Agricultural Water Management
Manuscript Draft

Manuscript Number: AGWAT3330

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Article Type: Research Paper

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Seasonal changes of maximum daily shrinkage reference equations for irrigation scheduling in olive trees: influence of fruit load

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Abstract

Maximum daily shrinkage (MDS) is the parameter of daily cycle of trunk diameter most widely suggest in irrigation scheduling of several fruit trees. However, as in other plant-measured approach, the irrigation decision may be difficult due to the influence of the environment in the values obtained. Reference equations of MDS have been established in order to avoid the effects of environmental conditions. Such equations are usually related with simple meteorological data, in order to estimate easily MDS values in full-irrigated conditions. This work studies the influence of the fruit load and the inter-annual variations in the reference equation of MDS in olive trees. These reference equations were calculated during 4 seasons in a full-irrigated orchard and the equations were validated with the data of a different season. The values of MDS were related with vapour pressure deficit (VPD) and temperature obtained near the experimental orchard. In addition, meteorological data were considered as mean daily or as midday values. The validation of the equations were made using the fits with all the meteorological data considered (midday and mean daily of VPD and temperature). In each meteorological data, in addition, two different fit, one according fruit load and other with the complete pool data were used. The equations fit were significantly different each season in all the meteorological data considered. Although, seasons with similar fruit load were more similar. In both meteorological data considered (VPD and temperature) the midday values improve the fit respect to mean daily values. The reference equations in which temperature was used obtained best fit that the ones calculated with VPD. No significant differences were found in the validation when equations according with fruit load or using the complete pool data were compared. The limitations and usefulness of these reference equations is also discussed.

Keyword: LVDT, RDI, trunk diameter fluctuations.

1. Introduction

Irrigated agriculture is actually the largest fresh water consumer in the world. In the last decades, olive production in the Mediterranean region has intensified, and the traditional rainfed crop is now frequently irrigated (Eris and Barut, 1995). The scarcity of water supplies and the increasing demand of other water-user sectors impose to the Mediterranean agriculture an increasing pressure to limit its water consumption, and so there is a constant need to improve the water use by the crops using better irrigation management (Fereres and Evans, 2006). Among the tools that olive growers can use to achieve this goal are more precise irrigation scheduling methods which involve the determination of water requirements by crop and/or the application of regulated deficit irrigation.

Measurement of the plant water condition may be useful for irrigation scheduling because of its dynamic nature, which is directly related with climatic and soil conditions, as well as crop productivity (Fereres and Goldhamer, 2003; Goldhamer et al., 2003).

The trunk or stem of all plants presents daily cycles of swelling and shrinking that is known as trunk diameter variations (Kozlowski, 1967). Continuous records of stem diameter have been proposed as a management tool for irrigation scheduling (Huguet et al., 1992; Cabibel and Isberie, 1997; Cohen et al., 2001; Goldhamer and Fereres, 2001). In a recent paper Ortuño et al. (2010) have reviewed the state of the art regarding the use of trunk diameter variations derived parameters for irrigation scheduling in woody crops. As so far as we know, Goldhamer and Fereres (2004) were the first to demonstrate that is possible to develop a deficit irrigation schedule based only on maximum daily trunk shrinkage (MDS) in almond trees. García Orellana et al. (2007), Velez et al. (2007) and Ortuño et al. (2009c) confirmed that in citrus MDS is a good indicator for scheduling deficit irrigation. Other useful parameter derived from the trunk daily cycles of swelling and shrinking is the trunk growth rate (TGR) as defined by Goldhamer and Fereres (2001) that can be used for irrigation scheduling of fruit trees.

The use of the absolute values of the plant-based water status indicators could be meaningless and thus we need to obtain reference values for these indicators. Reference values can be obtained by maintaining trees under conditions of non-limiting soil water supply. At the same time is necessary to develop reference equations to help us to interpret the values of a plant-based water status indicator. These reference equations can be obtained by relating their values in trees under non-limiting soil water conditions with evaporative demand of the atmosphere (Moreno et al., 2006; Conejero et al., 2007b; Ortuño et al., 2009b and 2010).

