Universidad Politécnica de Cartagena

Departamento de Producción Vegetal

**Programación del riego deficitario
controlado en melocotonero
extratemprano con sensores del
diámetro del tronco**

Carmen Diana Mellisho Salas

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Programación del riego deficitario controlado en melocotonero extratemprano con sensores del diámetro del tronco

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Ingeniera Agrícola

Directores: María Fernanda Ortuño Gallud

Wenceslao Conejero Puente

Memoria presentada para optar al Grado de Doctor
por la Universidad Politécnica de Cartagena

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Regulated deficit irrigation scheduling in early maturing peach trees using trunk diameter sensors

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La presentación de la Tesis Doctoral titulada "Programación del riego deficitario controlado en melocotonero extratemprano con sensores del diámetro del tronco", realizada por D^a. Carmen Diana Mellisho Salas, bajo mi dirección y supervisión, en el Departamento de Riego del Centro de Edafología y Biología Aplicada del Segura, y que presenta para la obtención del grado de Doctor por la Universidad Politécnica de Cartagena.

En Cartagena, a 1 de Septiembre de 2011

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Comisión de Doctorado

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POR LA COMISIÓN ACADÉMICA RESPONSABLE DEL PROGRAMA**

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*Mamata, taytata imaypis kaykayanqa shunquchauwan piqachau.
Turikunata, nanakunata paylla willapaynikikunatawan shuqapaynikikunata.*

*María Fernanda Ortuño Gallud, Wenceslao Conejero Puente, Arturo
Torrecillas Melendreras, Félix Lucas Moreno paylla hatun
yanasakashqantsikta, wayichaunau katsiyamashqikita, qamkunan imaypis
haqiyamarqunkishu.
Llapan rurashqapitan haqikikuna kallaa.*

“Kawaypa hatun qamaqinninga warayni, nuspaynikita rurarkur rikarinki”

Paulo Coelho

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Abstract/Resumen

Abstract

The research reported in this Thesis was carried out i) to review the state of the art as regards the use of trunk diameter fluctuations (TDF) derived parameters for irrigation scheduling, considering the strengths and weaknesses of these continuously measured plant-based water status indicators, their agronomic and physiological significance and the perspectives of the use of maximum daily trunk shrinkage (MDS) as a precision tool in deficit irrigation scheduling, ii) to analyse the interannual variability of the MDS reference equations and the effect of carbon balance on these equations and iii) to evaluate the possibility of scheduling regulated deficit irrigation (RDI) using exclusively MDS measurements.

The review showed that Linear Variable Displacement Transducer (LVDT) sensors are able to measure daily TDF with great precision, generating sensitive parameters which, in general, strongly correlate with established plant water status parameters. Moreover, the ease with which LVDT sensors can be computerised and their remote connection to automatic irrigation control systems is another positive feature of TDF for irrigation management.

The results of research into the selection of suitable TDF-derived indicators to diagnose changes in plant water status are not uniform, pointing to the convenience of using specific indicators not only as a function of tree age but also of plant material. In this sense, in young woody crops under conditions of fast trunk growth, MDS is not always a robust indicator of plant water status, and others indicators as daily maximum and minimum trunk diameter are more reliable. In adult trees, most authors have indicated the convenience of using MDS as a plant water status indicator for irrigation scheduling. However, in some cases such as olive trees and grape vines MDS does not seem a suitable soil

water deficit indicator. Also, some authors have pointed to other factors, in addition to soil water availability and environmental conditions, such as tree age, phenological period or crop load, that may affect MDS values, which leads to the idea that stem diameter variations should be considered not only in the context of the water balance of the plant but also in the carbon balance of the plant. Moreover, it is necessary to look carefully at other related aspects, such as cultivar and rootstock effects on TDF-derived indicators.

In spite of the difficulty involved in interpreting plant water measurements due to the highly dynamic nature of the plant water status, the proposals to use the concept of signal intensity (SI) rather than absolute values for evaluating plant water status, is a turning point in irrigation decision-making development. MDS reference values can be obtained in well irrigated trees located in the same plot or by means of previously obtained reference, base-line equations, by relating the values obtained in plants under non-limiting soil water conditions with climatic variables, mainly those measured on a whole day basis.

The possibility of using RDI strategies, capable of reducing seasonal ET without affecting fruit yield and quality by means of MDS measurements is supported by the fact that continuous deficit irrigation can be reliably scheduled using only MDS measurements, and that by maintaining MDS signal intensities at values close to unity, it is possible to fulfil the crop water requirements.

