Using continuous soil and plant water status sensors calibrated against stem water potential for irrigation scheduling – nectarine as a test case

Eyal Nevo
1Institute of Soil, Water and Environmental Sciences, ARO Volcani Center
Nativ Rotbart
nativ@gri.org.il
Shamir research institute, University of Haifa, Israel
Alexander Slutsky
Shamir research institute, University of Haifa, Israel
Rony Wallach
The Hebrew University of Jerusalem
Yoni Gal
Department of Agriculture and Rural Development extension services,
Amos Naor
Migal - Galilee Technology Center
Shabtai Cohen
1Institute of Soil, Water and Environmental Sciences, ARO Volcani Center

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Abstract

This study investigated the use of on-site calibrated soil and plant based sensors for irrigation control in a nectarine *(Prunus persica)*, orchard on heavy clay soil. Irrigation was applied according to predetermined mid-day stem water potential (SWP) thresholds for each of the three phenological stages of fruit development. Calibration of sensors relative to SWP was done in a drying and wetting plot in a separate part of the orchard. Irrigation was withheld in that plot for several periods of time during two seasons, allowing SWP of six nectarine trees to reach values of moderate water stress. The readings of continuous tensiometers, soil volumetric water content sensors and dendrometers were regressed on those of SWP at that time. Water stress thresholds were then calculated from the regressions and subsequently used for irrigation scheduling. The irrigation aimed to keep non-limiting conditions in stages □ and □ by keeping SWP at ~-0.9 MPa, and moderate water stress in stage □ by keeping SWP at ~-1.5 MPa. Adjustments were made weekly in five treatment plots for each sensor type, according to the thresholds. Results showed that tensiometers could be used for stages □ and □, as they were highly sensitive to small changes in soil wetness. However, when stress was applied soil water tension exceeded the range of the tensiometer sensors at 30 cm depth.

Introduction

Pressure on limited water resources, as well as economic pressure from increasing water prices have led to continued research over decades to improve crop water use efficiency. Recent improvements in water stress sensors together with sophisticated IOT solutions for measurement, interpretation, transmitting results to farmers and decision support have made the use of water stress indicators more attractive. However, practical operational issues of the various sensors, including setting thresholds, are yet to be resolved. Here, we report the results of a study regarding soil and plant based sensors, their calibration against stem water potential, and their use for orchard irrigation management. The study includes analysis of how many sensors are required to properly represent orchard water status and whether the sensors operate in the range needed for water saving deficit irrigation schemes.

Soil water content and water potential sensors provide good indications of soil moisture availability because they respond to the soil hydraulic conductivity near the roots, the main limiting factor of soil water absorption by plants (Polak and Wallach 2001). Stem xylem water potential (SWP) is measured in the field using a portable pressure chamber, and in recent years several sensors have been developed which provide direct continuous measurement of water potential (e.g. ICT dew point psychrometer, Florapulse, Davis, CA), and may be available to farmers. SWP has been considered the best indicator of water status in fruit trees because it is correlated with fruit size and crop yield (Shackel et al. 1997) in prune (McCutchan and Shackel 2019), apple (Naor and Cohen 2003), nectarine (Naor et al. 1999), and plum (Intrigliolo and Castel 2004). Dendrometers are used to monitor daily growth and shrinkage in trunk radius, where the maximum daily trunk shrinkage (MDS) was found to be highly correlated with plant water status (Ortuño et al. 2010). Thus, SWP provides a solid solution for water stress assessment, and it is widely used in Israel, California and other places over the past two decades. However, its measurement using a pressure chamber is tedious, limited to a few hours at midday, and it is manually operated. This limitation of the pressure chamber method can be resolved by using easy to operate sensors such as tensiometers, soil water content sensors, and dendrometers, after their calibration to stem water potential thresholds. Soil water potential and SWP have been used for monitoring of soil and plant water status in plum (Intrigliolo and Castel 2004), soil water content and SWP in apricot and peach (Mounzer et al. 2008; Perez-Sarmiento et al. 2010) and MDS and SWP in apple (Naor and Cohen 2003). The sensitivity of soil and tree water status to deficit irrigation was evaluated in peach trees (Goldhamer et al. 1999) and soil parameters were found to be more responsive to the onset of stress than tree water stress indicators.

Nectarine is an important cash crop in many parts of the world, including northern Israel where it is grown for local consumption. It is a pome fruit, characterized by three fruit growth stages, which differ in fruit development sensitivity to deficit irrigation (López et al. 2008; Vera et al. 2013). During stage Ⅰ, from fruit set until pit hardening fruit are tolerant to relatively low irrigation, mainly in locations where the evaporative demand is relatively low at that stage or in early varieties with short stage Ⅰ. Nevertheless, in warm regions with limited winter precipitation and late varieties, fruit development in stage I could be sensitive to water stress. Stage Ⅱ (pit hardening) is favorable for deficit irrigation because on the one hand the requirement for assimilates is limited due to the low fruit growth rate and on the other hand, when well irrigated the canopy tends to have excessive growth which decreases fruit color (López et al. 2008). Stage Ⅲ (from pit hardening to harvest) is the most sensitive to water stress because of the rapid fruit growth in this stage (Naor 2001). In order to manage irrigation levels in different stages of fruit growth, monitoring of soil and plant water status is needed (Grant et al. 2009). This could be achieved by using tensiometers or soil water content sensors for soil water status, and/or by using dendrometers, which measure daily stem contraction and growth, or SWP for plant water status (Jones 2008).

The objective of this project was to investigate the applicability of continuous plant and soil water status sensors as alternatives for stem water potential monitoring for irrigation scheduling of nectarine. We believe that the results are relevant to other tree crops, especially those in which deficit irrigation can be applied. We used the continuous sensors after calibrating them against stem water potential at a range of soil moistures and for different fruit growth stages.

Materials and Methods

Experimental orchard - The experiment was conducted in a drip irrigated commercial nectarine orchard of cv. Arctic Mist, located in Kfar Haruv, Israel (32.75N, 35.67E). The soil consisted of 64% clay, tree spacing was 3 x 5 m and row orientation was North-South. Irrigation was applied via two laterals per row with 1.6 L/h pressure compensated Uniram drippers (Netafim) spaced 50 cm apart.

