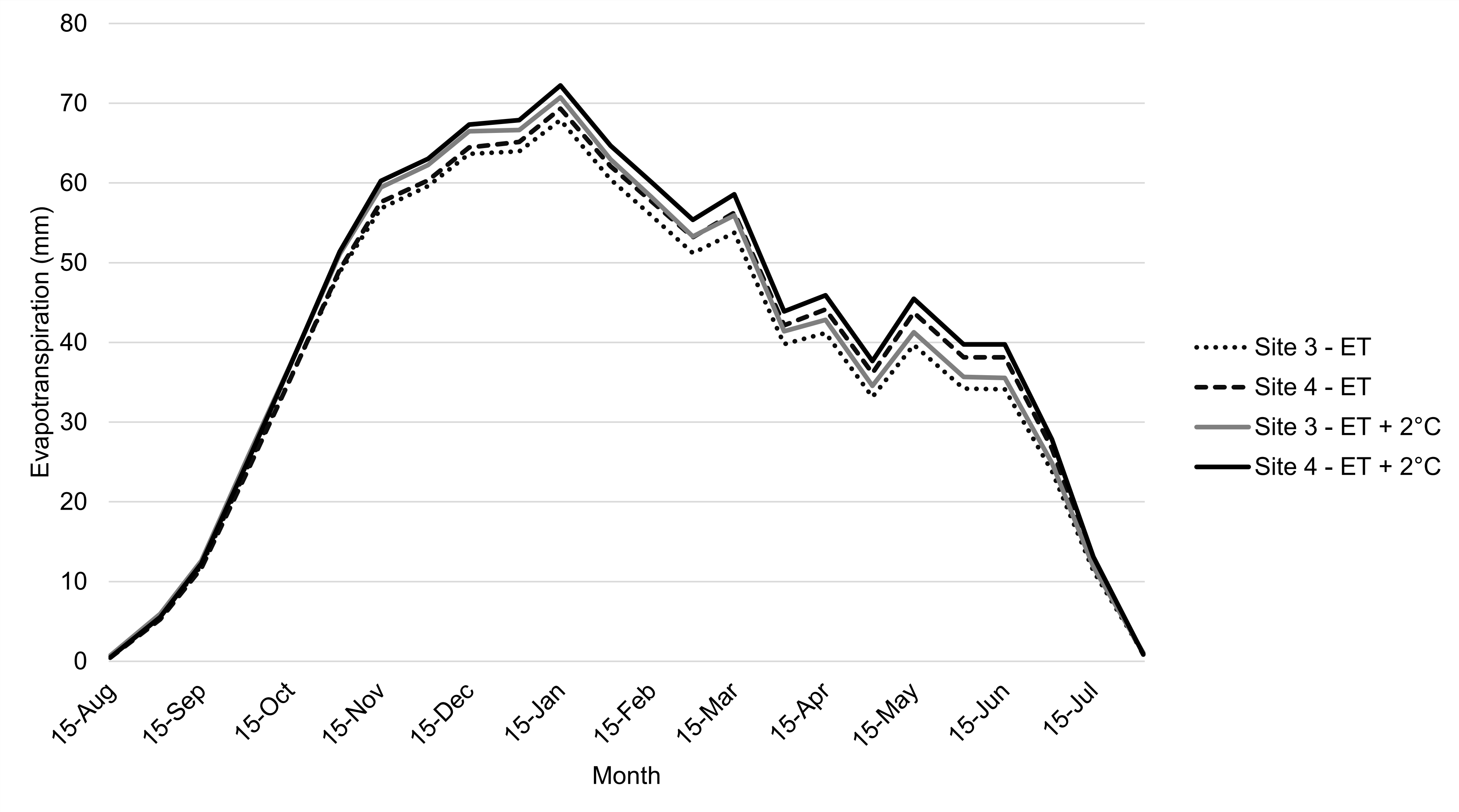

Figure 3.4: Current and future evapotranspiration (mm) prediction, with an adjusted increase in temperature by 2°C for pecans at Hermon, Sites 3 and 4, from the start of the season (September) until the end (August) using historical data from 2009 -2020.

