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Research paper

Fruit growth and water use of two pear cultivars grown in South Africa: implications for precision irrigation scheduling

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In South Africa, as in other semi-arid countries, sustainable production of high-value crops requires precise management of limited water resources. We investigated daily and seasonal changes in stem and fruit growth as indicators of water stress in pear (*Pyrus communis* L.) trees, in the Western Cape Province. Stem and fruit growth data were collected hourly throughout the 2022–2023 growing season on 2 cultivars commonly planted in South Africa – Packham's Triumph and Forelle. Soil water content, tree sap flow, and orchard microclimate were also monitored. Fruit maximum daily shrinkage (MDS) was highly sensitive to soil water deficit and more sensitive than stem size changes. However, the patterns of fruit MDS for both cultivars changed as the season progressed. Early in the season (October–December), there was a strong correlation between fruit MDS and soil water deficit (R^2 ~ 0.72). The fruit shrunk with increasing soil water deficit as water loss through transpiration exceeded gains through xylem and phloem inflows. In contrast, daytime fruit size swelled from late December until harvest (February/March), likely because of the dominance of phloem inflows and decreased peel transpiration as the fruit matured. Correlation between fruit expansion and soil water deficit was weaker (R^2 ~ 0.32) during the later stage even though fruit growth continued until harvest. Stem MDS consistently showed midday shrinkage throughout the season in response to soil water deficit, but with more scatter (R^2~ 0.37). Seasonal total transpiration was greater for Forelle (733 mm) than Packham's Triumph (539 mm) because of the higher leaf area index of the Forelle and the longer growing season. This study suggests that pear fruit growth data can provide accurate estimates of tree water status, but only during the early stages of growth. Towards maturity, fruit size changes respond indirectly to water deficit, possibly through reductions in photosynthesis.

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INTRODUCTION

The production of major commercial fruit exported from South Africa (SA), like apples, pears, citrus etc., depends entirely on irrigation (Gush and Taylor, 2014; Volschenk, 2017; Dzikiti et al., 2018). The Western Cape Province is a key producer of these fruit, accounting for more than 90% of apples and pears produced in SA (Key Deciduous Fruit Statistics, 2022), while contributing substantially to other fruit types. However, water resources in the province are increasingly coming under pressure from the rapidly growing population of the Cape Town Metropolitan, increased industrial activities, and the threats posed by extensive stands of invasive alien plants that consume large amounts of water (Dzikiti et al., 2013, 2016; Le Maitre et al., 2018), among others. The increasing frequency and severity of droughts, because of climate change, exacerbates the threats to water availability (Midgley and Lötze, 2011). Climate change projections suggest that severe droughts that occurred in the prime fruit-producing areas in South Africa in recent years will likely become more common in future (Ziervogel et al., 2022). Therefore, there is a need to improve water resources management, especially through precise irrigation scheduling, for the sustainability and growth of the fruit industry. Information on crop water use is essential for water allocation purposes and future planning and to understand the water needs of the crops.

Irrigation scheduling in South African orchards, and elsewhere, is commonly done using probes that monitor the soil water status in the rootzone (Lategan and Howell., 2016; Volschenk, 2017). Given that most physiological processes that influence plant growth and productivity respond to changes in tissue water status (Bacon, 2004; Jones, 2004; Steppe et al., 2006), most precision irrigation approaches advocate sensing stress directly from the plants themselves. Examples of plant-based irrigation scheduling approaches include use of the pressure chamber to quantify the predawn leaf and/or midday stem water potential (Dzikiti et al., 2010; Shackel et al., 2021). This is the most widely used method, but it is destructive, and has a poor spatial representation (Jones, 2004). In addition, the pressure chamber measurements cannot be automated although there have been recent attempts to develop automated sensors that produce equivalent outputs such as the micro-tensiometers (Blanco and Kalcits, 2021). Other studies have investigated changes in leaf turgor pressure as an indicator of water stress, e.g., using leaf patch clamp pressure probes (Ehrenberger et al., 2012), or canopy temperature dynamics (García-Tejero et al., 2011) using remote sensing platforms, etc.

Some commercially available irrigation platforms employ dendrometry, where irrigation decisions are based on monitoring and analysing trends in plant growth parameters (Corell et al., 2014; Fernandez et al., 2018). Dendrometers detect water deficit stress either from changes in the maximum daily shrinkage (MDS) or from changes in the daily growth rate, among other variables.

Advantages of using dendrometers are that they are non-destructive, and the measurements can be automated. However, uncertainties in defining stress thresholds and the low sensitivity of some plant organs to water deficit limit the practical use of this approach (García-Tejero et al., 2011; Corell et al., 2014).

Besides studies by Fernandes et al. (2018), few other studies have attempted to identify the most sensitive organs for monitoring water deficit stress in fruit trees. Some researchers argue that reproductive organs such as fruit are likely to be more sensitive to water deficit stress than other plant parts (Bacon, 2004; Hou et al., 2020). To our knowledge, no studies have investigated, in detail, the hourly growth dynamics of pear fruit throughout an entire growing season. There is no documented information on how changes in fruit growth patterns might influence the accuracy of irrigation scheduling in pear orchards. Morandi et al. (2014) studied the growth dynamics for the Abate Fetel pear cultivar in Italy over 3 short window periods spread over the growing season. Each window period lasted less than a week, at 40 days (after cell division), 90 days (rapid growth phase), and 140 days (before harvest) after full bloom. They used dendrometers that used linear variable displacement transducers to monitor the growth. However, data from large parts of the growing season were not available. So, detailed responses of the fruit size to dynamic changes in tree water status could not be quantified.

The present study seeks to close these important information gaps by analysing and documenting the fruit and stem growth trends for 2 pear cultivars over the course of an entire growing season. Can pear fruit growth data be used for precise irrigation scheduling throughout the growing season? To answer this question, we collected data in well-managed high-performing pear orchards in which irrigation was managed optimally. Specific objectives were to: (i) derive and interpret growth trends for the 'Packham's Triumph' and 'Forelle' pear fruit; (ii) identify growth parameters that best predict tree water status; and (iii) quantify the water use of the two cultivars for which no information currently exists.