MDS values can be affected by several factors, such as tree age (Moriana and Fereres, 2004), phenological period (Marsal et al., 2002; Intrigliolo and Castel, 2004; Moriana and Fereres, 2004; Conejero et al., 2007b) and fruit load (Conejero et al., 2010; Marsal et al., 2002; Intrigliolo and Castel, 2006). In olive trees the alternate bearing can be a factor that can affect MDS values. In a recent paper by Moriana et al. (2010) have shown that MDS is no the best indicator for optimal irrigation scheduling in olive trees but can be a good tool to be used in deficit irrigation scheduling. In this case, the stress level will be indicated by MDS values lower than the one obtained in the base lines or reference equations.

The objectives of this paper were: (1) to obtain reference equations of MDS for olive trees based on its relation with the evaporative demand of the atmosphere; (2) to study the interannual variation of the reference equations, and (3) to evaluate the influence of fruit load on the MDS vs evaporative demand parameters relationships.

2. Material and Methods

2.1. Description and design of the experiment

Experiments were conducted at La Hampa, the experimental farm of the Instituto de Recursos Naturales y Agrobiología (CSIC), which is located at Coria del Río near Seville (Spain) (37º17’’N, 6º3’W, 30m altitude) during 5 consecutive seasons (from 2005 to 2009). The sandy loam soil (about 2 m deep) of the experimental site was characterized by a volumetric water content of 0.33 m^3 m^{-3} at saturation, 0.21 m^3m^{-3} at field capacity and 0.1 m^3m^{-3} at permanent wilting point, and 1.30 (0-10cm) and 1.50 (10-120 cm) g cm^{-3} bulk density.

The experiment was performed on 37-year-old olive trees (Olea europaea L cv Manzanillo). Tree spacing followed a 7m x 5m square pattern. Pest control and fertilization practices were those commonly used by the growers and no weeds were allowed to develop within the orchard.

Irrigation was carried out during the night by drip using one lateral pipe per tree row and five emitters per plant, delivering 3 L h^{-1} each. Plants irrigation requirements were determined according to daily reference evaotranspiration (ETo) and a crop factor based on the time of the year and the percent of ground area shaded by the tree canopy (Fernández et al., 1998). During the experimental period (from end of april until beginning of October), total crop evapotranspiration (ETc) was 430 mm (2005), 413 mm (2006), 414 mm (2007), 430 mm (2008), 392 mm (2009).

During the experimental period, olive trees were irrigated daily above their water requirements in order to obtain non-limiting soil water conditions. A total amount of water (rainfall not included) of 476 mm (2005), 442 mm (2006), 410 mm (2007), 644mm (2008), 605mm (2009), measured with in-line water meters, was applied during the experiment.

The design of the experiment was completely randomized with four replications, each replication consisting of the three adjacent rows of five trees. Measurements were made in the inner tree of the central row of each replicate, the other trees served as borders.

2.2 Measurements

Micrometeorological 30 min data, namely air temperature, solar radiation, air relative humidity and wind speed at 2 m above the soil surface were collected by an automatic weather station located some 40 m from the experimental site. Daily reference evapotranspiration (ETo) was calculated using the Penman-Monteith equation (Allen et al., 1998). Mean daily vapour pressure deficit (VPD_m) was calculated from the maen daily vapour pressure and relative humidity (Goldhamer and Fereres, 2001).

Trunk diameter fluctuations were measured throughout the experimental periods in four trees, using a set of linear variable displacement transducer (LVDT) (model DF±2.5 mm, accuracy ±10 μm, Solartron Metrology, Bognor Reis, UK) attached to the trunk, with a special bracket made of Invar, an alloy of Ni and Fe with a termal expansion coefficient close to zero (Katerji et al., 1994). Measurements were taken every 10 s and the datalogger (model CR10X with AM 416 multiplexer, Campbell Sci. Ltd., Logan, USA) was programmed to report 30 min means. Maximum

The data obtained during the five seasons were analyzed taking into account the years with low fruit load (2005, 2007 and 2009) and years with full fruit load (2006 and 2008). Data from 2009 were used to validate the relationships obtained in previous years. Linear regression analysis was carried out to explore relationships between variables (MDS and climatic variables). Differences between regression lines were determined with a T-test of the slope and y-intercept.