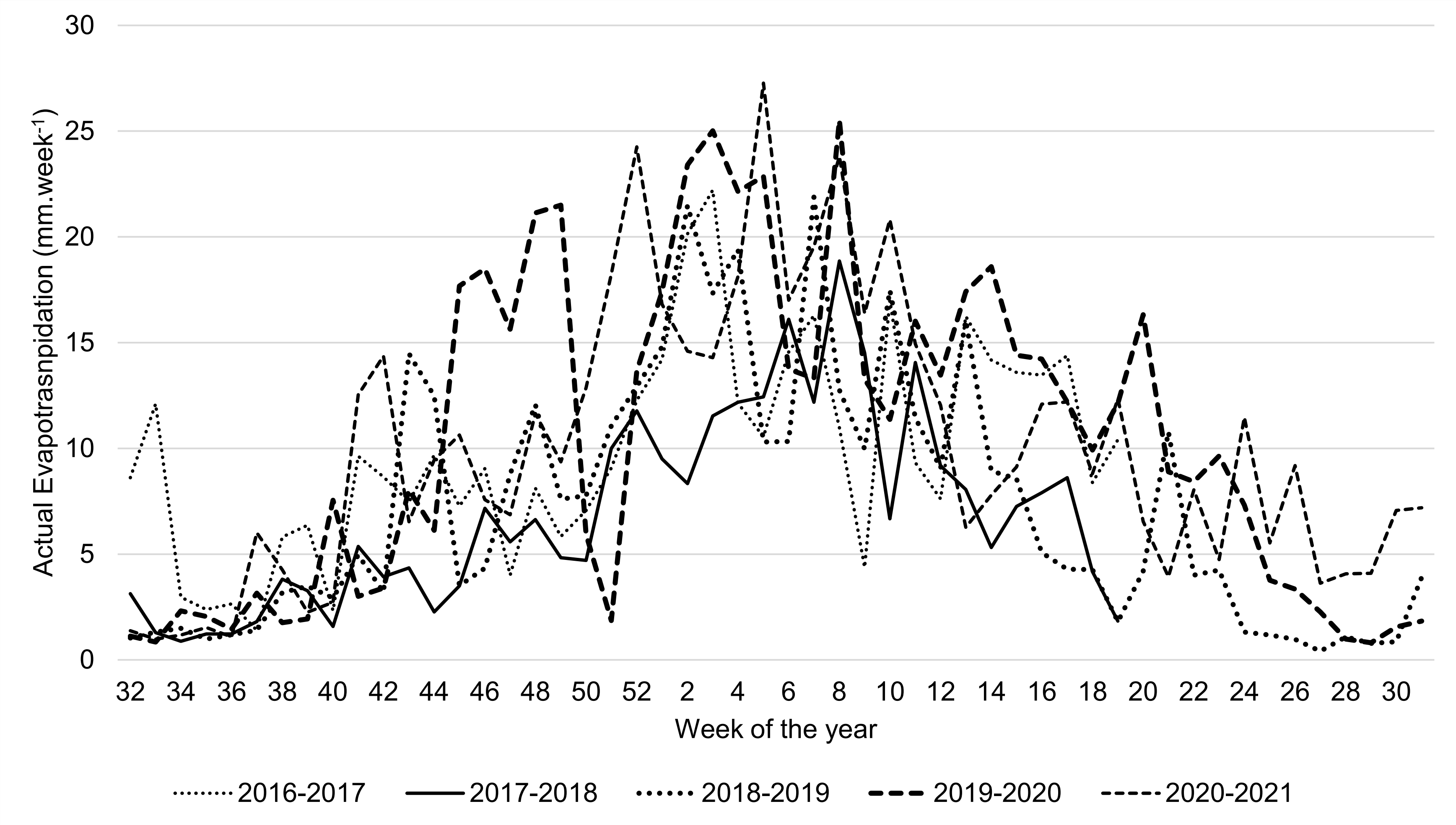

Figure 3.5: Weekly actual evapotranspiration (mm.week^{-1}) of 'Wichita' pecans, at Site 1 (10 x 8 m) in Vredendal, from 2016 to 2021, using Fruitlook® satellite imagery.