Measurements of midday stem water potential (Ψ_{stem}) and MDS were taken over a 4-year period in early maturing peach trees (*Prunus persica* (L.) Batsch cv. Flordastar) grafted on GF-677 rootstock. Plants were irrigated daily above their water requirements in order to obtain non-limiting soil water conditions. Seasonal reference equations could be obtained for MDS and Ψ_{stem} using crop reference evapotranspiration (ET_o), daily mean vapour pressure deficit (VPD_m) and mean daily air temperature

(T_m) in the case of MDS, and ET_o and VPD_m in the case of Ψ_{stem} . In this way, VPD_m was seen to be the best predictor of MDS and Ψ_{stem} , without both were influenced significantly by yield or crop load variations between years.

When the postharvest regression between MDS or Ψ_{stem} and the meteorological parameters mentioned were broken down into early and late postharvest periods, the correlation coefficients improved and were closely related to the presence or absence of sugar-demanding sinks, such as active root growth. A negative linear relationship between MDS and Ψ_{stem} was found, pointing to unchanging radial hydraulic conductivity in the bark tissues and suggesting that MDS depends to a great extent of the water potential.

The effects of high crop load (unthinned trees, 22–23 fruits cm^{-2} of trunk cross-sectional area (TCSA)), commercial crop load (3–4 fruits cm^{-2} of TCSA), and no crop load (all fruitlets removed) on MDS, trunk growth rate (TGR) and Ψ_{stem} were studied during the fruit growth period and 20 days following harvest in fully irrigated trees. Even though crop load did not affect plant water status, the MDS and TGR values increased and decreased, respectively, as a result of the crop load effect. In this sense, for the same Ψ_{stem} value, there was a linear increase in MDS with crop load, with a slope of 6.6 mm MPa^{-1} per unit of crop load increment.

The possibility of scheduling regulated deficit irrigation (RDI) using exclusively MDS measurements, and that RDI strategies can be applied in early maturing peach trees reducing significantly the seasonal water use was also tested. During three growing seasons, 6-year-old peach trees were submitted to different drip irrigation treatments. Control (T0) plants were irrigated above the estimated crop evapotranspiration level ($\approx 130\% ET_C$) and T1 plants were submitted to RDI, which were irrigated in order to maintain MDS signal intensity (SI) values close to unity (no irrigation-

related stress) from the fruit thinning stage to 2 weeks after harvest, at MDS SI values close to 1.3 during the early postharvest period, and at MDS SI values of 1.6 during the late postharvest period. The RDI strategy assayed reduced the seasonal water applied by 35–42% with respect to estimated ET_C without affecting yield efficiency components or the distribution of different peach fruit categories, while improving water productivity. The only vegetative growth component affected by RDI was pruning weight, indicating that vigor regulation as a result of RDI may decrease the competition for assimilates between vegetative apices and reserve tissues. Also, the absence of any significant effect of RDI on the ratio between yield and the increase in trunk cross sectional area suggested similar carbon partitioning schemes during fruit growth.

Resumen

Las actividades realizadas en este trabajo de tesis doctoral se centraron en una revisión previa del estado actual de conocimientos respecto a la utilización de los parámetros derivados de las fluctuaciones del diámetro del tronco (FDT) en la programación del riego, atendiendo a las fortalezas y debilidades de estos indicadores del estado hídrico, su significado fisiológico y agronómico, así como a las perspectivas sobre la utilización de la máxima contracción diaria del tronco (MCD) como herramienta de precisión en la programación del riego. Posteriormente, se analizó la variabilidad interanual de las ecuaciones de referencia de la MCD y el efecto sobre ellas del balance de carbono, y finalmente se evaluó la posibilidad de programar el riego deficitario controlado (RDC) utilizando exclusivamente medidas de la MCD.

La revisión bibliográfica corroboró que los transductores de desplazamiento lineal (LVDT) son sensores capaces de medir las FDT con gran exactitud, generando parámetros altamente sensibles que

pueden ser utilizados como precisos indicadores del estado hídrico de las plantas. Además, la posibilidad de recibir en un ordenador las señales de estos sensores vía inalámbrica, así como la de enviar a un controlador de riego ordenes sobre apertura y cierre de válvulas, constituye otro aspecto altamente interesante de las FDT en el manejo del riego.