3. Results

The MDS vs mean daily temperature relationship during the four years of the experiment showed the best fit in a lineal form (Table 1 and Fig. 1a). The increase in temperature produces an increase in the MDS in a rate around 0.04 mm ºC^{-1}. The range of variations in mean daily temperature was wide enough for the Seville conditions of olive growth and varied from around 10 to 30ºC. The equations of each year for mean daily temperature are shown in Table 1. All the equations were significantly different in the slope and the intercept. The coefficient of determination was significant in all the years but low, except in the 2008 season when it was clearly higher (r^2=0.82). When the data were grouped in full fruit load (FFL) and low fruit load (LFL) years there were no significant differences in the slope but it was in the intercept. The LFL equations tended to lower values of MDS than the FFL equations when the same mean daily temperature is considered.

When the temperature considered is the ones that occurred at midday the scatter of the points is reduced (Table 1 and Fig. 1b) in comparison with that of mean daily temperature (Fig. 1a). The range of variations in temperature (Fig. 1b) is similar to that in Fig. 1a, and changes from around 20 to 40ºC. The equations in each year were significantly different between them, as in the case of mean daily temperature. The coefficients of determination were slightly higher than the ones of mean daily temperature (Table 1). The equations of LFL and FFL years were significantly different for the intercept but not for the slope. As in the data of Fig. 1a, the values during LFL year tended to be lower than the ones of the FFL year when the same range of temperature is considered.

The relationship between MDS and VPD was also lineal. The increase in VPD produces an increase in the MDS in full irrigated conditions (Fig. 2). When the mean daily VPD is considered the range of data were from near 0 to 4 KPa (Fig. 2a). The equations of each year were significantly different in the intercept and the scatter was slightly higher than in the midday temperature relationship (Table 1 and Figs. 1b and 2a). There were also significant differences between the equations when they were grouped in FFL and LFL. The MDS in FFL year tended to higher values than in LFL year when the same mean daily VPD is considered.

The scatter in the MDS vs VPD relationship is slightly reduced when the values at midday (Figure 2b) are considered instead of the daily average (Figure 2a). Although the coefficient of determination was slightly higher than the mean daily VPD, they were lower than the ones obtained in midday temperature relationships (Table 1). The range of variations of midday VPD was also higher than mean daily VPD and it extended until 6 KPa (Fig. 2). There were significantly differences in the intercept but not in the slope of the equations between years. There were also significant differences between the equations when they were grouped in full fruit load and low fruit load years (Table 1).

The MDS in FFL year tended to higher values than in LFL year when the same midday VPD is considered.

The equations obtained with the data of 2005 to 2008 seasons were validated with the data of 2009 season (Figs. 3 and 4; Table 2). Although all the seasons were statistically different in both meteorological parameters (temperature and VPD) considered (Table 1), from the point of view of irrigation scheduling in a commercial orchard the variation between seasons was considered small. Only the influence of fruit load was evaluated. However, even though, alternative bearing may be common in field conditions, in commercial orchards is difficult to identify most of the seasons as low fruit load or as full fruit load year. Therefore, the validation was made with two equations, one of them related to the fruit load and the other with the one that considered all the seasons, which so called from here "total" equation (Table 1). In 2009 season, the orchard had very low yield (around 4 kg per tree), therefore for each variable (midday and mean daily temperature and midday and mean daily VPD) the validations were made with the low fruit load year equations (Table 1). The fit of the observed and estimated MDS when the temperature is considered (Fig. 3) was significantly different from line 1:1 in all the cases (Table 2). The midday temperature, however, tended to nearer values to the 1:1 line than the mean daily temperature (slope 0.80 and 0.73 respectively, Table 2). The data of the fits with mean daily temperature showed higher scatter (higher MSE, lower r^2) than the midday temperature (Fig. 3 and Table 2). However, there were no significant differences between the equations of Table 2. When the same kind of temperature is considered the low fruit load equations were nearer to 1:1 line than the "total" equations. Nevertheless, in all the cases the fit obtained with LFL or “total” data were not significantly different in slope but it was in intercept (always lower in LFL equations).