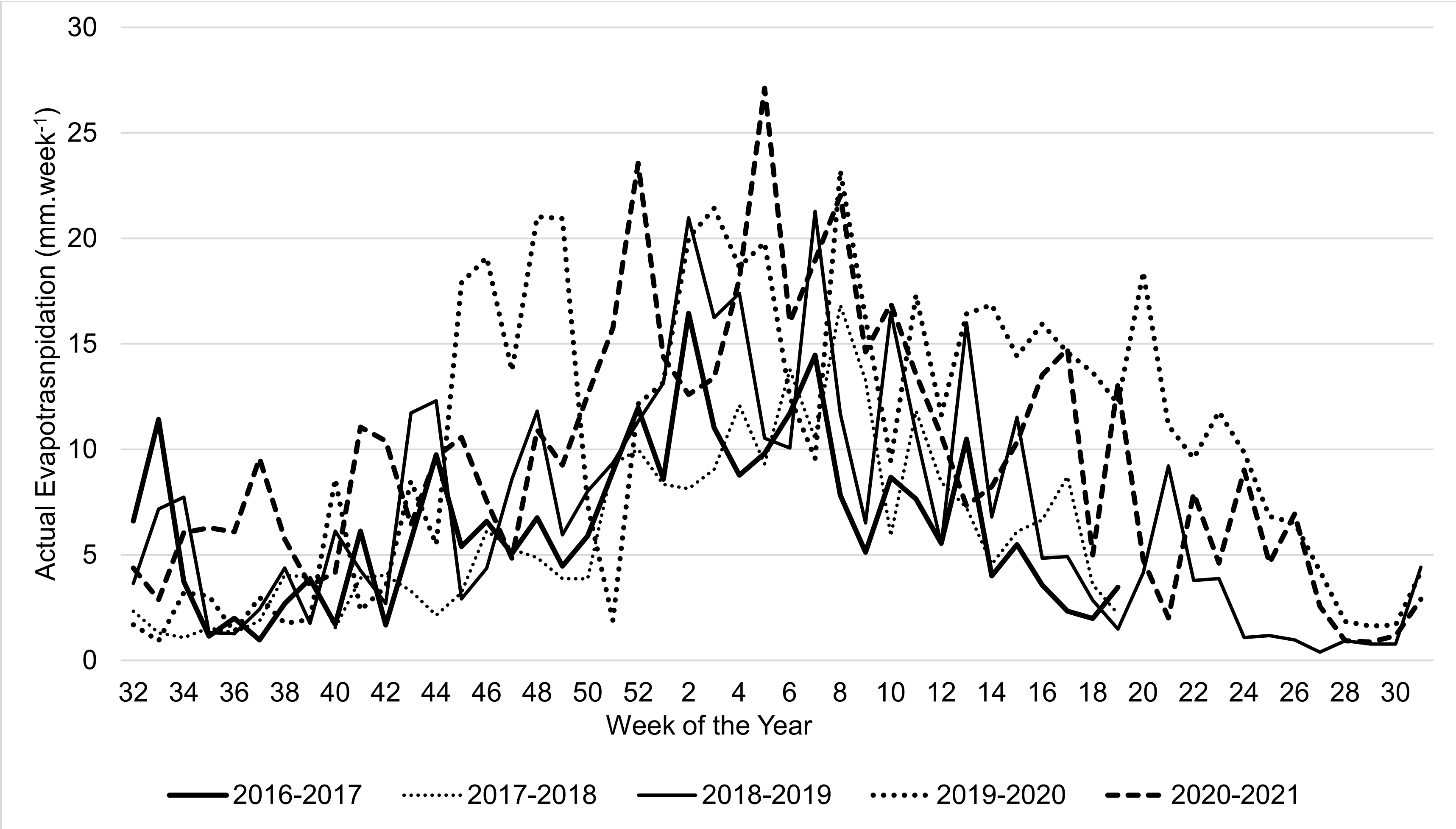

Figure 3.6: Weekly actual evapotranspiration (mm.week^{-1}) of 'Wichita' pecans, at Site 2 (10 x 5 m) in Vredendal, for five seasons from 2016 to 2021, calculated by Fruitlook® satellite imagery.

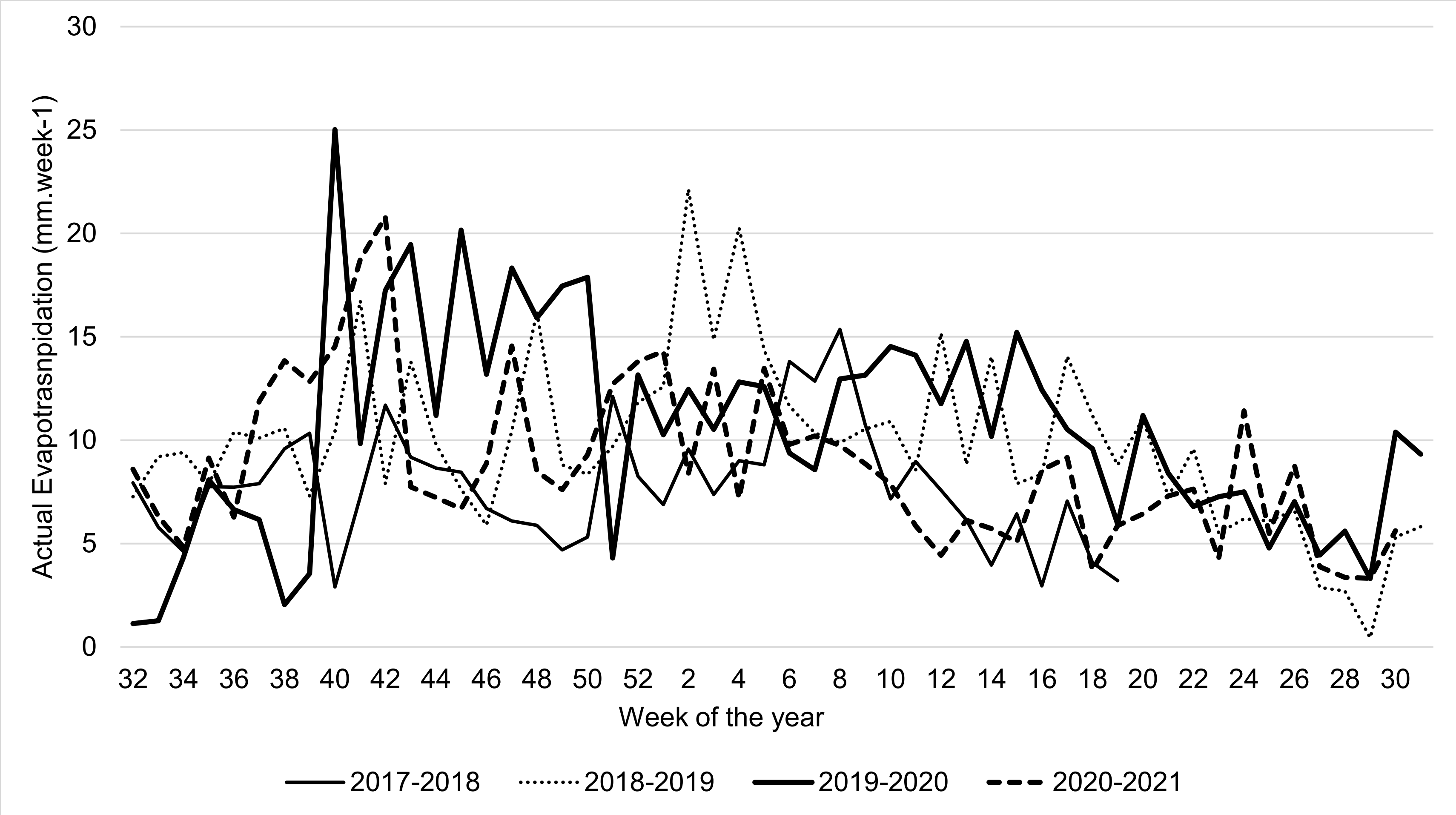

Figure 3.7: Weekly actual evapotranspiration (mm.week^{-1}) of 'Wichita' pecans, at Site 3 (8 x 4m) in Hermon, for four seasons from 2017 to 2021, calculated by Fruitlook® satellite imagery.