Treatments and water status measurements – Four irrigation treatments with the same desired stress level but different measuring method, were applied. The water status of each of the first three treatments was monitored by different continuous sensor, and in the fourth treatment stem water potential was monitored as control. The soil water potential (Ψ_{soil}) was measured with tensiometers (Netafim, Hazerim, Israel) with standard clay porous cups at two depths, 30 cm and 60 cm (treatment TEN). Soil water content (θ_{soil}) was measured with EC 5 capacitance sensors (decagon, USA) located at two depths, 30 cm and 60 cm (treatment SWC). Stem radius changes, and from them maximum daily trunk shrinkage (MDS) were monitored using point dendrometers (Netafim, Hazerim, Israel) installed on the north side of the trunk, 30 cm above ground, below the first branch (treatment DEN). The mid-day stem water potential (SWP) was measured with a pressure chamber (Ari-Mad 2, Kfar Haruv, Israel) (treatment PC).

SWP was measured once a week with a pressure chamber in all treatment plots for reference; leaves were covered with re-sealable aluminum-coated bags, and were left for at least two hours prior to measurement to allow water potential to equilibrate with xylem water potential. In the four treatments, two leaves per tree from two trees were measured in each replicate (10 trees per treatment), and one leaf per tree was measured from each of the six trees in the wetting and drying plot.

Each of the four irrigation treatments had its own irrigation system and all of them were controlled by an irrigation controller (Galcon, Israel). Each treatment was replicated five times in a complete randomized block design, where each replicate consisted of three rows having five trees each. The internal two trees in each plot were used for measurements and the rest served as border trees. In an additional experimental plot in the orchard, adjacent to the main experiment, the response of the sensors to drying and wetting cycles was examined. It consisted of three rows having eight trees each, where sensors were installed in the six middle trees of the middle row. The continuous sensors were connected to a data logger (Netafim, Hazerim, Israel) and average readings were recorded every 30 minutes. For the two soil sensors, daily averages between 06:00 and 09:00, before the start of the irrigation, were calculated and considered the maximum stress values. MDS was calculated by subtracting the minimum from the maximum daily readings.

Setting thresholds for the continuous sensors – Target SWP thresholds were – 0.9 MPa for stages I and III of fruit growth, and – 1.5 MPa for stage II. The continuous sensors were calibrated against SWP by withholding irrigation for approximately 20 days in the drying/wetting plot. Calibration was performed in stages I, II, and III of fruit growth in 2011 and 2012. The sensor readings at the corresponding SWP thresholds were set as irrigation thresholds.

A standard weather station for computing Penman-Monteith reference evapo-transpiration was installed on a mast approximately 1 m above the orchard. The weather station values compared favorably with those from a nearby station belonging to the Israel Meteorological Service's network, which was used as the standard (Avnei Eitan field station). The weather station in the orchard consisted of a solarimeter (Kipp and Zonen CM11 pyranometer, Delft, The Netherlands), a wind sensor (Met One 010, Campbell Sci., Logan UT) and temperature and relative humidity sensor (HMP45, Campbell Sci. Logan UT) wired to a CR1000 data logger (Campbell Sci., Logan UT).

Irrigation management and dosage adjustment – Basic irrigation dosages began with standard irrigation table values for Israeli conditions (based on Penman-Monteith reference evapotranspiration; Israeli Ministry of Agriculture extension service). Once a week daily average sensor readings for the past week for each sensor treatment were regressed on time and if the linear regression line showed a deviation of 0.1 MPa or more from the SWP equivalent threshold then the dosage for that treatment was adjusted by adding or subtracting 1 mm for each 0.1 MPa difference from the threshold. If the sensor was out of range then the adjustment was made according to SWP measured in the treatment.

Computation of number of sensor stations required – According to the Central Limit Theorem, the standard deviation of the mean (s_n) of n samples of a normally distributed variable with standard deviation s, is:

$$s_n = s/\sqrt{n}$$

For the mean of measurements made by n sensors, the 95% confidence interval is approximately $2\ s_n$. If we know the standard deviation then we can solve for n_{req}, the number of samples required in order to obtain the desired value for the maximum deviation of the sensor average is:

$$n_{req} = \left[\frac{2s}{x_{req}}\right]^2$$

Where x_{req} is the required value for the 95% confidence interval. In our case, we were interested in determining the number of measurement stations required in order for the 95% confidence interval for average SWP or its equivalent, i.e. x_{req}, to be 0.1 MPa.

Results and discussion

The relationships between SWP and the continuous sensors

Calibration of the continuous sensors against SWP was performed with data from drying and wetting cycles in 2011 and 2012, and the data of the two years was averaged. The response of the sensors to SWP was similar in stages II and III (not shown), so calibration was performed for both of them together. The relationships between SWP and the continuous sensors were different along the season, and adequate regression fits were linear in stage I and polynomial in stages II + III together (Table 1).

Stage I soil sensor readings were less responsive to changes in SWP and when translated to SWP they gave higher values compared with values from stages □ and □, suggesting that drier soil in stage □ could lead to less plant water stress compared with stages □ and □ (Table 1). This may indicate that the actual soil water capacity was near field capacity in the whole soil profile, unlike that in the irrigated areas, for the early stages of the season following the winter rains. Water outside the irrigated area may have provided a large part of plant requirements while in irrigated parts, which may have had more roots that are active where the soil sensors measured, water capacity was lower. In stages ▯ and ▯ the polynomial regression gave minimum values for both soil sensors at 30 cm depth at a SWP of -1.4 MPa, which is higher than the threshold aimed for in stage ▯, i.e. -1.5 MPa. The latter suggests that the tensiometers were near their measuring limits at those soil and tree water conditions for stage ▯ water stress at 30 cm depth. DEN showed differences between stage ▯ and stages ▯ and ▯ as well, and MDS tended to be more sensitive to lower SWP values in stages ▯ and ▯ (Table 1). The explanation for this behavior of the dendrometer sensors may also be related to fruit growth rate or tissue elasticity, which are different for the beginning and end of the season (Fernández and Cuevas 2010; Intrigliolo et al. 2011), together with changes in weather conditions which effect the readings (Ortuño et al. 2010).

Table 1

Parameters and r^2 for the relationship between SWP and Ψ_{soil}, and θ_{soil} and MDS. For Stage ▯ the equation is linear y = a*SWP + b and for Stages ▯ & ▯ the equation is a two order polynomial, y = a*SWP^2 + b*SWP + c (minimum value for soil sensors 30 cm depth is -1.4 MPa).