The validation of the VPD equations (Fig. 4) showed that the prediction were poorer that the ones obtained with any of the temperatures (Fig.·3). The parameters of the relationship MDS observed vs measured were significantly different from the line 1:1 and significantly lower that the ones obtained with temperature, specially the slope that were around 0.5 while in temperature were around 0.8 (Table 2). There were no significant differences between the slope of the LFL and “total” equations but it were in the intercepts. The LFL equations tended to intercept nearer to zero than the “total” although in all the cases were higher that the ones obtained with the temperature.

4. Discussion

MDS is considered a good indicator of the transpiration stream (Herzogt et al 1995) but the relationship with VPD was poorer than the ones obtained with temperature (Tables 1 and 2). Similar results have been reported in several works in different fruit trees (almond, Fereres and Goldhamer (2003); plum (Intrigliolo and Castel, 2006); olive (Moreno et al, 2006); lemon (Ortuño et al, 2009)). In addition, the relationship along the season was steady and lineal and apparently, there was no influence of the phenological stage of trees as in other fruit trees (plum, Intrigliolo and Castel, 2007). The midday parameters presented a better fit than the daily average (Tables 1 and 2). MDS is a parameter that is calculated during the most active transpiration phase and the “mean VPD or mean temperature” included values for the complete day where there are periods in which transpiration even is null. “Midday parameters”, however, are likely more related with the phase of shrinkage because the higher rate of shrinkage occurred around this moment of the day. All the equations were significantly different each season, though the ones with the similar crop load tended to be nearer. Such differences between seasons may indicate that the MDS is an accurate measurement that is likely affected in several ways for the physiology of the plant. Genard et al (2001) suggested that the trunk diameter varied according to several factors such as xylem, osmotic and turgor water potential and for the elasticity of the wall. Therefore, in theory, is difficult that the same relationship between MDS and temperature may be obtained each year even in the same orchard.

MDS has been traditionally considered the best indicator of trunk diameter variations for irrigation scheduling in most of the fruit trees (Huguet et al, 1992; Goldhamer and Fereres, 2001; Ortuño et al 2010). However, in olive trees, this indicator presented several limitations for using in full irrigated conditions. There are several works in olive trees that presented no variations in MDS in conditions of mild water stress (Moriana et al 2003; Moriana and Fereres, 2002), only in conditions of very severe water stress MDS is reduced (Moriana et al 2000; Moriana et al 2003). Such response has been suggested that is related with the physiology of the specie (Moriana et al, 2010). On one hand, MDS increase in full irrigated conditions quickly due to the evaporative demand, while the ones of the stressed trees increase slower. Therefore, conditions of mild water stress produced clear differences in water potential meanwhile similar values in MDS (Moriana et al. 2010). Nevertheless, the deficit irrigation strategies in olive trees suggest a moderate or even severe water stress conditions during the pit hardening (Goldhamer, 1999; Moriana et al 2003; Tognetti et al 2007). In these conditions reference values of MDS may be probably very useful for controlling the level of water stress but using in the opposite way that in the rest of fruit trees. During the pit hardening the reduction of MDS from reference values will indicate moderate or severe water stress conditions. Several questions arise then. The first, how much MDS may be reduced should be answered in further experimental works. The others are about which reference equation may be used. According to the results of this work (Tables 1 and 2) in commercial orchard the differences between the crop load and the equation that included all the data ("total equation") is small. The validation of both VPD and temperature equations (Table 2) suggest that the estimation is very close, even though the 2009 season was a clear low fruit load year (the yield was almost null). Therefore, in commercial conditions when commonly low fruit load and full fruit load years are difficult to identify the "total" midday temperature will be the best selection. On the other hand, there is no data about the feasibility of this equation out of the experimental farm even though the same cultivar would be used. Moriana and Fereres (2004) suggested different baselines in cv Picual using mean VPD, with different age and density but similar conditions to the present work (this experimental farm is around 150 Km far from the plot of this work and with very similar climatic conditions). The one-year equations presented by these authors (Moriana and Fereres, 2004), were similar in slope to the ones obtained in the present work (Table 1) in full fruit load and low fruit load years in mature trees. According with the results of the present work, VPD estimation would be worse than temperature estimation. The baselines of midday temperature obtained in the present work (Table 1) may be a good tool for irrigation scheduling of olive trees, at least from the point of view of commercial management, if the orchard is under similar climatic conditions to that of our experimental farm.