MATERIALS AND METHODS

Study sites and plant material

Data were collected in 2 pear orchards during the 2022–2023 growing season in the Western Cape Province of South Africa. The study area has a Mediterranean-type climate, mostly receiving rainfall during the winter months from May to September. One 13-year-old orchard was planted to 'Packham's Triumph' on 'BP1' rootstock in Wolseley (33°27'37.51"S; 19°11'40.44"E, 258 m asl). 'Packham's Triumph' is a late-maturing green-yellow fruit with a creamy-white flesh and is usually harvested in South Africa around early February. Orchard size was about 2.75 ha. Tree spacing was 4 m X 1.5 m, giving a tree density of 1 667 trees/ha. The orchard was on flat terrain and the trees were planted on low ridges (< 20 cm). The soils were deep sandy loams of the Fernwood soil form (Soil Classification Working Group, 1991). Irrigation was via a micro-sprinkler system with one micro-sprinkler per tree, with each micro-sprinkler delivering about 32 L/h. Irrigation was scheduled using DFM soil moisture probes (IrriCheck Pty Ltd).

The second orchard was planted to 19-year-old 'Forelle' on 'BP1' rootstock just outside Ceres (33° 22'42.90"S: 19° 21'29.24"E, 512 m asl). The orchard size was about 6.5 ha. 'Forelle' pears have a green-yellow background colour and sun-exposed fruit develop a red blush. Since blushed fruit fetch higher prices, trees are usually managed to expose the greatest possible proportion of fruit to sunlight. 'Forelle' fruit has a longer growing season than 'Packham's Triumph', being harvested around the last week of February to early March. Tree spacing was 4.5 X 1.5 m, giving a tree density of about 1 481 trees/ha. The trees were irrigated with a micro-sprinkler system that delivered about 32 L/h with one micro-sprinkler per tree. Irrigation scheduling was also done using the DFM profile soil moisture probes. The soils were clayey loam soils of the Tukulu soil form (Soil Classification Working Group, 1991), with a high stone content of about 6% at 30 cm depth, increasing to about 13% at 90 cm depth.

Tree water use and fruit growth measurements

Orchard microclimate data were collected using automatic weather stations that measured the maximum and minimum air temperature and relative humidity, solar irradiance, windspeed and direction, and rainfall. The volumetric soil water content was measured using 3 time-domain reflectometer probes per orchard (Model CS 616: Campbell Scientific, Utah, USA). The sensors were installed in the root zone of the trees at 30, 50, and 80 cm depth. The weather and soil water content data were collected hourly throughout the study period. Tree transpiration was measured using the heat ratio method of monitoring sap flow (Burgess et al., 2001). Three trees were instrumented in the 'Forelle' orchard and four trees in the 'Packham's Triumph' orchard. The sap flow system comprised a single tree box on each instrumented tree that contained the electronics for measuring sapwood temperature, and injecting heat. Sapwood temperature was measured using 4 T-type thermocouples aligned along the vertical axis of the tree about 0.5 cm up and downstream from the central heater hole. A metal template was used to guide the drilling of the holes to minimize errors due to probe misalignment. Four pairs of thermocouples were installed at different depths per tree to account for the radial variation in the sap velocity (Wullschleger and King, 2000). All of the thermocouples were connected to a multiplexer (Model AM16/32B: Campbell Scientific, Uta, USA), which in turn was connected to a CR1000 datalogger. Pulsing of the heat was done hourly through a control port on the datalogger and the duration of each pulse was less than 10 s. The heat pulse velocity data were corrected for wounding due to sensor implantation according to the procedure by Burgess et al. (2001). The sap flow volume per tree was calculated as a weighted sum of the products of the sap velocity represented by a specific probe and the sapwood area represented by that probe. The leaf area index of the trees (LAI – 1-sided leaf area per m^2 of ground area) was measured at regular intervals throughout the growing season using a leaf area meter (Model: LAI – 2000, Li-COR, Nebraska, Lincoln, USA).

Fruit growth data were collected on 2 actively growing sun-exposed fruit per cultivar. One fruit was located to the east and the other to the west of the canopy, and commercial strain gauge-type dendrometers (Model DEX 100: Dynamax Inc. Houston, USA) were used. The sensors were installed after fruit set on 27 October 2022, when average fruit diameter was about 3.4 and 3.6 cm for 'Forelle' and 'Packham's Triumph', respectively. A third dendrometer was installed on the stem of the fruit gauge–instrumented trees. Data were collected hourly until harvest, which was around 16 February 2023 for 'Packham's Triumph' and 18 March 2023 for 'Forelle'.

RESULTS

The two growing regions had somewhat different climatic conditions. Ceres, for example, has colder winters than Wolseley and small differences exist in the summer temperatures, as is evident from the weather data for the 2022–2023 growing season (data not shown). Maximum and minimum temperatures of 35.2°C and −3.2°C, respectively, were recorded in Ceres, and 39.5°C and 1.7°C, respectively, in Wolseley. The vapour pressure deficit of the air (VPD) was slightly higher in Wolseley, peaking at 2.1 kPa in January 2022 compared to 1.6 kPa for Ceres, implying a slightly higher atmospheric evaporative demand in Wolseley. The summer season of 2022–2023 received slightly more rainfall than the long-term averages for both study areas (Dzikiti et al., 2018).

Total rainfall during the growing season from September to May in this study was 406 mm in Ceres and 366 mm in Wolseley. The total reference evapotranspiration (ETo – Allen et al., 1998) was similar between the sites, at 1 069 mm in Wolseley and slightly lower at 1 059 mm in Ceres.

Variations in soil water content in the rootzone of the 'Packham's Triumph' trees are shown in Fig. 1. Soil moisture data for the 'Forelle' orchard were discontinued in December 2022 due to equipment malfunction. As expected, changes in the soil water content were related to rainfall and irrigation and both orchards were irrigated until late April 2023. The full-bloom date was earlier for 'Forelle' (around mid-September) and later for 'Packham's Triumph' (first week of October). The leaf area index (LAI) of the trees showed clear seasonality, as illustrated in Fig. 2.