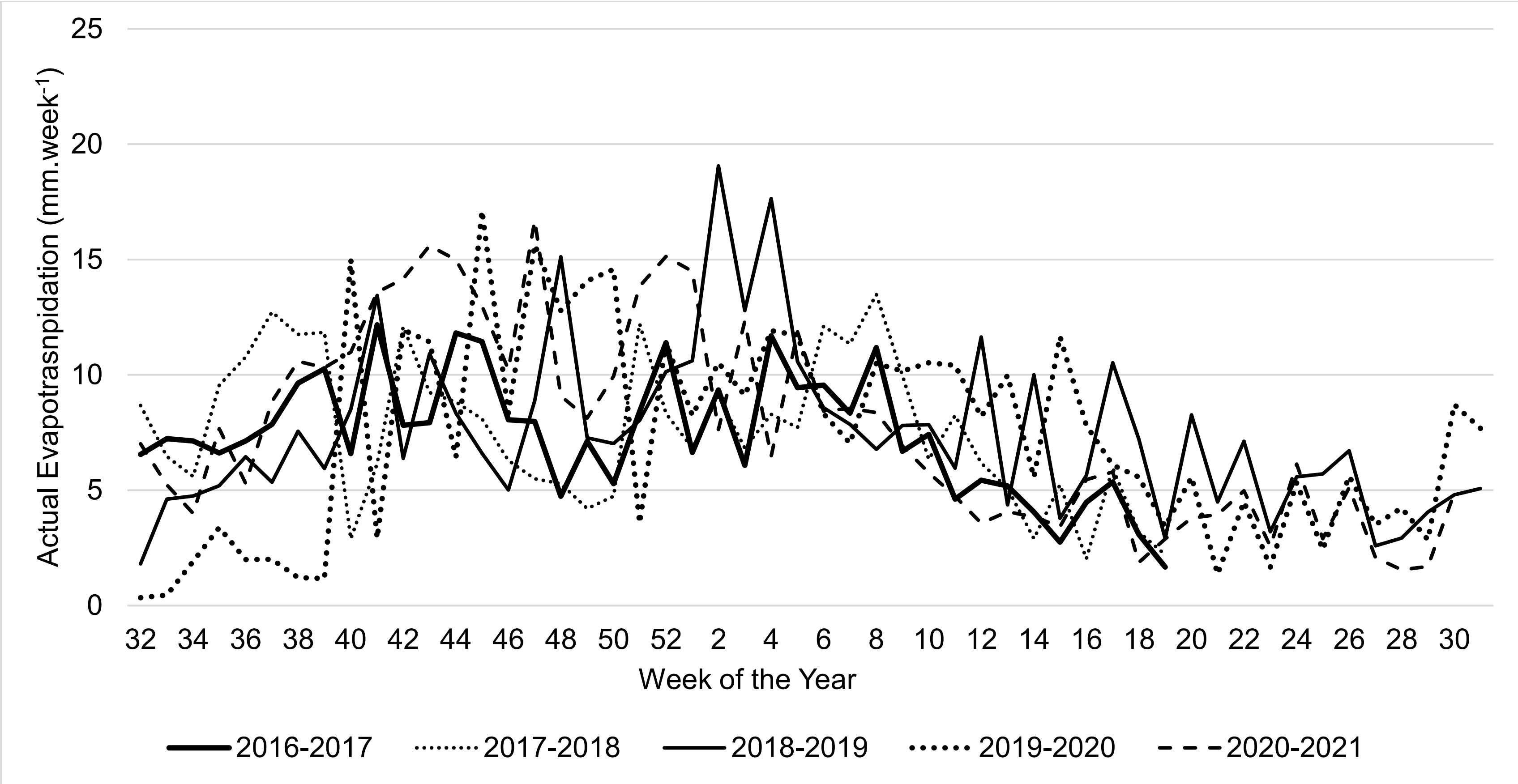

Figure 3.8: Weekly actual evapotranspiration mm.week^{-1} of 'Wichita' pecans, at Site 4 (8 x 6 m) in Hermon, for five seasons from 2016 to 2021, calculated by Fruitlook® satellite imagery.