5. Conclusions

MDS was related with the VDP and temperature, although the fits calculated with temperature were better than the ones obtained with VPD. The best fits were obtained with values measured at midday instead of the mean daily. This better agreement is likely related with the period when the shrinkage is produced. The equations obtained were different each season, though the season with similar fruit load presented similar equations. The MDS values of full fruit load (FFL) seasons tended to be higher than the low fruit load (LFL) seasons. However, when the equations were validated with an additional low fruit load season, there were no significant differences between equations that considered LFL data or the one that considered the completed pool of data. The parameters of other MDS reference equations found in the literature were similar in mature trees when the same fruit load was considered. Therefore, though cultivar or density may be factors that affect the reference equations, fruit load and age of the tree are probably the most important. The reference equations of midday temperature obtained in the present work (Table 1) may be a good tool for irrigation scheduling of olive trees, at least from the point of view of commercial management, if the orchard is under similar climatic conditions to that of our experimental farm.

Acknowledgements

This research was supported by the Spanish Ministerio de Ciencia e Innovación (MICINN), (CICYT/FEDER AGL2004-0794-C03-02 and AGL2007-66279-C03-02/AGR). Thanks are due to J. Rodriguez for help with field measurements.

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Figure Captions

Figure 1. Relationship of MDS with the mean daily temperature (a) and the midday temperature (b) during four consecutive seasons (2005 to 2008). ■ 2005; ● 2006; □ 2007; ○ 2008. The regression equations obtained with each season, the “FFL (full fruit load)” and “LFL (low fruit load)” season and the total pool of data is presented in Table 1.

Figure 2. Relationship of MDS with the mean daily VPD (a) and the midday VPD (b) during four consecutive seasons (■ 2005; ● 2006; □ 2007; ○ 2008). Line represent the fit of all the data. The regression equations obtained with each season, the “FFL (Full fruit load)” and “LFL (Low fruit load)” season and the total pool of data is presented in Table 1.

Figure 3. Validation of the reference equations with the measured data of MDS in full irrigated trees during 2009 season. The equations used are the ones obtained with the mean daily temperature (a) and the midday temperature (b). White circle are the equation obtained with the LFL (low fruit load) years and black circle are the equation using the pool data, total equation (see Table 1 for equations). In all the cases the relationship between MDS measured and estimated are significantly different from the line 1:1.

Figure 4. Validation of the references equations with the measured data of MDS in full irrigated trees during 2009 season. The equations used are the ones obtained with the mean daily VPD (a) and the midday VPD (b). White circle are the equations obtained

with the LFL (Low fruit load) years and black circle are the equations with the pool data, “total equation (Table 1). In all the cases the relationship between MDS measured and estimated are significantly different from the line 1:1.

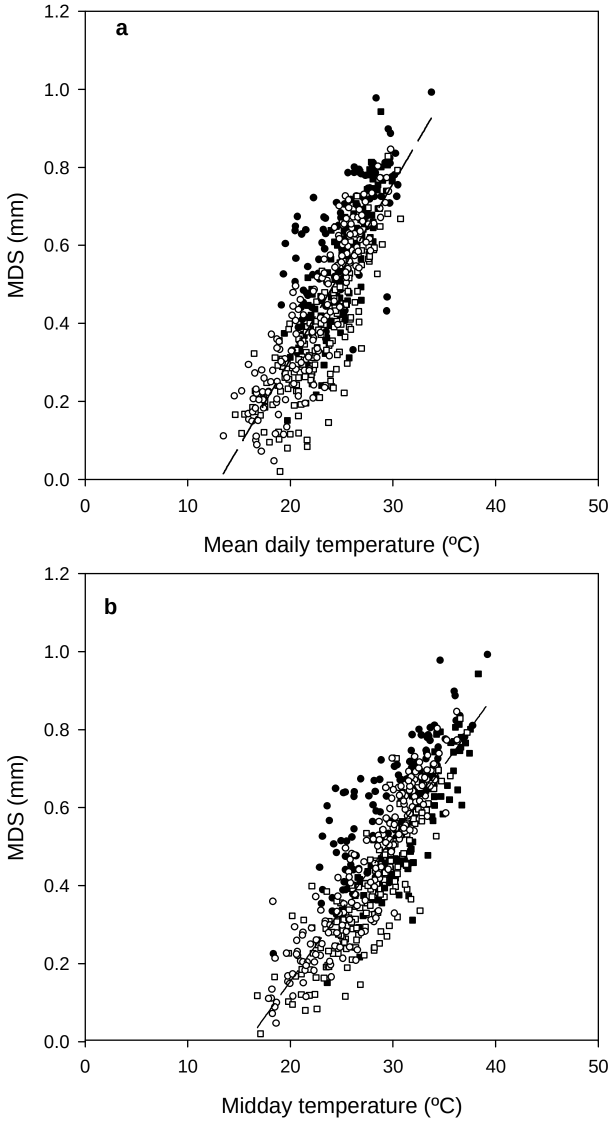
Table 1. Equations, coefficient of determinations (r^2) obtained in the relationships of Figs. 1 and 2. Each season is presented and, in addition, the results when they are grouped according to the crop load (LFL, low fruit load; FFL, full fruit load). "Total" is the equation considering all data (four seasons). RMSE: residual mean squared error. N: number of data. Statistic Dif: statistical differences between equations