The 'Forelle' orchard had a larger canopy with a peak LAI around 3.8, while that of 'Packham's Triumph' was about 3.3. This LAI trend was unexpected given that the blushed 'Forelle' trees are usually maintained with more open canopies to maximize light penetration to improve fruit colour. Our data on fruit colour is too limited to be able to draw reliable conclusions on the effects of excessive shading on colour development in the 'Forelle' orchard. Leaf fall began in mid-June and accelerated in early July. The LAI was zero by the end of July. Fruit from the two cultivars had similar diurnal growth trends, although 'Packham's Triumph' had a faster growth rate (Fig. 3), which culminated in larger fruit size of about 70 mm compared to around 67 mm for 'Forelle'. The average growth rate of 'Packham's Triumph' was about 0.30 mm/d, which was maintained until close to harvest. The maximum growth rate for the 'Forelle' fruit, on the other hand, was lower, at about 0.22 mm/d between October and mid- January, slowing down to less than 0.10 mm/d close to maturity.

The detailed fruit growth trends between successive days are illustrated in Fig. 4. On the one hand, there were clear differences in the early and late season trends for both cultivars, as illustrated in Fig. 4a and c. The diurnal stem trends, on the other hand, remained the same throughout the growing season (Fig. 4b and d). Early in the season, fruit diameter shrunk during the day as water loss by transpiration exceeded xylem and phloem inflows into the fruit. From late afternoon into the evening, fruit size increased as transpiration dropped when the stomata on the fruit peel closed. The water potential gradient between the tree's xylem and the fruit caused water to flow into the fruit leading to swelling during the night. The stem size changes over the entire growing season followed the same trend as that of the fruit in early season.

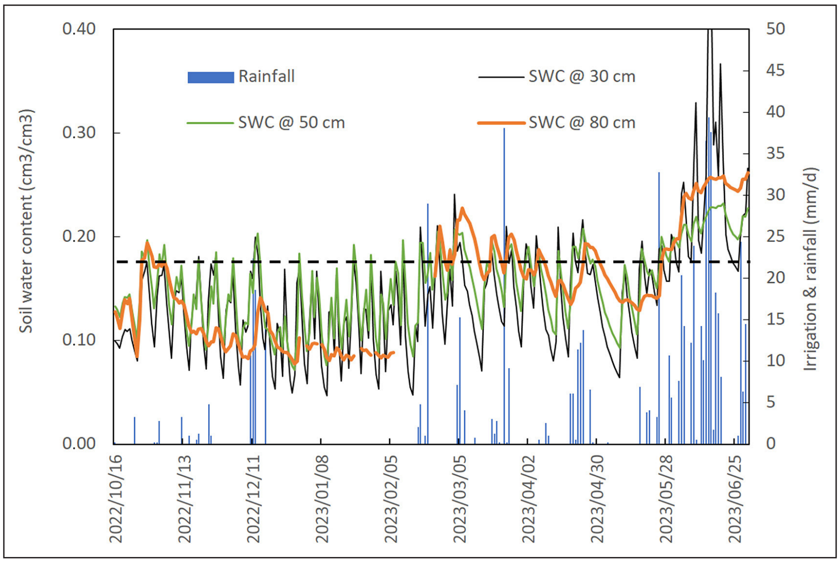

Figure 1. Soil water content dynamics in the rootzone of a mature 'Packham's Triumph' pear orchard. The dotted line indicates the volumetric soil water content at field capacity (~0.18 cm^3/cm^3).

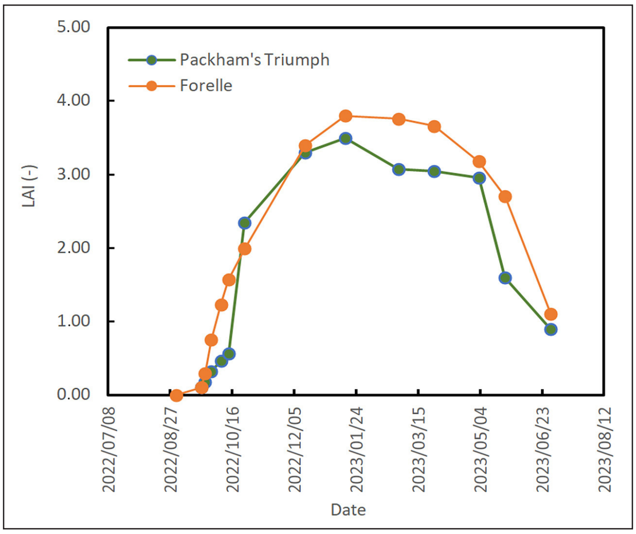

Figure 2. Variations in the leaf area index of the 'Forelle' and 'Packham's Triumph' orchards during the 2022–2023 growing season

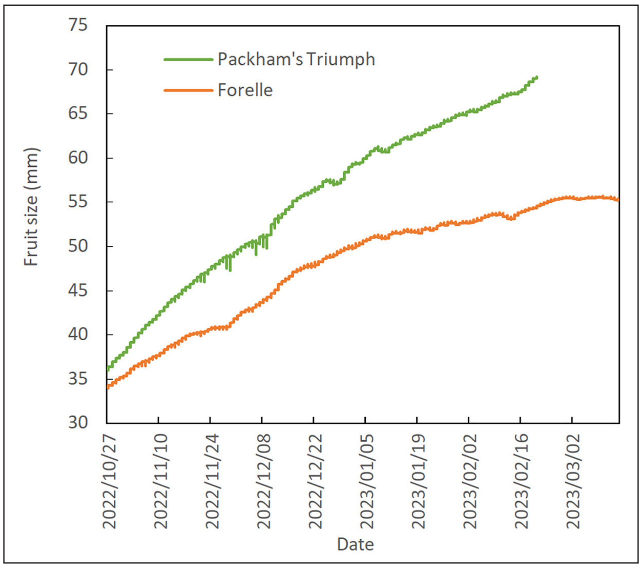

Figure 3. Seasonal trends in the growth rate of 'Packham's Triumph' and 'Forelle' fruit measured hourly from 27 October 2022 until harvest