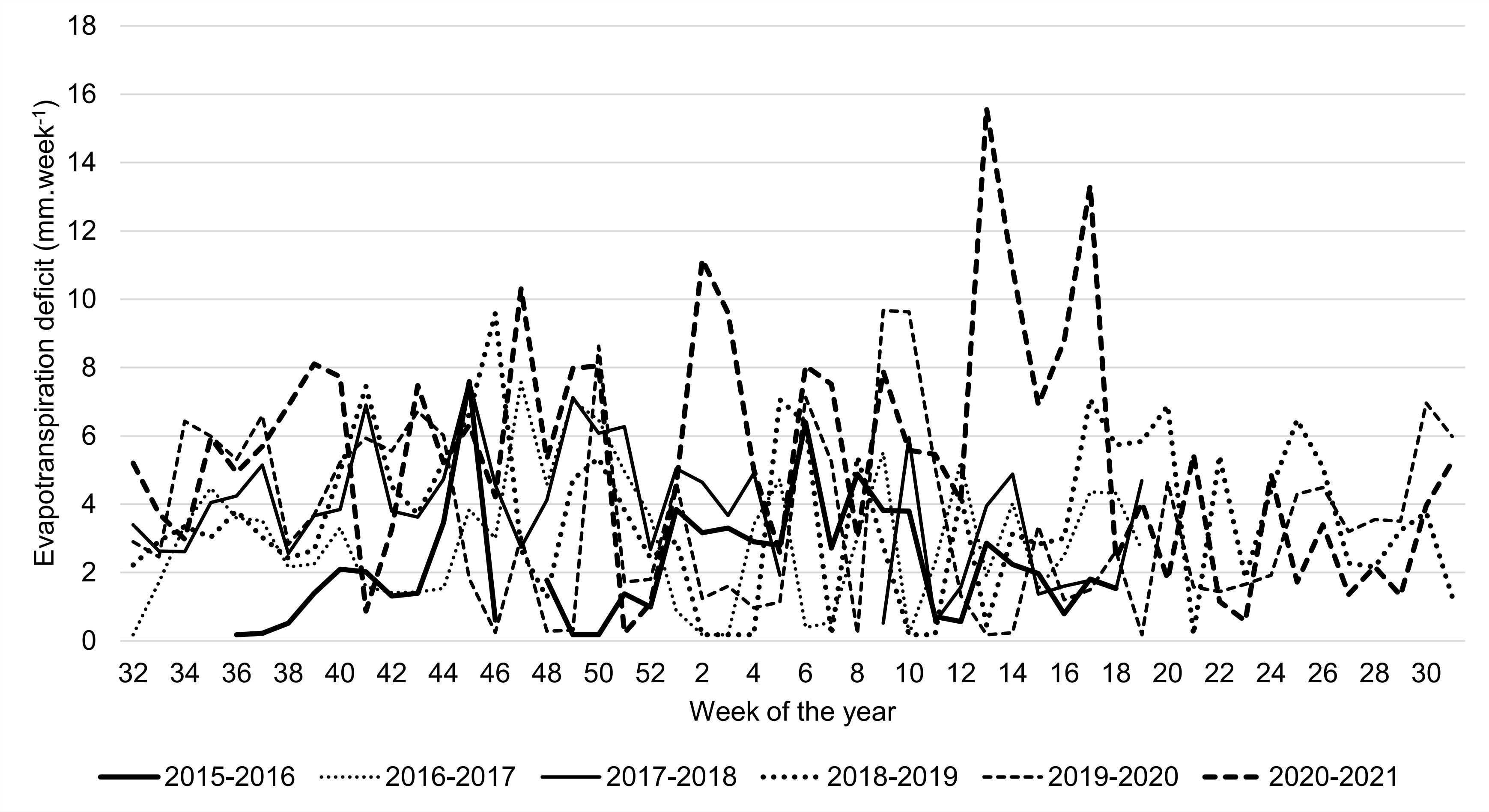

Figure 3.9: Weekly evapotranspiration deficit (mm.week^{-1}) of 'Wichita' pecans, at Site 1 (10 x 8 m) in Vredendal, from 2016 to 2021, calculated by Fruitlook® satellite imagery.