Period		**Ψ_{soil} 30**	**Ψ_{soil} 60**	**θ_{soil} 30**	**θ_{soil} 60**	**MDS**
	a	16.614	32.819	3.897	13.159	-167.900
Stage I	b	-62.843	-13.067	27.767	36.485	-75.742
	r^2	0.73	0.90	0.90	0.92	0.90
	a	206.360	65.454	34.541	14.564	-52.092
Stages II & III	b	564.520	214.070	94.913	54.279	-239.220
	c	310.400	118.880	86.301	70.472	-107.860
	r^2	0.95	0.97	0.96	0.97	0.94

Application of irrigation using the calibrated continuous sensors

Irrigation scheduling using the continuous sensors enabled maintenance of the target SWP in each of the sensor treatments (Fig. 1). Drying and wetting cycles were applied during the growing season in the dedicated plot, during which SWP of that plot to drop to minimum values of -1.8 MPa (Fig. 1).

At the beginning of the season (stage ▯) water stress in the irrigated plots was low (with relatively low irrigation) and the SWP was high, ~-0.6 MPa for all treatments (Fig. 1). In stage II, SWP declined continuously and reached – 1.4 MPa by the end of the stage (Fig. 1). This level of stress is considered moderate for nectarine's stage ▯ deficit irrigation protocol. Water stress in stage III was reduced gradually due to increasing irrigation amounts towards harvest, reaching SWP values around – 0.9 MPa, i.e. the target SWP value (Fig. 1).

The seasonal evolution of minimum daily Ψ_{soil} (TEN), θ_{soil} (SWC) and MDS (DEN) in 2013 and the operational thresholds (30 cm depth thresholds for soil sensors) in stage III, are presented in Figs. 2, 3 and 4, respectively. At the beginning of the season (stage □) SWP was high and was reflected in low MDS values for the DEN treatment (Fig. 4) and high values for TEN and SWC treatments (Figs. 2, and 3). In stage II, as water stress developed the sensor readings reached maximum MDS and minimum Ψ_{soil} and θ_{soil}. In Stage III, the main fruit growth stage, low water stress was measured in all the sensors according to the irrigation protocol.

For the TEN treatment, there were more fluctuations in stage □ than in the rest of the season (Fig. 2). The DEN treatment had more fluctuations in MDS during stages □ and □ and more stable readings in stage □ (Fig. 4). The fact that all treatments achieved moderate water stress during stage □, as intended (Fig. 1), demonstrates that all three measuring methods are sensitive to water stress and the seasonal course of the response shows that irrigation management with continuous sensors was sufficient to increase stress in stage □ and decrease stress in stages □ and □. Even so, there were different sensitivities of the sensors to changes in soil and tree water status. The seasonal maximum stress values (compared with no stress conditions) were different for each measuring method. The maximum absolute values of TEN, DEN and SWC treatments were 9.5, 4.8 and 2.5 times greater than no stress conditions, respectively (Figs. 2, 4 & 3). This suggests that the response to water stress would be more obvious to the irrigation manager using TEN and DEN sensors than for SWC. In that respect, it is likely that TEN and DEN would give a more obvious response to water stress developed in stage □ than SWC. However, TEN, which have the highest relative value, reached the end of its operating range and might not respond to small changes in irrigation at that stage. In addition, the accuracy of a sensor, which is probably a more important criteria, is defined by the ratio between sensitivity and variance, as will be shown below.

Irrigation rates at the beginning of stage III changed twice, on DOYs 183 and 188 for all treatments. Irrigation rate was approximately 2.0 mm/day at the beginning of that period, increased to 5.5 mm/day on DOY 183, and again to 7.0 mm/day on DOY 188. As a result, Ψ_{soil} rose from – 61 to -18 kPa at 30 cm depth, moving from below the lower threshold of -1.0 MPa up to close to the upper value of -0.8 MPa (Fig. 2b). In the deeper soil layer (60 cm) TEN readings showed the same trend of Ψ_{soil} but reached only – 45 kPa, below the lower SWP threshold of -1.0 MPa (Fig. 2c).

At the beginning of stage III, θ_{soil} at 30 cm was much lower than the lower threshold (25.9%) and with unusual low variance between sensors. This could mean either that the low irrigation level before that stage led to extreme drought, close to the permanent wilting point, or that the SWC sensor had some difficulty measuring at lower water capacities in the clay soil in the experiment orchard. The second explanation is more likely because the water stress was only mild as shown by other sensors (TEN and DEN treatments) as well by SWP in SWC plots. For 30 cm depth, θ_{soil} crossed the lower threshold only after 14 days in stage III (Fig. 3b). At 60 cm, θ_{soil} was less responsive to increasing irrigation at the beginning of stage III and remained below the lower threshold after 14 days (Fig. 3c).

θ_{soil} and Ψ_{soil} increased and reached thresholds at 30 cm depth but not at 60 cm (Figs. 2 & 3). This might suggest either that threshold values for 60 cm are not applicable, or that in order to compensate for the shortage in water capacity during stage II, the irrigation amount that we applied was not sufficient to refill the soil, even though the crop requirement was smaller. Minimum and maximum reference evapotranspiration (ETo, based on the Penman-Monteith equation) during the first two weeks in stage III were 5.7 and 6.7 mm/day, respectively, while irrigation exceeded that from DOY 188 and on.

The soil water profile on DOY 182 was depleted due to a period of relatively low irrigation and moderate stress applied during stage II. Thus, the soil sensors showed that the deeper layer was below the − 1.0 MPa threshold. The gap between upper and deeper root layers started to close at the beginning of stage III due to increased irrigation levels, but still a different SWP threshold was established at that time. This is a good example for the dilemma of irrigation management with soil monitoring of two root zone layers that the irrigation manager must deal with.

MDS tended to decrease during the first 14 days of stage III and fluctuated between values equivalent to -0.8 and − 0.9 MPa (Fig. 4b). Unlike TEN and SWC sensors which indicated low SWP, MDS (DEN) at first remained between the upper and lower MDS thresholds (Fig. 4b), but a few days later MDS decreased and was lower than the lower threshold, equivalent to higher stem water potential. For the same period (i.e. the first two weeks of stage III) soil moisture sensors gave readings below − 1.0 MPa and increased to -0.8 MPa only for the TEN upper layer (Figs. 2 & 3). DEN readings indicated that SWP was higher than − 0.9 and increased. For comparison, actual SWP in treatment plots was measured on DOY's 186 and 191, and was, for DOY 186, -1.03, -1.01 and − 0.99 MPa and for DOY 191 − 0.96, -1.00 and − 0.95 MPa for TEN, SWC and DEN treatments, respectively.