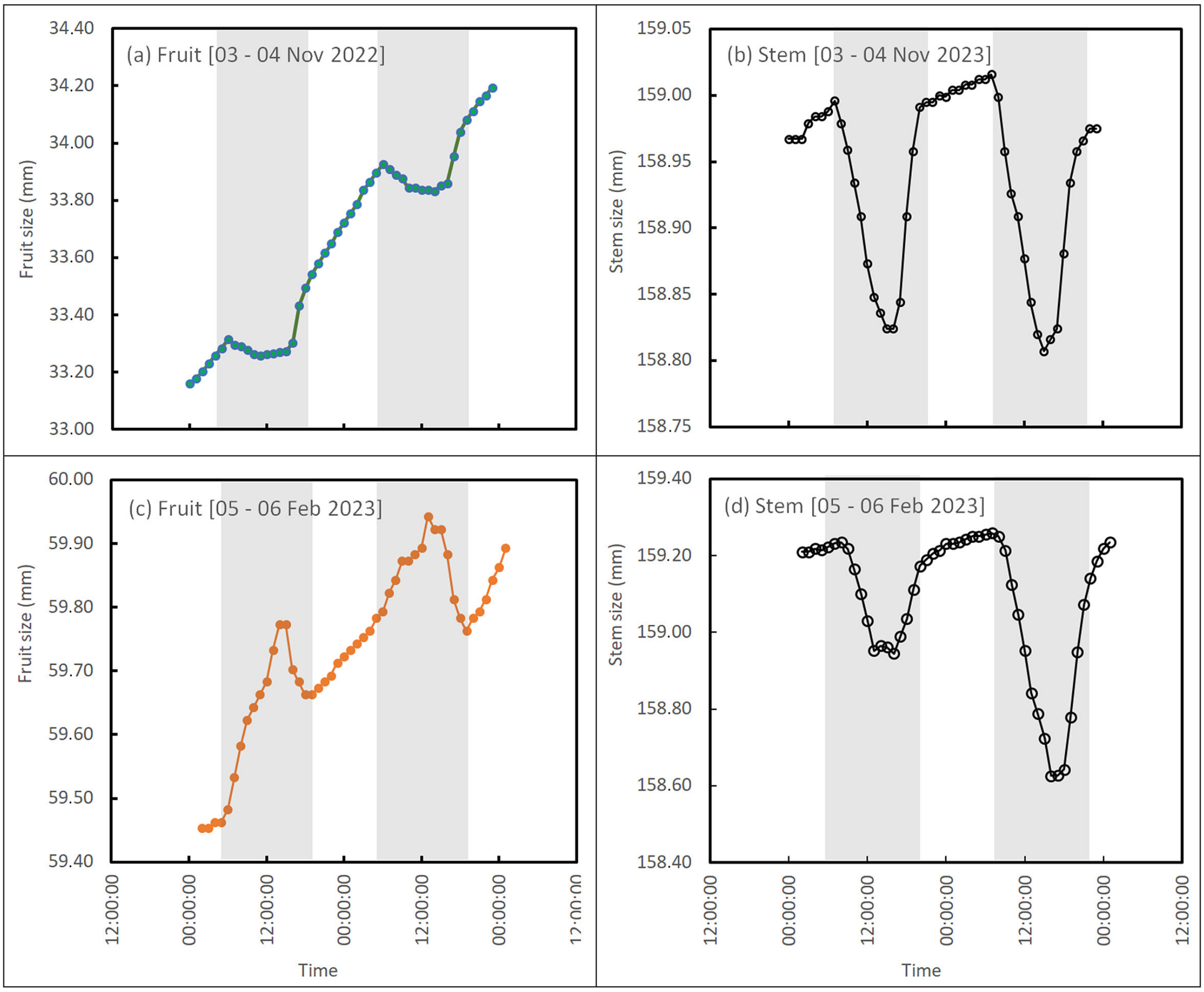

Figure 4. Changes in the size for a 'Packham's Triumph' fruit at (a) the beginning and (c) end of the growing season; corresponding changes in stem diameter at (b) the beginning and (d) end of the growing season

Later in the season (Fig. 4c), the fruit MDS trend flipped around, to swelling in the morning until around midday for both cultivars, while the stem trends remained like those measured earlier in the season. These changes in fruit growth patterns highlight the need for caution when using pear fruit growth data to interpret tree water status. For example, Fig. 5a shows that early in the season, changes in MDS for the fruit had a strong, albeit, non-linear relationship to the soil water content (green dots), with a coefficient of determination of about 0.72. Daytime fruit swelling late in the season was poorly related to the soil water content