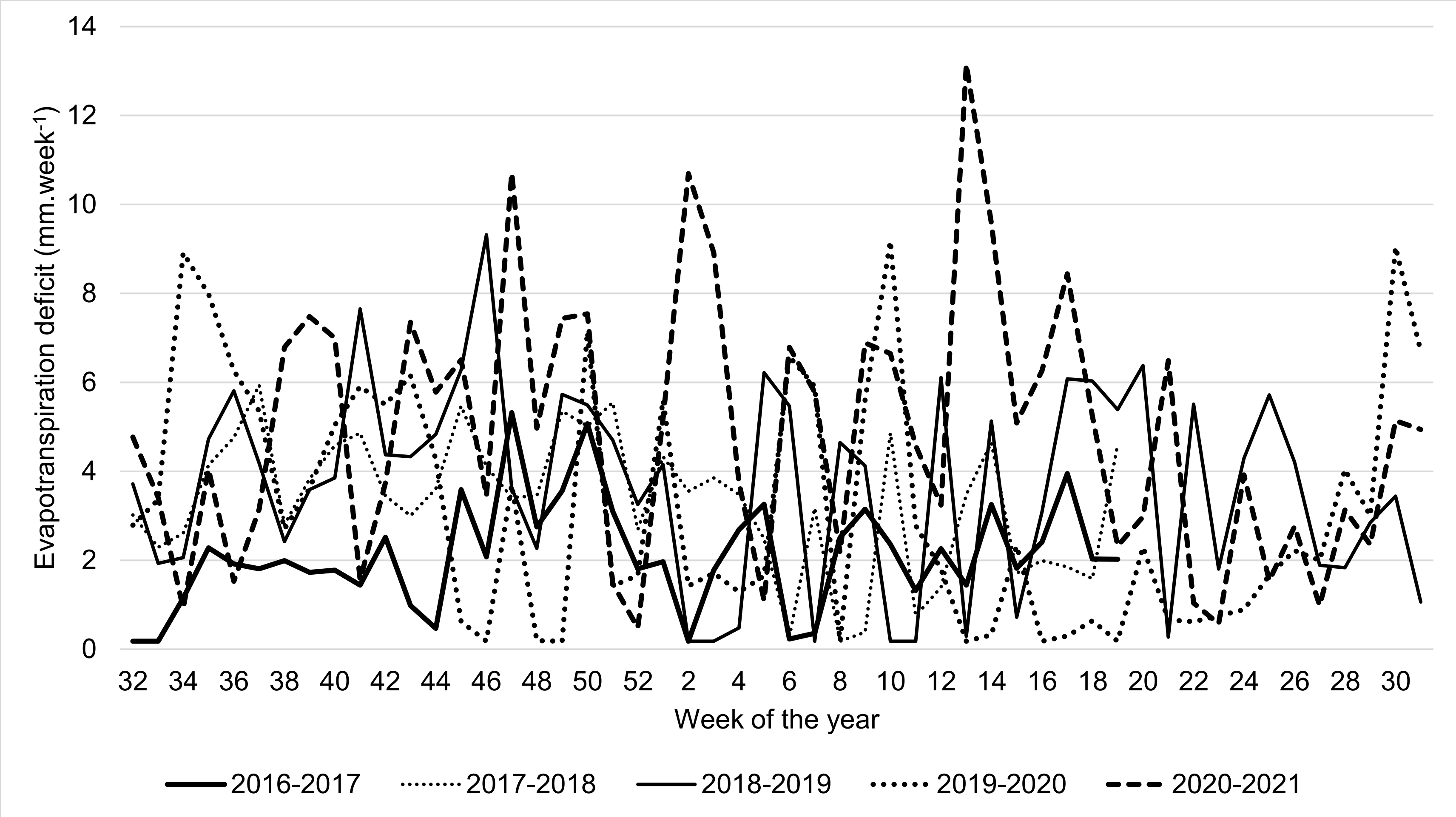

Figure 3.10: Weekly evapotranspiration deficit (mm.week^{-1}) of 'Wichita' pecans, at Site 2 (10 x 5 m) in Vredendal, for five seasons from 2016 to 2021, calculated by Fruitlook® satellite imagery.