This suggests that either climatic conditions or fruit load had some impact on MDS for those soil water conditions, giving erroneously high water potential equivalents. Average daily vapor pressure deficit (VPD) was between 0.96 and 1.33 kPa, which is relatively low for semi-arid zones. In addition, fruit yield in 2013 averaged 65 kg/tree, which is moderate for that plantation, while 2012 average was 95 kg/tree. All the treatments had similar crop yield in 2013, where the DEN treatment had approximately 8% lower (not significant) yields. Moderate fruit yield is accompanied by a decrease in MDS as compared with higher yields (Conejero et al 2010), and that, together with the relatively low VPD which also decreases MDS (Goldhamer and Fereres 2001; Ortuño et al 2010) might explain why DEN measured low MDS, which usually indicates higher SWP.

Calibration of the continuous sensors using wetting-drying cycle data

All sensors responded to withholding irrigation in the drying and wetting plot, as indicated by increases or decreases in the readings as water stress developed (Fig. 5a, b & c). For TEN there was a different reaction at depths 30 cm and 60 cm. Ψ_{soil} dropped rapidly in the upper 30 cm while below 30 cm a more moderate decrease was observed. Values reached − 30 kPa at 60 cm while at the 30 cm depth values of

-55 kPa were found (Fig. 5a). In the first six days after withholding irrigation, the decrease in SWP was more gradual and began approximately after three days. The Ψ_{soil} decrease during that period was more rapid and the maximum daily drop was reached (Fig. 5a). In the next six days, a parallel reaction was observed for both soil sensors and SWP. The decrease in Ψ_{soil} was similar for both 30 cm and 60 cm, as it was for SWP. The last eight days were characterized by a more moderate change of Ψ_{soil} at both 30 cm and 60 cm soil layers as the sensors reached their minimum values at 30 cm. SWP change was approximately the same as in the earlier periods at that time. During the last eight days of drying the relative decrease in Ψ_{soil} was less than that of SWP, which continued to decrease at the same rate, with values reaching – 1.5 MPa (Fig. 5a).

That was not the case for plum trees soil and plant water potentials on a sandy soil (Intrigliolo and Castel 2004), as Ψ_{soil} continued to decrease while SWP did not, where SWP reached values of -2 MPa. The explanation for those differences could be related to the measuring devices that were different for the plum experiment and allowed measuring Ψ_{soil} at much lower values.

θ_{soil} showed a similar but more moderate reaction to withholding irrigation than Ψ_{soil} (Fig. 5b). At the beginning of drying values were 32.5% and 37.5% for 30 and 60 cm depth, respectively. The change was greater for 30 cm than for 60 cm for the first 6 days, as values dropped to 22.5% and 30%, respectively. For the following 6 days, a similar change in θ_{soil} was observed for both 30 and 60 cm depths (Fig. 5b). In the last 8 days, θ_{soil} almost leveled off.

The difference in the rate of drying between 30 cm and 60 cm (Fig. 5a & b) has previously been reported, as the upper layer of the soil profile showed greater changes in drying fruit trees such as lychee, orange and apple (Stern et al. 1998; Green and Clothier 1999; Polak and Wallach 2001) and in field crops such as corn (Li et al. 2002). This could be explained by more active roots being located in the upper soil (Green and Clothier 1999; Sokalska et al. 2009). As drying began in the soil, it was not yet found in the plant for several days (Fig. 5a & b), as SWP did not respond to the stress conditions for some 3 days after TEN and SWC sensors did. This delayed response has previously been shown for peach trees when irrigation was withheld, as θ_{soil} began to decrease 10 days before there was a significant response in SWP (Goldhamer et al. 1999). This may suggest that if soil sensors are placed in restricted volume, smaller than the wetting zone, they might be used for early detection of decreasing moisture availability. Soil sensors can be misleading if they are located incorrectly, and should be accurately installed in wetted areas of the root zone and not outside of it.

MDS had more fluctuations than soil measurements, and a different reaction to withholding irrigation was observed. MDS changes were small at the beginning of drying and started to increase approximately 4 days after irrigation stopped. From that point, MDS changed similarly to SWP until day 17 and from then on, a tendency to diverge from SWP measurements was observed (Fig. 5c).

The reduced sensitivity of MDS close to the end of drying cycles could be related to the mechanism suggested by Fernández and Cuevas (2010) and De Swaef et al. (2009); as water stress progresses, recovery during the night becomes less effective and maximum daily diameter is reduced, causing MDS to decrease at more severe water stress. Jarén et al (2001) demonstrated a decrease in MDS for higher SWP for olive, lemon, mandarin and grapevines. Fluctuations found in MDS measurements could be explained by the effect of climatic conditions (VPD especially) on MDS, as reported for many deciduous species (Goldhamer and Fereres 2001; De Swaef et al. 2009; Conejero et al. 2010; Ortuño et al. 2010). Although the VPD influence on MDS was not investigated in this experiment, it is well known that high VPD and increased MDS in non-stress conditions are related.

Relative sensitivity of the various water stress indicators

Relative sensitivity of the different sensor systems was analyzed by computing the signal to noise ratio (SNR, after Goldhammer and Fereres, 2001). Signal intensity was calculated by dividing a sensor's reading on a specific day by the minimum stress value of the phenological stage. Noise was calculated as the coefficient of variation (CV) for each stage, computed as the standard deviation divided by the mean for each day. Table 2 presents SNR for all four treatments in the three stages of fruit growth (Table 2). Signal intensity for the TEN treatment was dramatically higher for all stages while the noise of that treatment was closer to that of SWC and DEN, with only SWP showing much smaller values (Table 2).

Intrigliolo and Castel (2004) found higher signal intensity and noise for Ψ_{soil} (measured with Watermark gypsum blocks, Irrometer, riverside, CA) than for MDS and SWP of plum trees, Nonetheless, SNR was higher for MDS than for Ψ_{soil}, a result that does not agree with our findings. In almond trees Goldhamer and Fereres (2001) found greater SNR for MDS than for SWP, the higher signal intensity of MDS contributed to the overall SNR more than the higher noise that was also found for MDS.

TEN SNR in stages [illegible] and [illegible] was greater in 30 cm and in stage [illegible], the opposite was shown. SWC was more stable and showed similar SNR for the 30 and 60 cm layers for all three stages of fruit growth (Table 2). It is possible that TEN would be a more sensitive tool than SWC to small changes in root zone water availability in heavier soils (here we had 64% clay), but it is important to consider which layer is representative of the real stress that developed in the field.