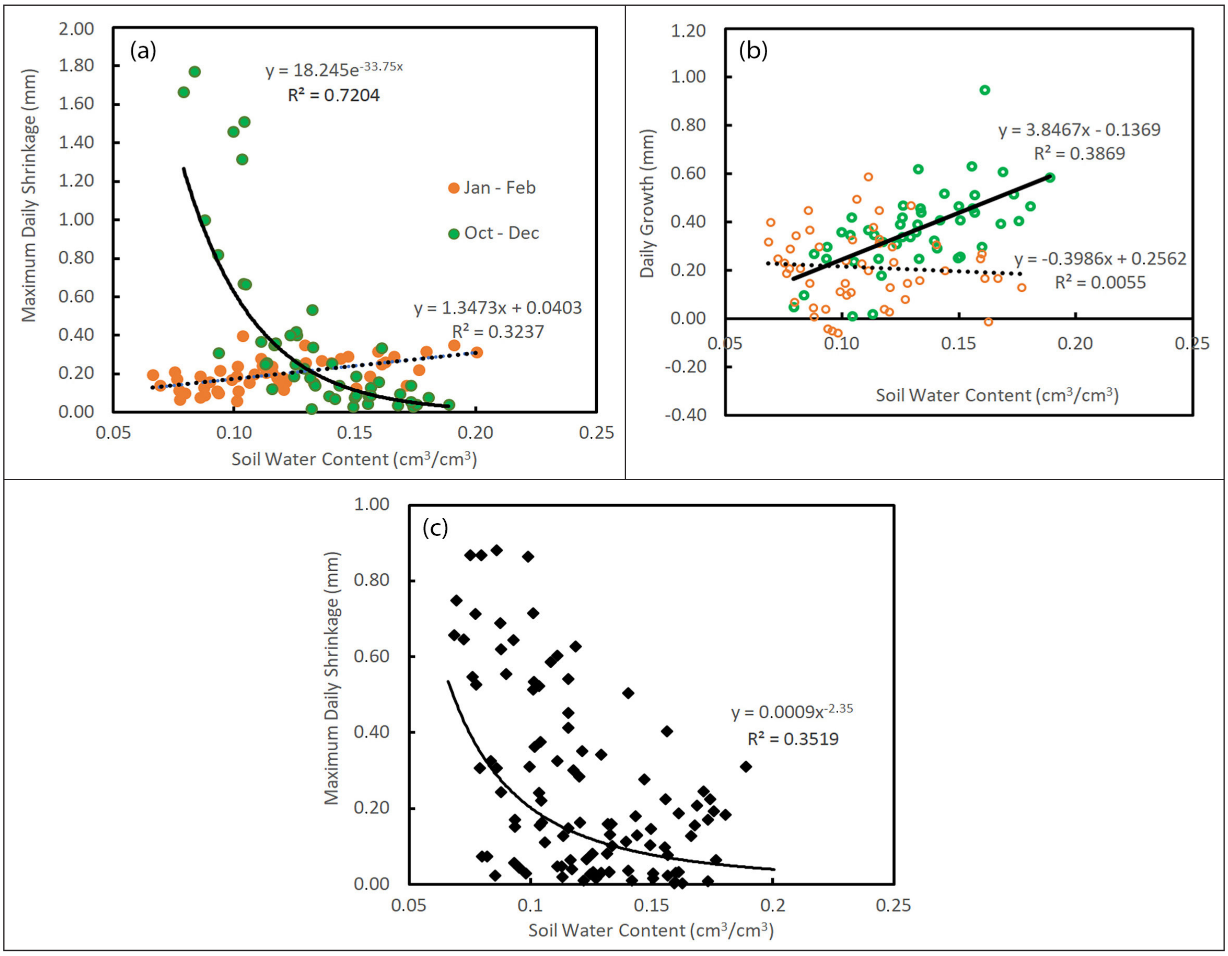

Figure 5. Changes in pear fruit maximum diameter shrinkage (a), fruit growth rate (b), and stem maximum diameter shrinkage (c) for 'Packham's Triumph' fruit

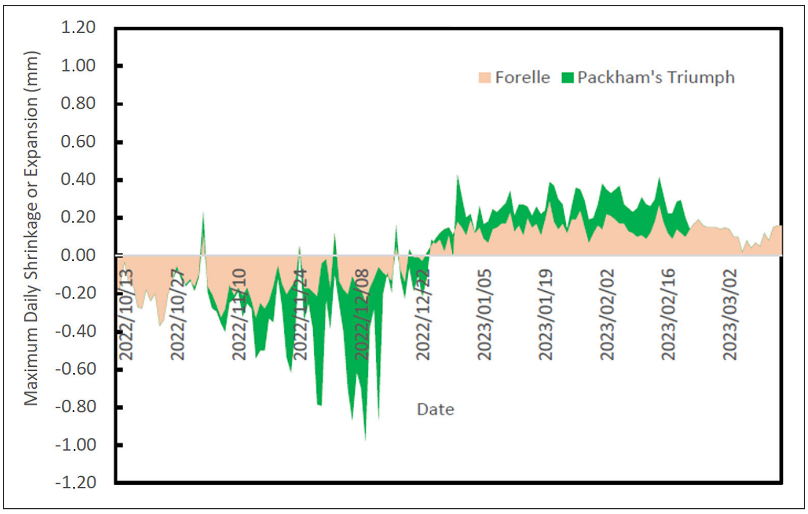

Figure 6. Changes in the maximum daily shrinkage or expansion of 'Packham's Triumph' and 'Forelle' fruit over the 2022–2023 growing season

(R^2 ~ 0.32). The daily fruit growth was weakly related to the soil water deficit early in the season (Fig. 5b). There was no correlation between these variables late in the season ($R^2 < 0.1$). The stem MDS for the mature trees showed more scatter in relation to the root zone soil water content compared to the fruit MDS (Fig. 5c). The flipping of the daytime fruit MDS signal from shrinkage to expansion was a progressive process that became apparent between 20 and 30 December for both cultivars (Fig. 6).

The daily peak transpiration per tree was around 25 L for 'Packham's Triumph' compared to around 37 L for 'Forelle' which had a larger canopy size. Expressed in equivalent water depth units, orchard transpiration for 'Forelle' peaked at around 4.9 mm/d compared to 4.4 mm/d for 'Packham's Triumph' (Fig. 7). The seasonal total transpiration was 733 and 539 mm for the 'Forelle' and 'Packham's Triumph' orchards, respectively (Table 1). The transpiration fluxes for both cultivars were lower than the reference evapotranspiration through much of the season, but became similar late in the season. The basal crop coefficients (transpiration/ETo) increased from zero in winter when the trees were leafless to a peak around 0.60 in mid-summer at full canopy cover.

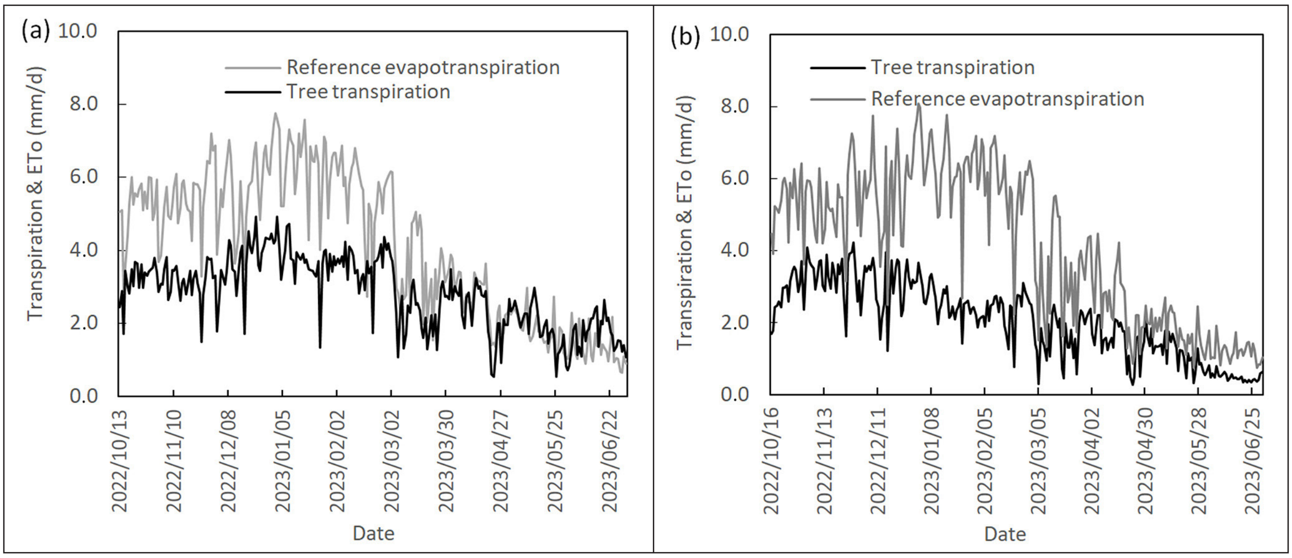

Figure 7. Daily transpiration dynamics of (a) 'Packham's Triumph', and (b) 'Forelle' orchard during the 2022 – 2023 growing season