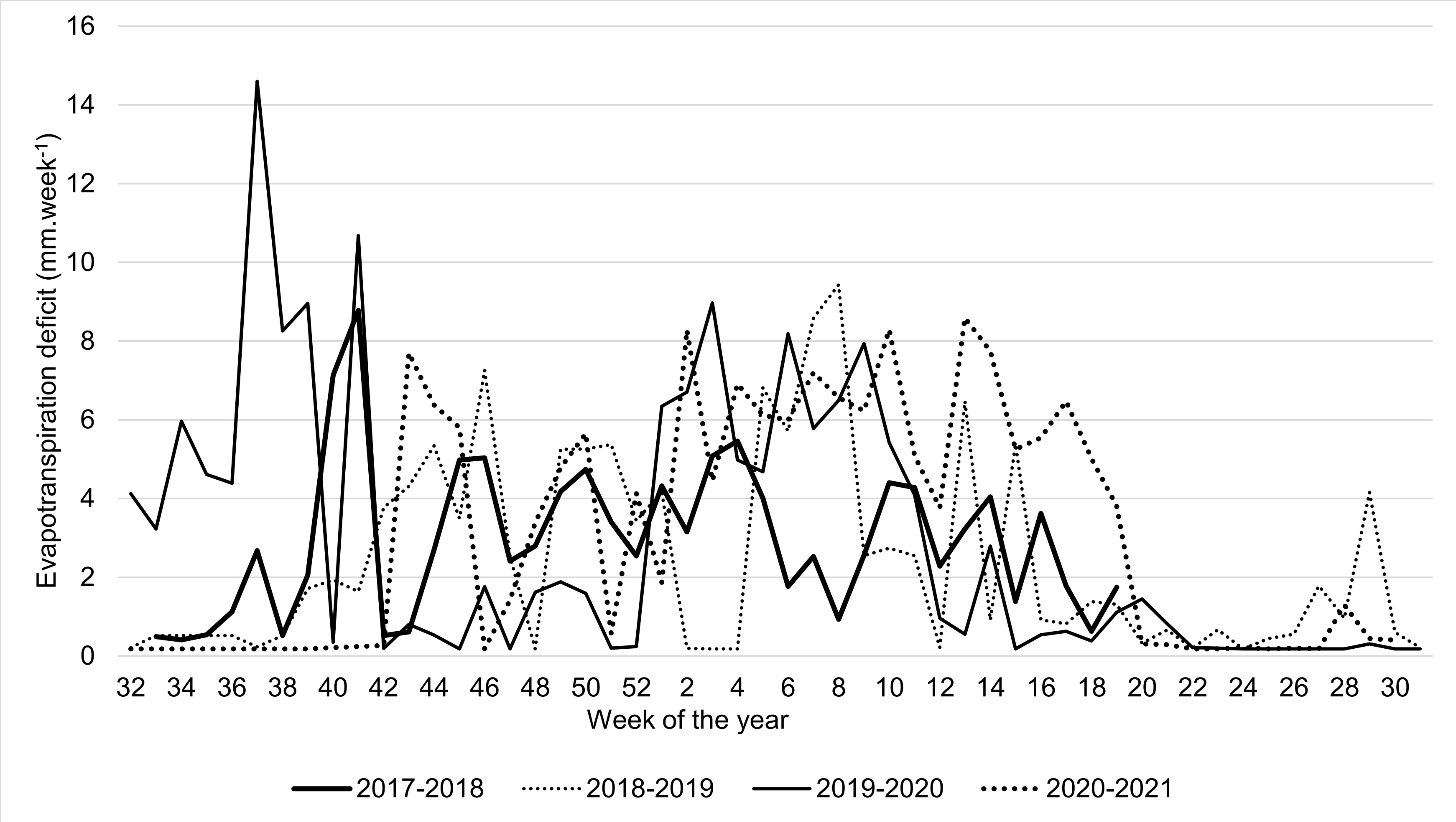

Figure 3.11: Weekly evapotranspiration deficit (mm.week^{-1}) of 'Wichita' pecans, at Site 3 (8 x 4m) in Hermon, for four seasons from 2017 to 2021, calculated by Fruitlook® satellite imagery.

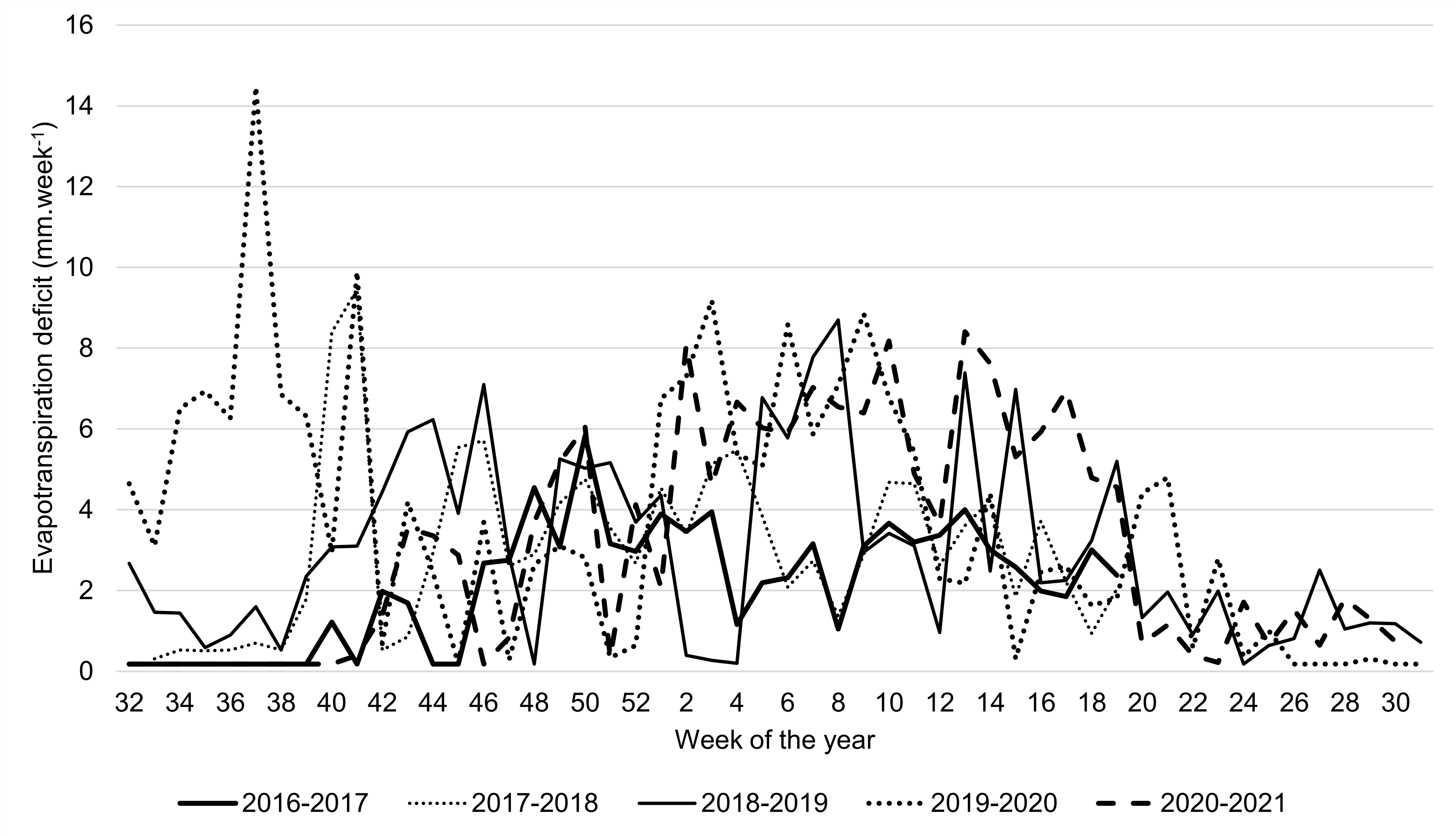

Figure 3.12: Weekly evapotranspiration deficit (mm.week^{-1}) of 'Wichita' pecans, at Site 4 (8 x 6 m) in Hermon, for five seasons from 2016 to 2021, calculated by Fruitlook® satellite imagery.

GENERAL CONCLUSION

Different tree spacing can lead to a higher pecan production, with a lower density orchard leading to higher yields per tree, whilst a higher density orchard producing a higher yield per hectare.