Overall seasonal average SNR rankings were SWP > TEN30 > TEN 60 > DEN > SWC 30 > SWC 60. This causes a dilemma regarding which method should be used by the farmer as measures showed different sensitivity for different phenological stages. It is difficult to determine whether the SNR rankings found in our experiment represents new and different trends of SNR for the methods investigated. However, it is also quite clear that higher signal and noise would be expected for TEN than for MDS and SWP. The higher noise of soil monitoring parameters than of MDS and SWP relates to the variability of the different measurements, that was found to be greater for soil sensors compared with plant measurements (Naor et al. 2005). The much higher signal intensity for TEN could lead to greater overall higher SNR in some stages as shown in this case. The specific setup of soil sensors in relation to the wetting zone of a specific crop, emitter discharge and spacing, irrigation frequency, and soil hydraulic properties may affect its sensitivity, and therefore its location in the hierarchy of sensors under study.

Table 2
Signal, noise and signal to noise ratio for all four treatments in the three fruit growth stages.

Period	Index	TEN 30	TEN 60	SWC 30	SWC 60	DEN	SWP
	Signal	5.32	2.10	0.75	0.80	1.67	1.28
stage □	noise (CV)	0.48	0.40	0.30	0.35	0.42	0.16
	Ratio	11.14	5.20	2.50	2.27	4.00	7.77
	Signal	1.45	1.29	0.80	0.91	2.05	1.16
stage □	noise (CV)	0.35	0.13	0.29	0.45	0.37	0.11
	Ratio	4.17	10.05	2.76	2.01	5.49	10.22
	Signal	4.15	3.98	0.84	0.87	1.34	1.14
stage □	noise (CV)	0.59	0.70	0.29	0.39	0.53	0.11
	Ratio	7.08	5.72	2.90	2.24	2.54	10.47

Practical implications for using calibrated continuous sensors

A calculation of the number of measurements that should be made with each sensor type in order to get the 95% confidence interval of the mean to be equivalent to a SWP of 0.1 MPa was made. The average standard deviation of 3 representative cycles from stage □ in the drying and wetting plot, multiplied by two to give an approximate 95% confidence interval, was divided by the absolute value of the difference between the − 0.8 and − 0.9 MPa references in stage □ (i.e. the 0.1 MPa interval), and then squared (see materials and methods). From the calculations we found that two TEN, seven DEN and ten SWC stations should be installed in the field to get the previously defined interval. The size of a plot that will be representative for continuous sensors was not tested in this study. Even so, it is desired, according to financial abilities of the crop, that each irrigation valve controlled individually be monitored with the number of sensors mentioned above for precise irrigation control. For comparison, the labor required for one plot, with SWP measurements made once a week by a skilled technician with the proper equipment and an ATV, should be approximately three full days, equal to 24 hours, for one season. Another important implication would be the difference between continuous and discrete data collected in the field. Although the parameters investigated here were all daily, (minimum for TEN & SWC, and the difference between maximum and minimum for DEN) the significance of dynamics and trends of hourly inputs could be of great value for investigating tree and soil water status.

Conclusions

The response of the soil water content sensors to water capacity changes was slower than that of the other methods. Therefore, it might be difficult to apply precise irrigation based on these kind of measurements alone in heavy soils. In contrast, dendrometers, which measure plant variations continuously responded quickly and could be a useful tool for the irrigation manager even for moderate water stress. That is true despite their sensitivity to climatic conditions when soil water status is not adequate. Analysis of the variance between sensors in the irrigation experiment showed that if a 95% confidence interval of the mean, equivalent to 0.1 MPa SWP, is desired, then 2 tensiometers, 10 soil water content sensors and 7 dendrometers stations are needed. Ranks according to SNR were SWP > 30 cm tensiometers > 60 cm tensiometers > dendrometers > 30 cm soil water content sensors > 60 cm soil water content sensors for the full season. Nonetheless, in some stages of fruit growth, the TEN SNR was greater than that of SWP. Thus, our findings show that soil and plant based continuous monitoring can inform decision-making in nectarine irrigation to attain desired stress levels during the fruit growth season. It might be advantageous in that sense to use TEN or DEN rather than SWC because of their greater relative responses to stress conditions. Soil sensors react sooner to the early development of water stress and would be better indicators for low levels of stress. For mild water stress developed in stage ▯, both soil and plant monitoring are sensitive and would be appropriate indicators, although classical TEN sensors, which cannot measure soil water potentials exceeding about – 90 kPa, might be close to the end of their range for this kind of stress. Sensitivity of the treatments compared with SWP showed a preference for TEN over DEN and SWC, as indicated by the SNR. Stress thresholds are essential for irrigation scheduling with soil and plant water status monitoring. The thresholds suggested here were tested over one season, after being calibrated for two seasons, and were found to be different between stage ▯ and stages ▯ and ▯.

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Declarations

The authors declare no conflicts of interest.

Author Contribution

EN carried out the research work under the guidance of AN, SC and RW.YG and AS coordinated the field work and data acquisition. EN and NR wrote the main manuscript text . The manuscript was reviewed thoroughly by AN SC and RW.