Table 1. Summary of monthly water use of two pear orchards in the Western Cape Province, South Africa

Date	'Packham's Triumph'		'Forelle'	
	Eto (mm)	*T* (mm)	ETo (mm)	*T* (mm)
October	84.9	44.6	97.9	60.7
November	160.5	101.1	161.6	94.8
December	177.6	94.2	177.2	114.8
January	197.5	80.8	198.8	115.1
February	162.4	65.1	155.2	100.9
March	108.3	51.1	112.0	73.7
April	77.2	44.8	79.8	69.0
May	54.7	36.0	56.0	59.2
June	46.1	15.2	40.2	51.2
Total	1 069.2	532.8	1 059.3	739.4

DISCUSSION

Innovative and practical solutions are required for precise scheduling of irrigation in orchards, especially in water-scarce areas that are expected to get drier in future due to climate variability and change (Lotter and Le Maitre, 2014). Traditionally, irrigation consultants, researchers, and farmers have used soil moisture probes to decide when to irrigate and with how much water (Annandale et al., 2011). Besides the pressure chamber, plant-based irrigation scheduling methods are not common in orchards. Yet there is evidence to suggest that they are more accurate indicators of stress, given that they integrate the effects of the soil and atmosphere on plant physiological processes (Bacon, 2004; Jones, 2004; Dzikiti et al., 2010; Fernandez and Cuevas, 2010). They use the plant itself as a biosensor. This study provides, for the first time, detailed information on the growth dynamics of fruit from 2 pear cultivars, namely Packham's Triumph and Forelle, on an hourly basis throughout the growing season. We relate the fruit growth data to the soil water status in the rootzone of the 'Packham's Triumph' trees to establish whether these data can be used as indicators of tree water status.

Our data showed that, for pear fruit, the maximum daily shrinkage (MDS) is a more accurate indicator of water deficit in the root zone than the daily growth rate. Early in the season, when the fruit xylem and phloem pathways were still actively transporting water and photosynthates, and when the stomata on the fruit surface were actively regulating transpiration (Fernandez, 2018), the maximum daily shrinkage (MDS) was strongly correlated to the soil water status. It is probable that changes in fruit size may have occurred before a noticeable decline in the soil water status occurred, according to Jones (2004). However, we did not measure leaf gas exchange in this study to independently confirm this. Towards maturity, the fruit MDS trends flipped and the daytime expansion of the fruit was not strongly related to the water deficit in the root zone. The significance of these data is that fruit growth trends are inconsistent indicators of tree water status. There is a need to change the interpretation of the data at some stage during the growing season. This can introduce significant uncertainties in irrigation scheduling when the turnover periods are not well defined. Daytime swelling of pear fruit towards maturity was also observed by Morandi et al., (2014). According to Morandi et al. (2014), the daytime increase in fruit size can be explained by the reduction in fruit surface permeability as the stomata become dysfunctional. At this time, the functionality of the xylem is also reduced.

Phloem inflows into the fruit become the dominant flux late in the season, likely associated with upregulated photosynthesis as the demand for photosynthates grows (Morandi et al., 2014). This latter aspect is the subject of an ongoing study under South African conditions. The finding that the correlation between daily fruit swelling and the soil water status was weak later in the season was surprising as fruit growth continued until harvest.

What little water is available to the tree is expected to be preferentially shunted towards the fruit because of the stronger tree–fruit water potential gradient (Morandi et al., 2014). Phloem inflows into the fruit, on the other hand, depend on the photosynthetic rate, which is influenced by soil water availability. It is probable that changes in soil water status first influenced the photosynthetic rates and then the daytime fruit size leading to an indirect relationship. Therefore, there is need for caution when using pear fruit growth data to schedule irrigation, as diurnal changes in fruit size at different stages in the season may mean different things.

Another perspective on the change in shape of the fruit growth signal late in the season is that this could be related to increases in cell volume. As the cells get larger, the amount of water stored increases which, coupled with the reduced peel permeability, could reduce the response of the fruit to water loss given the high specific heat capacity of water. This could contribute towards a delayed response in the changes in fruit size, thus explaining the fruit shrinkage observed in the early evening and the continued growth at night shown in Fig. 4c. Further research is required to confirm this explanation. The stem MDS, on the other hand, had a consistent trend throughout the season, albeit with a lower sensitivity to soil water deficit, consistent with the observations by Javier et al. (2022) on pear trees. This was likely because of the thicker bark on the trunks of the mature trees. Removing some bark or installing the gauges on younger branches possibly could provide more reliable data throughout the season.

The switch in fruit MDS reflected changes in the dominant fluxes that determine fruit growth. For example, data from Morandi et al. (2014) suggests that the xylem vessels connecting the fruit to the tree were actively involved in the transport of water in and out of the fruit early in the season. This phase is the best time to spray xylem mobile micronutrients such as calcium for strengthening cell walls in fruit. Little to no uptake is likely late in the season as the fruit xylem becomes dysfunctional. The role of a stronger (more negative) osmotic potential on the growth dynamics of the fruit as sugars accumulate in the fruit towards harvest is unclear. Such a gradient would draw more water into the fruit, but this requires that the xylem vessels be functional late in the season. This is something that we are uncertain about, and is the subject of an ongoing study.