Season	Equations	r^2	RMSE	N	Statistic Dif.
MDS vs Mean Temperature					
2005	-0.79+0.053X	0.68***	0.09	105	All of them
2006	-0.26+0.035X	0.48***	0.12	111	Statistical
2007	-0.52+0.038X	0.65***	0.09	160	Different
2008	-0.59+0.046X	0.82***	0.08	175	
LFL (05&07)	-0.67+0.046X	0.68**	0.10	265	Intercept different
FFL (06&08)	-0.55+0.045X	0.73***	0.10	286	
Total	-0.59+0.045X	0.67***	0.11	551	
MDS vs Midday Temperature					
2005	-0.78+0.042X	0.79***	0.07	105	All of them
2006	-0.37+0.033X	0.67***	0.09	111	Statistical
2007	-0.57+0.034X	0.73***	0.08	160	Different
2008	-0.61+0.038X	0.85***	0.07	175	
LFL (05&07)	-0.65+0.037X	0.80***	0.08	265	Intercept different
FFL (06&08)	-0.58+0.038X	0.78***	0.09	286	
Total	-0.58+0.037X	0.73***	0.10	551	
MDS vs Mean VPD					
2005	0.03+0.16X	0.69***	0.08	105	
2006	0.34+0.16X	0.57***	0.10	111	Intercept
2007	0.09+0.20X	0.63***	0.10	163	different
2008	0.08+0.24X	0.78***	0.09	167	
LFL (05&07)	0.17+0.13X	0.67***	0.10	268	All of them
FFL (06&08)	0.16+0.22X	0.64***	0.12	278	Different
Total	0.23+0.14X	0.48***	0.14	546	
MDS vs Midday VPD					
2005	-0.07+0.13X	0.82***	0.06	105	Intercept
2006	0.30+0.12X	0.68***	0.09	111	different
2007	0.06+0.13X	0.67***	0.09	160	
2008	0.11+0.14X	0.51***	0.13	167	
LFL (05&07)	0.13+0.10X	0.66***	0.10	265	All of them
FFL (06&08)	0.16+0.14X	0.53***	0.13	278	different
Total	0.20+0.10X	0.45***	0.14	543	

Table 2. Best fits of the relationship between MDS observed and estimated using different meteorological variables. The adjusted validated were obtained from 2005 to 2008 (Table 1), while the data used to compared such validations were measured during 2009 season (n=148). LFL, low fruit load equation. "Total" is the equation considering all data (four seasons). RMSE: residual mean squared error