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Figures

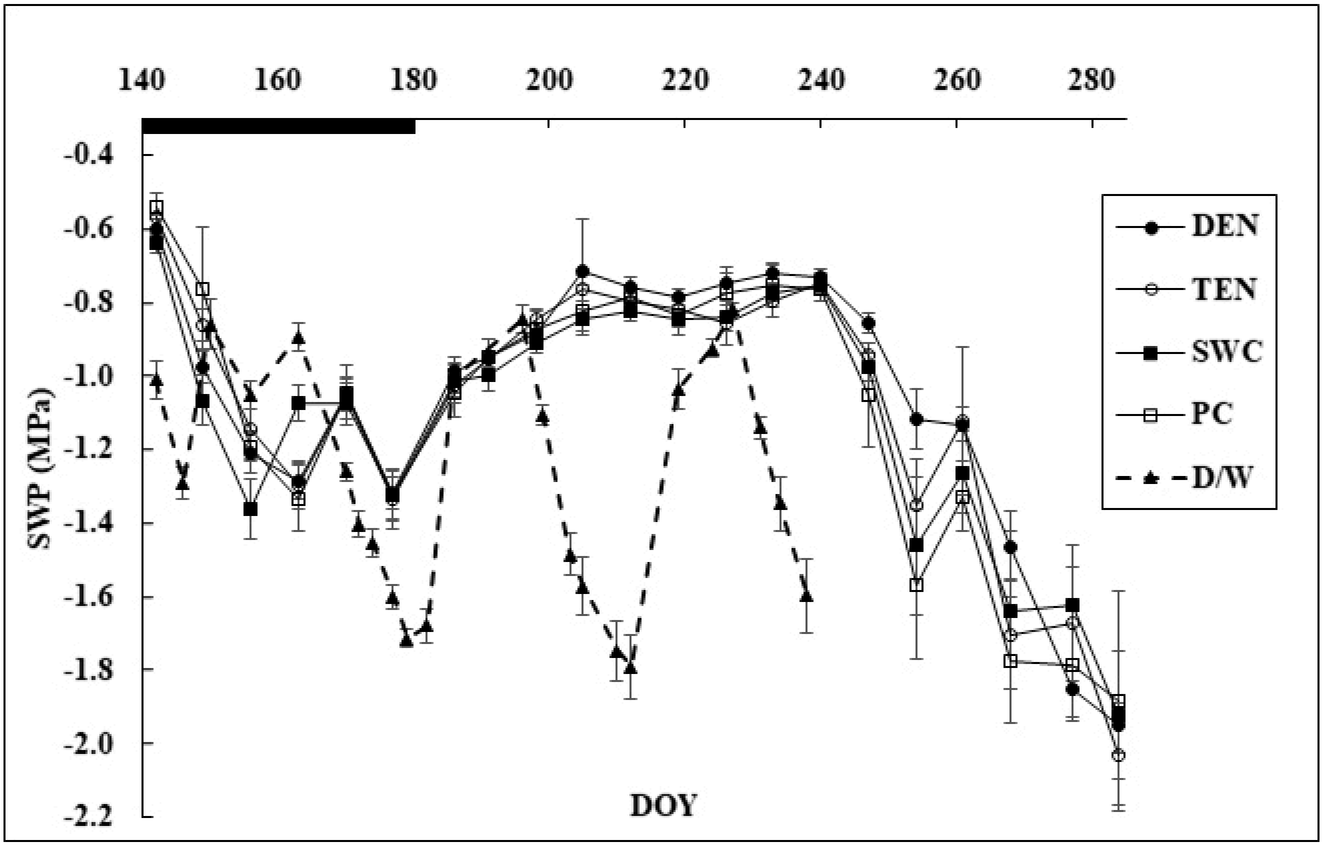

Figure 1

Midday stem water potential values for treatment plots and D/W for 2013 season. DEN closed circles, TEN open circles, SWC closed squares, PC open squares and D/W closed triangles. Black bar on the x-axis represents stage ⅰ.

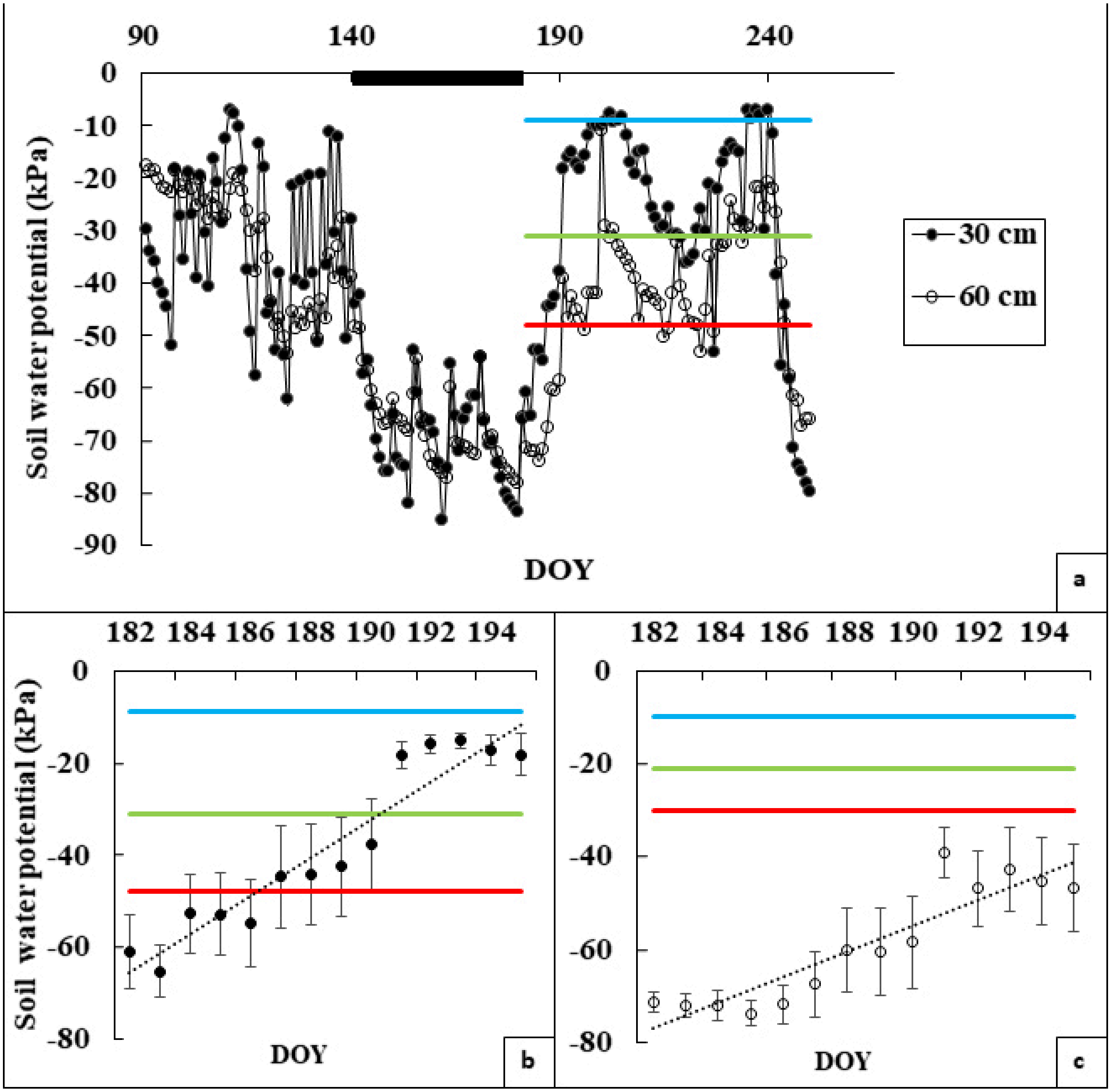

Figure 2

a. Seasonal evolution of Ψ$_{soil}$ at 30 cm and 60 cm (a) in 2013. The blue, green and red lines represent -0.8, -0.9 and -1.0 MPa thresholds respectively. **b** and **c**. the first 14 days in stage III for the Ψ$_{soil}$ at 30 cm (b), and 60 cm (c). Black bar on the x-axis represents stage Ⅱ.