Vegetative growth is also affected by tree density, with a lower density orchard tending to produce much bigger trees compared to the higher density orchards at the same age. This is especially the case when severe tree pruning has taken place with an almost double increase in tree volume of a lower density tree compared to a higher density orchard. Tree growth was also influenced by the different tree densities, with an orchard with a 10 x 5 m (312 trees ha^{-1}) spacing showing signs of overshadowing to occur at the age of five, with tree lateral branches starting to touch leading to an increase in tree height. ‘Choctaw’ pecans tend to produce bigger trees when compared to ‘Wichita’ or ‘Navaho’ pecans and was evident with ‘Choctaw’ producing much taller trees as well as much larger tree volumes, followed by ‘Navaho’ and then ‘Wichita’ (Meier, 2020).

Solar radiation interception was not affected by different tree densities, despite the age difference of some of the orchards, indicating that neither tree age nor density has an influence on the amount of light being intercepted. This finding suggests that tree shape/volume plays an important role in light interception, rather than tree age or tree density alone, also stated by Palmer et al. (1992), with leaf area distribution affecting the trees’ light interception. This was also evident when comparing the three cultivars, with same tree density, which also did not show any difference in light interception even with ‘Choctaw’ pecans producing much larger trees and having a much larger tree volume, emphasizing that light interception is not affected by tree size alone, but rather due to the trees’ shape.

The six-stage crop growth of pecans was also monitored for Vredendal and Hermon, with results indicating that Hermon is about two weeks earlier in terms of overall growth and production. Season differences in the timing of growth stages was also recorded and can be attributed to the decline in temperature differences experienced from the 2019/20 season to the 2020/21 season. Hermon also experienced much cooler temperatures, compared to Vredendal, with both areas averaging between the favourable temperature of between 24 and 3°C, whilst reaching a maximum temperature of 33.5 and 32.°C, which is less than the recommended maximum temperatures of 38 °C at which black nut will occur (Fronza et al., 2018; Ravindran et al., 2008).

The chill units recorded for Hermon was 574.5 DCPU; 307.5 CU and 438.5 DCPU; 196.5 CU (missing data for August) for the first and second season, whilst Vredendal recorded 450.5 DCPU; 193 CU and 344 DCPU; 88 CU (missing data for August). Hermon reached the required chill units (300 – 500 CU), with the exception of the second season, but this is due to missing data and therefore does fulfil the chilling required for successful flowering (Wells, 2015). Vredendal did not record the required chill units, despite the missing data, but this did not seem to impact tree performance. Historical data for Vredendal (236.3 CU), does indicate that this region reached the minimum chill unit requirement. Both areas, despite their recorded chill units, did receive enough for successful bud break for all three cultivars, which indicates that both regions are suitable for pecan production.

Yield was affected by tree age, with yields for both Trials in Hermon and Vredendal increasing with tree age. Site 2 (5 year old; 200 trees ha^{-1}) was the exception with a decrease in yield in the second season and possibly due to overcrowding starting to occur for the lower lateral branches, where most of the nuts are produced. Lower density orchards produced a higher number of nuts per tree with a higher yield on a per tree basis. However, this was not the case on a per hectare basis as a higher density orchard produced a larger yield compared to the lower density orchard, caused by the higher number of trees in a given space. Therefore, a higher yield per hectare can be expected with a higher density orchard, but a higher yield on a per tree basis for a lower density orchard since lower density orchards tend to produce much larger trees. These results should also be investigated further, and preferably done in an orchard with trees the same age. Additionally, overcrowding in younger trees at the age of five-years-old in higher density orchards should further be investigated, with the possible effect of severe pruning on production also being investigated.

‘Choctaw’ pecans produced much larger nuts compared to ‘Wichita’ and ‘Navaho’ pecans, therefore being so popular (Clark, 2020). However, even with a difference in nut size and difference in yield, the number of nuts per tree was not recorded when comparing the different cultivars. Yields of ‘Navaho’ pecans were also less than yields recorded by Dedekind (2020) in the Prieska area but recorded a much lower yield efficiency. Due to missing yield data from the first season, a conclusion cannot be made regarding productivity for the three different cultivars. Therefore, additional trials on the production of these three cultivars should be investigated, to further investigate the suitability and productivity.

Evapotranspiration measurements were much higher for Vredendal (1399 and 1342 mm) compared to Hermon (918 and 954 mm). Vredendal also showed a higher ET compared to results from Cullinan (Ibraimo et al. 2016). These results indicate an estimate of the water requirement for pecans in the Vredendal and Hermon area, using historical climatic data, with pecans in Vredendal theoretically needing much more water compared to pecans planted in Hermon. Vredendals' much higher ET measurements are directly linked to climatic differences, with Vredendal being a more arid region compared to Hermon and recording a higher average relative humidity, wind speeds and a lower rainfall. These measurements are not an indication of the survival and suitability of pecans in either region, only an indication of the amount of water being required if pecans are considered as an alternative crop, with pecans in Vredendal having a much higher water requirement. In addition, in field measurements of the actual water use and irrigation to these areas and other pecan production areas should be investigated for a more accurate representation of the potential water use of pecans. Further investigation regarding the ET for current and future climate conditions should be conducted on mature orchards, which will be key to indicate a more accurate potential water requirement and allocation of pecans under the local conditions of Hermon and Vredendal.

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