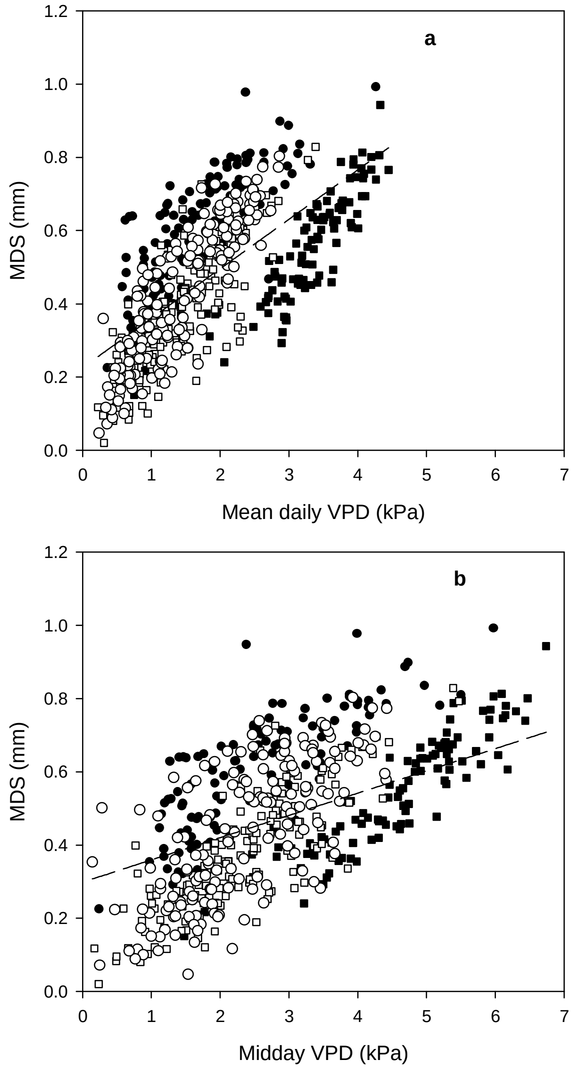
Eq. validated	**Equations**	**RMSE**	**r^2**
LFL Mean Temperature	Y= 0.11+0.74X	0.10	0.66***
"Total" Mean Temperature	Y=0.17+0.73X	0.09	0.66***
LFL Midday Temperature	Y=0.09+0.81X	0.06	0.85***
"Total" Midday Temperature	Y=0.15+0.80X	0.06	0.85***
LFL Mean VPD	Y=0.20+0.44X	0.05	0.75***
"Total" Mean VPD	Y=0.26+0.48X	0.05	0.75***
LFL Midday VPD	Y=0.17+0.54X	0.05	0.81***
"Total" Midday VPD	Y=0.24+0.54X	0.05	0.81***

Figure 1



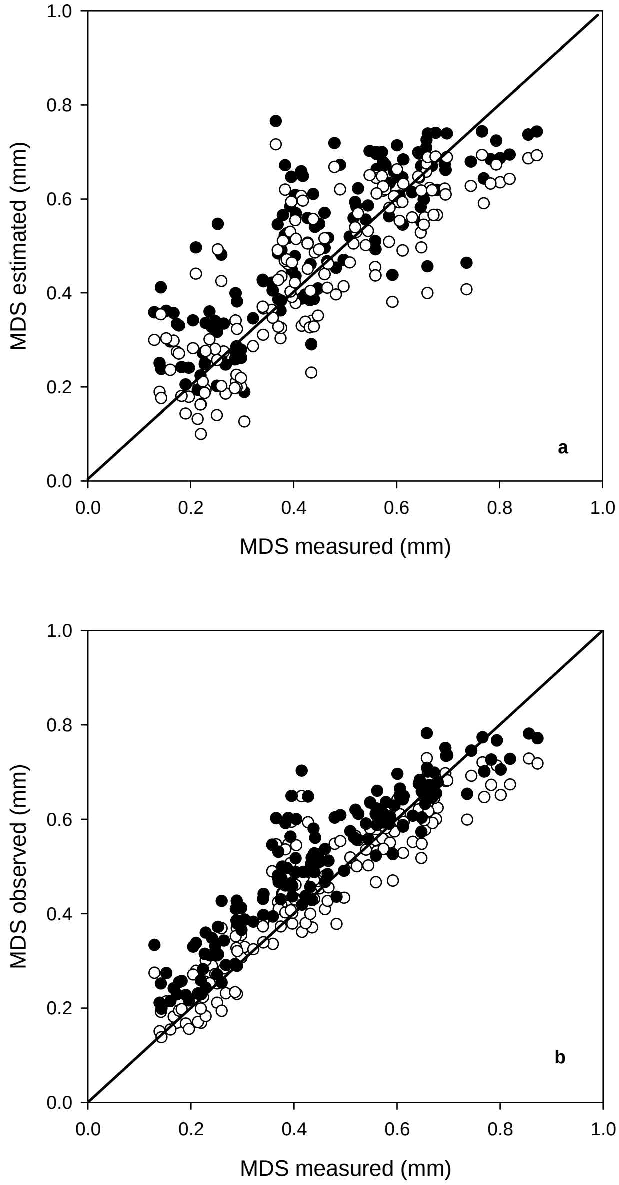
a
MDS (mm)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
Mean daily temperature (ºC)
b
MDS (mm)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
Midday temperature (ºC)