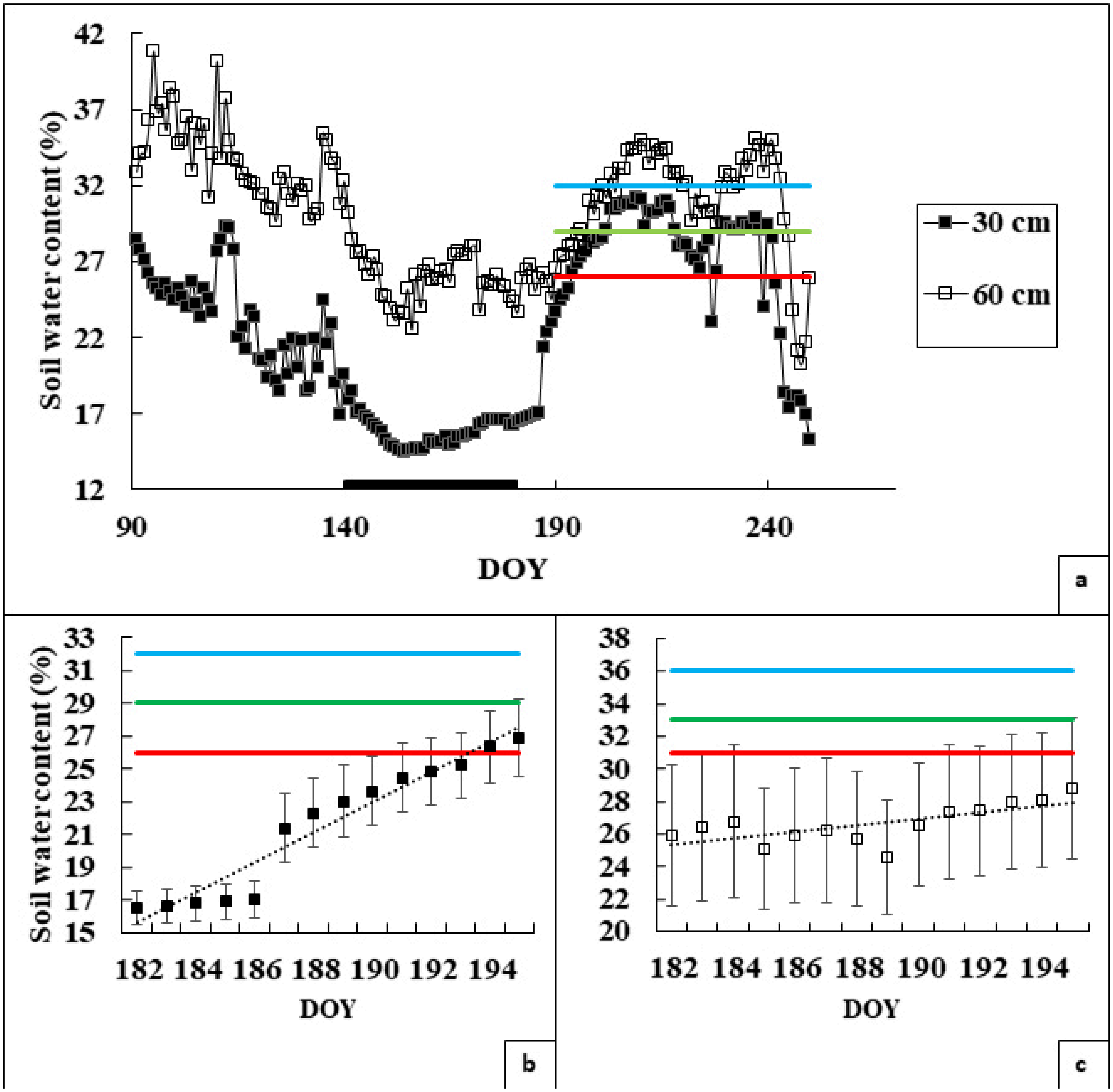

Figure 3

a. Seasonal evolution of θ_{soil} at 30 cm and 60 cm (a) in 2013. The blue, green and red lines represent -0.8, -0.9 and -1.0 MPa thresholds, respectively. **b** and **c**. the first 14 days in stage III for θ_{soil} at 30 cm (**b**), and 60 cm (**c**). Black bar on the x-axis represents stage Ⅱ.