Whole-tree sap flow data showed that the water use of the two pear cultivars was strongly driven by atmospheric factors, namely, solar radiation and VPD (data not shown), with $R^2 > 0.80$. Soil water deficit had a minimal effect on tree transpiration as the orchards were well-watered on most occasions. The seasonal total transpiration was higher for the ‘Forelle’ orchard (~ 7 330 m^3/ha) than for ‘Packham’s Triumph’ (~ 5 390 m^3/ha). In addition, the ‘Forelle’ flowered at least 2 weeks earlier than the ‘Packham’s Triumph’ so these trees began using water earlier. Yield for the ‘Forelle’ orchard was about 67 t/ha while the ‘Packham’s Triumph’ orchard yielded about 59 t/ha. Water productivity, defined as yield per unit volume of water transpired by the trees, was slightly higher for ‘Packham’s Triumph’ at 10.9 kg/m^3 compared to 9.1 kg/m^3 for the ‘Forelle’ orchard. These values are of the same order of magnitude as those reported for high-performing apple orchards, which ranged between 8 and 18 kg/m^3, but using data from a larger number of orchards (Dzikiti et al., 2018; Ntshidi et al., 2020; Lulane et al., 2022).

CONCLUSIONS

Irrigation consultants world-wide are actively searching for new and innovative ways to schedule irrigation with greater precision to combat the growing water-related challenges to fruit production. This study provides insights on the feasibility of using fruit and stem dendrometer data as indicators of water stress in pear trees. We highlight the advantages and pitfalls of sensing stress on each organ. While the fruits provide a high accuracy early in the season, uncertainties increase towards maturity. Because pear orchards are usually irrigated throughout the growth cycle, it is advisable to use dendrometer data from stem or branches for consistency. The stem dendrometers should not be on thick bark as this diminishes the sensitivity to changes in tree water status.

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AUTHOR CONTRIBUTIONS

Sebinasi Dzikiti – conceptualized, and wrote the manuscript; Johan Pienaar – collected and analysed data and contributed to the writing of the paper; Prince Dangare – collected and analysed data and contributed to the writing of the paper; Sarah Whitehead – analysed the fruit growth data and contributed to the writing of the paper; Matthew Gray – analysed the fruit growth data and contributed to the writing of the paper; Elke Crouch – contributed to the writing of the paper; Stephanie Midgley – contributed to the writing and proofreading of the paper; Wiehann Steyn – reviewed the manuscript to ensure that the horticultural aspects of the study were correctly represented, and contributed to the writing of the paper.

REFERENCES

ALLEN RG, PEREIRA LS, RAES D and SMITH M (1998) Crop evapotranspiration. FAO Irrigation and Drainage Paper 56. FAO, Rome.

ANNANDALE JG, STIRZAKER RJ, SINGELS A, VAN DER LAAN M and LAKER MC (2011) Irrigation scheduling research: South African experiences and future prospects. *Water SA* **37** (5) 751–763. https://doi.org/10.4314/wsa.v37i5.12

BACON MA (2004) *Water Use Efficiency in Plant Biology*. Blackwell Publishing, CRC Press, Oxford. 326 pp.

BLANCO V and KALCSITS L (2021) Microtensiometers accurately measure stem water potential in woody perennials. *Plants* **10** 2780. https://doi.org/10.3390/plants10122780

BLANCKENBERG A, MULLER M, THERON KI, CROUCH EM and STEYN WJ (2016) Harvest maturity and ripeness differentially affects consumer preference of ‘Forelle’, ‘Packham’s Triumph’ and ‘Abate Fetel’ pears (*Pyrus communis* L.). *Sci. Hortic.* **207**, 131–139. https://doi.org/10.1016/j.scienta.2016.05.012

CALVO G, CANDAN AP and LARRIGAUDIÈRE C (2019) ‘Packham’s Triumph’ superficial scald susceptibility is affected by maturity at harvest. *Acta Hortic.* **1256** 135–142. https://doi.org/10.17660/ActaHortic.2019.1256.19

CORELL M, GIRÓN IF, GALINDO A, TORRECILLAS A, TORRES-SÁNCHEZ R, PÉREZ-PASTOR A, MORENO F and MORIANA A (2014) Using band dendrometers in irrigation scheduling: Influence of the location inside the tree and comparison with point dendrometer. *Agric. Water Manage.* **142** 29–37. https://doi.org/10.1016/j.agwat.2014.04.005

DZIKITI S, VERREYNNE JS, STREVER A, STUCKENS J, VERSTRAETEN WW, SWENNEN R and COPPIN P (2010) Determining the water status of Satsuma mandarin orchards [Citrus Unshiu Marcovitch] using spectral indices and by combining hyperspectral remote sensing and physiological data. *Agric. For. Meteorol.* **150** 369–379. https://doi.org/10.1016/j.agrformet.2009.12.005

DZIKITI S, SCHACHTSCHNEIDER K, NAIKEN V, GUSH M and LE MAITRE DC (2013) Comparison of water use by alien invasive pine trees growing in riparian and non-riparian zones in the Western Cape, South Africa. *For. Ecol. Manage. J.* **293** 92–102. https://doi.org/10.1016/j.foreco.2013.01.003

DZIKITI S, GUSH MB, LE MAITRE DC, MAHERRY A, RAMOELO A and JOVANOVIC NZ (2016) Quantifying potential water savings from clearing invasive alien *Eucalyptus camaldulensis* using in situ and high resolution remote sensing data in the Berg River Catchment, Western Cape, South Africa. *For. Ecol. Manage. J.* **361** 69–80. https://doi.org/10.1016/j.foreco.2015.11.009

DZIKITI S, VOLSCHENK T, MIDGLEY SJE, LÖTZE E, TAYLOR NJ, GUSH MB, NTSHIDI Z, ZIREBWA SF, DOKO Q, SCHMEISSER M, JARMAIN C, STEYN WJ and PIENAAR HH (2018) Estimating the water requirements of high yielding and young apple orchards in the winter rainfall areas of South Africa using a dual source evapotranspiration model. *Agric. Water Manage.* **208** 152–162. https://doi.org/10.1016/j.agwat.2018.06.017