Figure 2



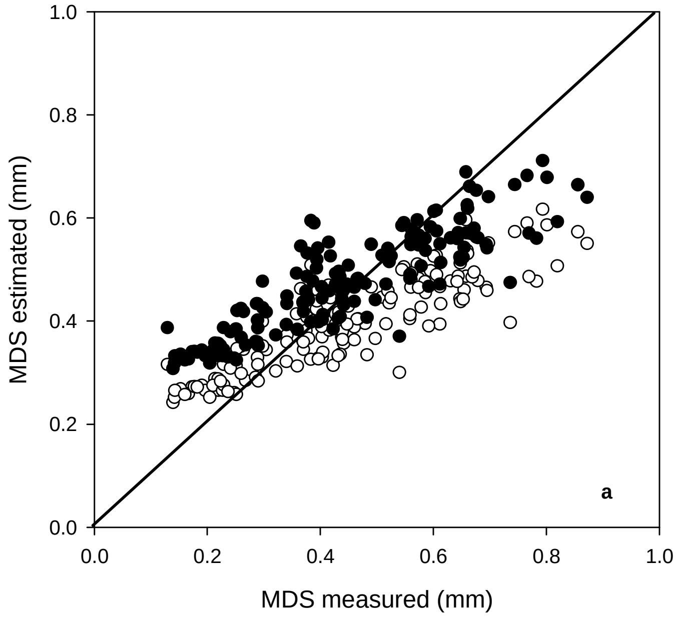
a
MDS (mm)
Mean daily VPD (kPa)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
b
MDS (mm)
Midday VPD (kPa)

Figure 3

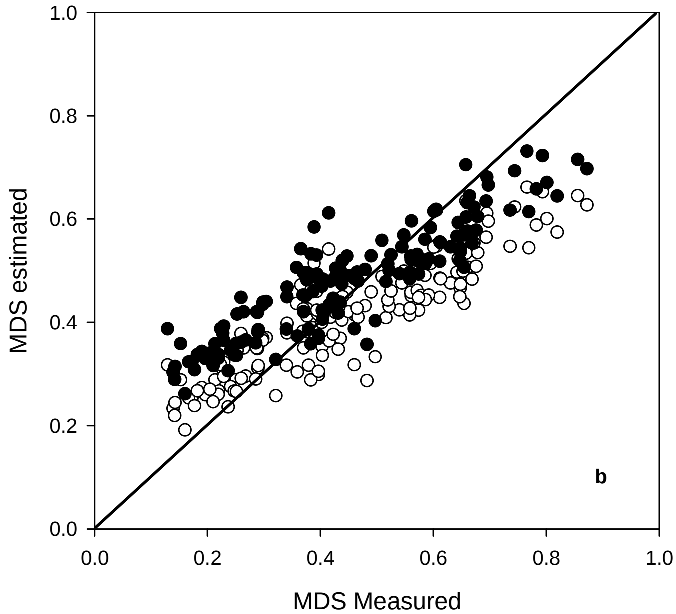


1.0
0.8
0.6
0.4
0.2
0.0
MDS estimated (mm)
a
0.0
0.2
0.4
0.6
0.8
1.0
MDS measured (mm)
1.0
0.8
0.6
0.4
0.2
0.0
MDS observed (mm)
b
0.0
0.2
0.4
0.6
0.8
1.0
MDS measured (mm)

Figure 4



MDS estimated (mm)
MDS measured (mm)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
a



MDS estimated
MDS Measured
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
b