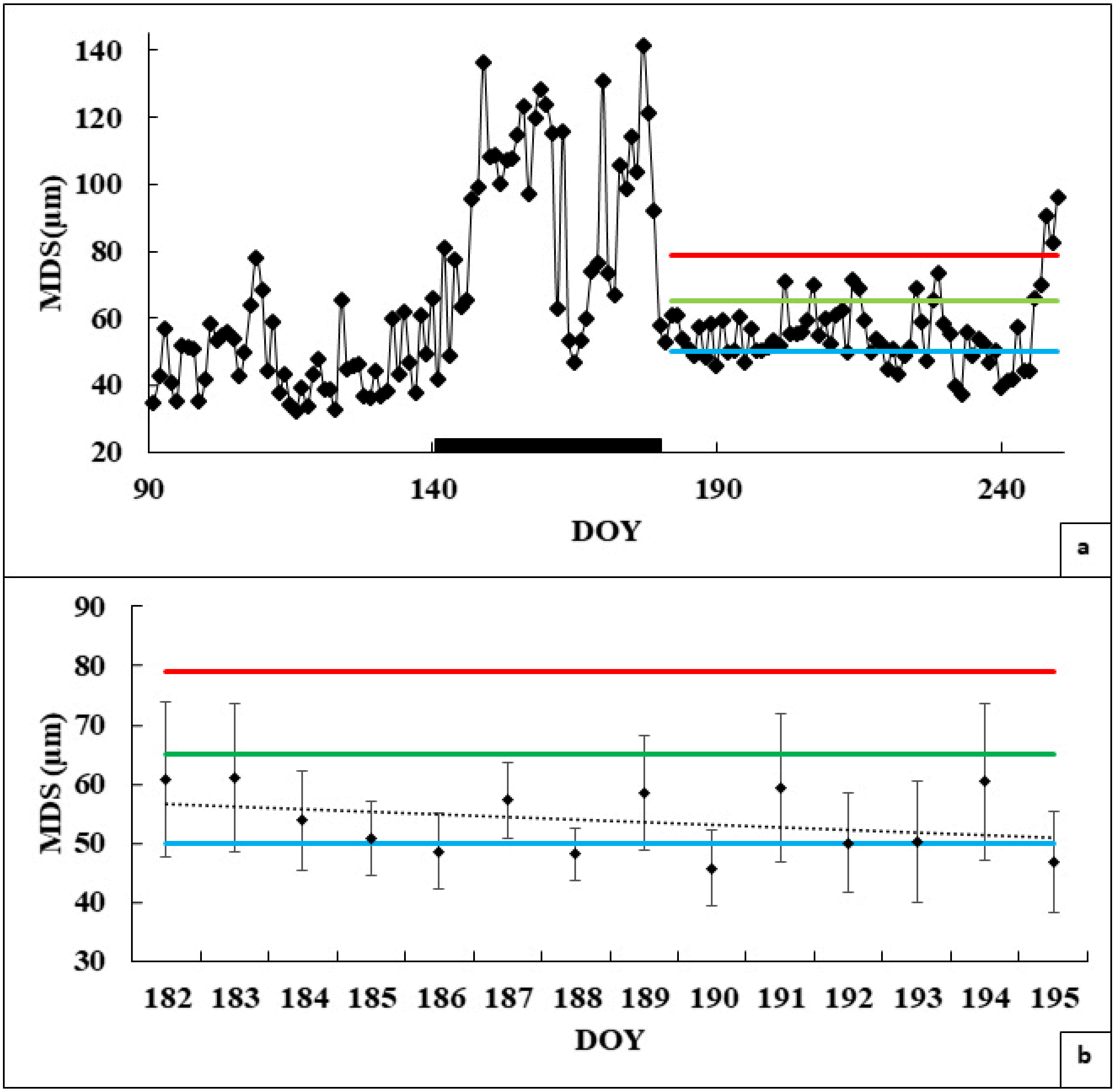

Figure 4

a. Seasonal evolution of maximum daily shrinkage in 2013. The blue, green and red lines represent -0.8, -0.9 and -1.0 MPa thresholds, respectively. b. the first 14 days of stage III (b). Black bar on the x-axis represents stage Ⅱ.

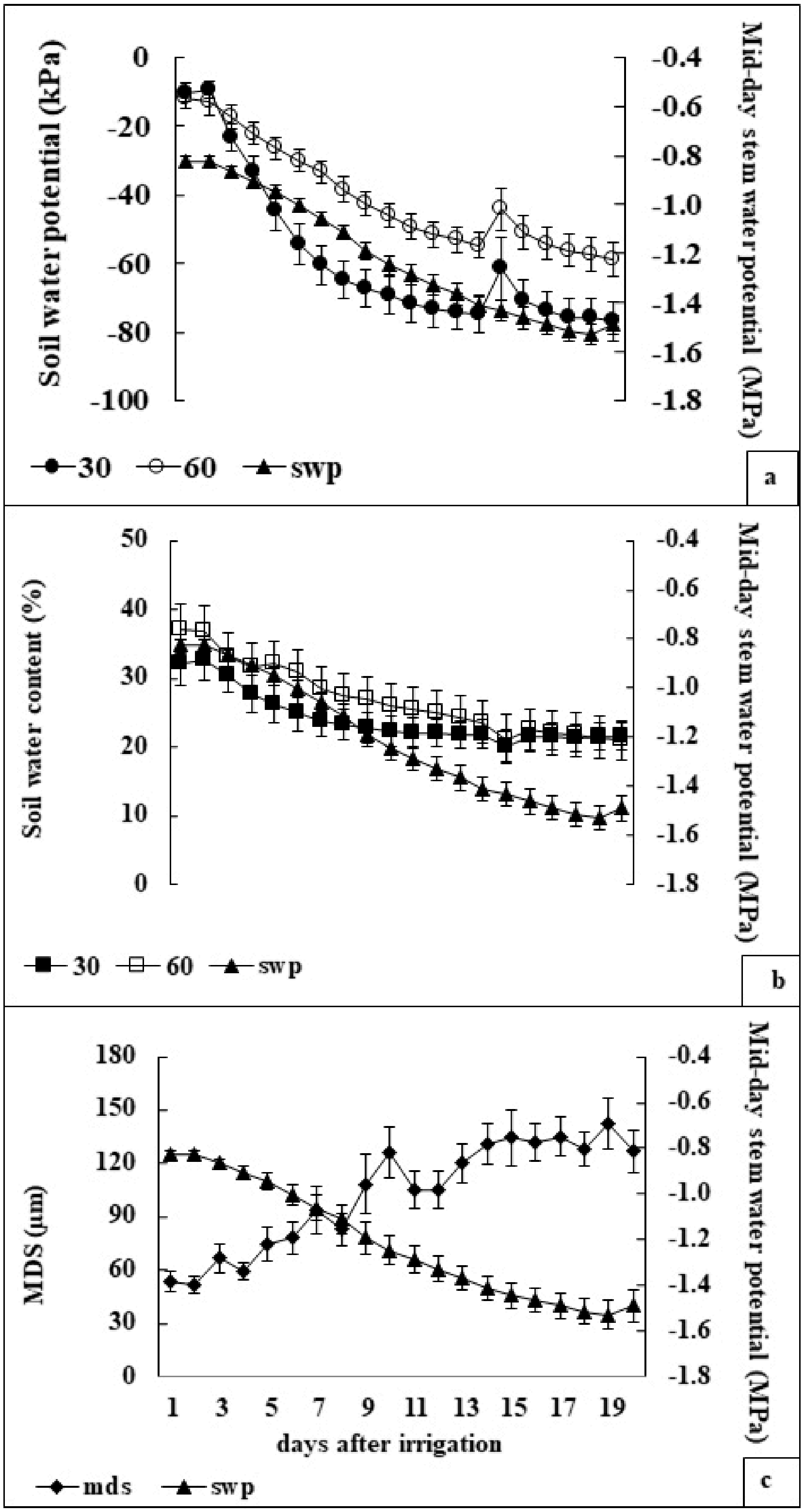

Figure 5

Ψ_{soil} at 30 cm depth (closed circles) and 60 cm (open circles), θ_{soil} at 30 cm (closed squares) and 60 cm (open squares), MDS (closed diamonds) and SWP (closed triangles) over time (days) in stage , after irrigation was stopped in the drying and wetting plot.