EHRENBERGER W, RÜGER S, RODRÍGUEZ-DOMÍNGUEZ CM, DÍAZ-ESPEJO A, FERNÁNDEZ JE, MORENO J, ZIMMERMANN D, SUKHORUKOV VL and ZIMMERMANN U(2012) Leaf patch clamp pressure probe measurements on olive leaves in a nearly turgorless state. *Plant Biol.* Jul **14** (4) 666–674. https://doi.org/10.1111/j.1438-8677.2011.00545.x

FERNÁNDEZ JE and CUEVAS MV (2010) Irrigation scheduling from stem diameter variations: a review. *Agric. For. Meteorol.* **150** 135–151. https://doi.org/10.1016/j.agrformet.2009.11.006

FERNANDES RDM, CUEVAS MV, DIAZ-ESPEJO A and HERNANDEZ-SANTANA V (2018) Effects of water stress on fruit growth and water relations between fruits and leaves in a hedgerow olive orchard. *Agric. Water Manage.* **210** 32–40. https://doi.org/10.1016/j.agwat.2018.07.028

GARCÍA-TEJERO I, DURÁN-ZUAZO VH, MURIEL-FERNÁNDEZ JL and JIMÉNEZ-BOCANEGRA JA (2011) Linking canopy temperature and trunk diameter fluctuations with other physiological water status tools for water stress management in citrus orchards. *Funct. Plant Biol.* **38** 106–117. https://doi.org/10.1071/FP10202

GUSH MB and TAYLOR NJ (2014) The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling. WRC Report No. 1770/2/14. Water Research Commission, Pretoria.

HORTGRO (2022) Key deciduous fruit statistics, South Africa. URL: www.hortgro.co.za (Accessed 10 November 2023).

HOU X, LI H, ZHANG W, YAO Z, WANG Y and DU T (2020) Water transport in fleshy fruits: Research advances, methodologies, and future directions. *Physiol. Plant.* https://doi.org/10.1111/ppl.13468

JAVIER EVS, HELBER EBL and PEDRO RH (2022) The water status of pear (*Pyrus communis* L.) under application of regulated deficit irrigation in high tropical latitudinal conditions. *J. Saudi Soc. Agric. Sci.* **21** (7) 460–468. https://doi.org/10.1016/j.jssas.2021.12.003.

JONES HG (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. *J. Exp. Bot.* **55** (407) 2427–2436. https://doi.org/10.1093/jxb/erh213

LATEGAN EL and HOWELL CL (2016) Deficit irrigation and canopy management practices to improve water use efficiency and profitability of wine grapes. Water Research Commission and Winetech. WRC Report No. 2080/1/16. Water Research Commission, Pretoria.

LE MAITRE DC, FORSYTH GG, DZIKITI S and GUSH MB (2016) Estimates of the impacts of invasive alien plants on water flows in South Africa. *Water SA* **42** (4) 659–672. https://doi.org/10.4314/wsa.v42i4.17

LÖTTER D and LE MAITRE DC (2014) Modelling the distribution of *Aspalathus linearis* (Rooibos tea): implications of climate change for livelihoods dependent on both cultivation and harvesting from the wild. *Ecol. Evol.* 2014 4(8) 1209–1221. https://doi.org/10.1002/ece3.985

LULANE EB, DZIKITI S, VOLSCHENK T and MIDGLEY SJE (2022) Quantifying water saving benefits of fixed white protective netting in irrigated apple orchards under Mediterranean-type climate conditions in South Africa. *Sci. Hortic.* 305 111439. https://doi.org/10.1016/j.scienta.2022.111439

MARTIN EM (2002) Ripening responses of 'Forelle' pears. Masters thesis, Department of Horticultural Science, Stellenbosch University. https://scholar.sun.ac.za/items/ef3933a7-c6f5-4e2f-9415-d06752c5d414 (Accessed 15 November 2023).

MIDGLEY SJE and LÖTZE E (2011) Climate change in the Western Cape of South Africa: trends, projections and implications for chill unit accumulation. *Acta Hortic.* **903** 1127–1133. https://doi.org/10.17660/ActaHortic.2011.903.157

MORANDI B, LOSCIALE P, MANFRINI L, ZIBORDI M, ANCONELLI S, PIERPAOLI E and GRAPPADELLI LC (2014) Leaf gas exchanges and water relations affect the daily patterns of fruit growth and vascular flows in Abbé Fétel pear (*Pyrus communis* L.) trees. *Sci. Hortic.* **178** (2014) 106–113. https://doi.org/10.1016/j.scienta.2014.08.009

NTSHIDI Z, DZIKITI S, D MAZVIMAVI and MOBE NT (2020) Contribution of understorey vegetation to evapotranspiration partitioning in apple orchards under Mediterranean climatic conditions in South Africa. *Agric. Water Manage. J.* https://doi.org/10.1016/j.agwat.2020.106627

SHACKEL K, MORIANA A, MARINO G, CORELL M, PÉREZ-LÓPEZ D, MARTIN-PALOMO MJ, CARUSO T, MARRA FP, AGÜERO ALCARAS LM, MILLIRON L, ROSECRANCE R, FULTON A and SEARLES P (2021) Establishing a reference baseline for midday stem water potential in olive and its use for plant-based irrigation management. *Front. Plant Sci.* **12** 791711. https://doi.org/10.3389/fpls.2021.791711

STEPPE K, DZIKITI S, LEMEUR R and MILFORD JR (2006) Stomatal oscillations in orange trees under natural climatic conditions. *Ann. Bot.* **92** 831–835. https://doi.org/10.1093/aob/mcl031

VOLSCHENK T (2017) Evapotranspiration and crop coefficients of Golden Delicious/M793 apple trees in the Koue Bokkeveld. *Agric. Water Manage.* **194** 184–191. https://doi.org/10.1016/j.agwat.2017.09.002

WULLSCHLEGER SD and KING AW (2000) Radial variation in sap velocity as a function of stem diameter and sapwood thickness in yellow-poplar trees. *Tree Physiol.* **20** 511–518. https://doi.org/10.1093/treephys/20.8.511

ZIERVOGEL G, LENNARD C, MIDGLEY G, NEW M, SIMPSON NP, TRISOS CH and ZVOBGO L (2022) Climate change in South Africa: Risks and opportunities for climate-resilient development in the IPCC Sixth Assessment WGII Report. *S. Afr. J. Sci.* **118** (9/10). https://doi.org/10.17159/sajs.2022/14492