Algunos autores indican que la edad del árbol e incluso el propio material vegetal condicionan qué parámetro derivado de las FDT es más adecuado para diagnosticar el estado hídrico. En este sentido, parece ser que cuando un árbol joven se encuentra en crecimiento activo, los valores del máximo o el mínimo diámetro del tronco resultan más sensibles que la MCD. Por otra parte, parece ser que en vid y olivo los valores de la MCD no reflejan de forma adecuada el estado hídrico del cultivo. Algunos artículos indican que además de la disponibilidad de agua en el suelo y las condiciones ambientales, hay otros factores, tales como la edad del árbol, el periodo fenológico o la carga productiva que pueden afectar a los valores de la MCD, por lo que cabe pensar que las variaciones diarias del diámetro del tronco también deben considerarse en el contexto del balance de carbono. Complementariamente, habría que dilucidar los posibles efectos del cultivar y el portainjerto sobre las FDT.

La utilización del concepto de intensidad de señal (IS) de un indicador del estado hídrico, en vez de sus valores absolutos, ha supuesto un claro punto de inflexión en los trabajos sobre programación del riego con medidas de la MCD. Los valores de referencia, bajo condiciones no limitantes de agua en el suelo, de la MCD pueden estimarse en árboles bien regados en la misma parcela o mediante el uso de ecuaciones, previamente elaboradas, en las que las variables climáticas, principalmente las de base diaria, actúan como variable independiente.

El hecho de que existiesen antecedentes de la posibilidad de programar el riego tanto cubriendo las necesidades hídricas del cultivo como de forma deficitaria, utilizando exclusivamente medidas de la MCD,

hacía albergar la posibilidad de desarrollar estrategias de RDC capaces de reducir la ET estacional sin afectar la producción, ni la calidad de la cosecha.

Durante 4 años, melocotoneros extratempranos (*Prunus persica* (L.) Batsch cv. Flordastar) sobre portainjerto GF-677, se regaron a fin de asegurar condiciones no limitantes de agua en el suelo. Los resultados mostraron la posibilidad de obtener ecuaciones de referencia estacionales de la MCD utilizando como variables independientes la evapotranspiración del cultivo de referencia (ET_o), el déficit de presión de vapor medio diario (VPD_m) o la temperatura media diaria (T_m), y del Ψ_{stem} utilizando la ET_o o el VPD_m . En este sentido, el VPD_m fue la variable que mejor predijo los valores de MCD y Ψ_{stem} , los cuales no resultaron afectados por la alternancia productiva del cultivo.

Cuando las regresiones obtenidas para el periodo posterior a la cosecha se subdividieron en dos periodos, los coeficientes de correlación mejoraron, demostrando un claro efecto de la presencia o ausencia de sumideros de azúcares, tales como el crecimiento activo de raíces. Los valores de la MCD y el Ψ_{stem} mostraron una estrecha relación, indicando una constancia de la conductividad hidráulica radial de los tejidos de la corteza y sugiriendo que los valores de la MCD dependen en buena medida del potencial hídrico.

Por otra parte, se estudió el efecto de una alta carga productiva (árboles sin aclareo de frutos, 22–23 frutos/cm² de sección del tronco (TCSA)), carga productiva comercial (3–4 frutos/cm² de TCSA), y la ausencia de carga (eliminación de todos los frutos) sobre la MCD, la tasa de crecimiento del tronco (TCR) y el Ψ_{stem} . Si bien la carga productiva no condicionó el estado hídrico, los valores de la MCD y TCR aumentaron y disminuyeron, respectivamente, por efecto de la carga. En este sentido, para un mismo valor de Ψ_{stem} se observó un aumento lineal de la MCD en

función de la carga, con una pendiente de 6.6 mm MPa^{-1} por un aumento de una unidad de carga.

Con el objetivo de verificar si el RDC podía programarse exclusivamente con medidas de la MCD, durante tres años, se estudió la respuesta de melocotoneros adultos a dos tratamientos de riego. Las plantas control (T0) se regaron por encima de los niveles de la evapotranspiración del cultivo ($\approx 130\% \text{ ET}_C$), y las plantas del tratamiento T1 (RDC) se regaron a fin de mantener la IS de la MCD en valores muy cercanos a la unidad desde el aclareo de frutos hasta dos semanas después de la recolección, a valores cercanos a 1.3 hasta mediados de Julio, y a valores de 1.6 hasta la caída de hojas.

El tratamiento de RDC supuso un claro aumento de la productividad del agua, ya que redujo el riego un 35–42% respecto de la ET_C , sin afectar la producción, ni el calibre de los frutos. El único componente del crecimiento vegetativo que resultó afectado por el RDC fue el peso de la poda, por lo que esta disminución del vigor pudo redundar en una menor competición por los asimilados entre los ápices en crecimiento y los frutos. La ausencia de efecto significativo del RDC sobre la relación entre producción y aumento de la sección del tronco sugiere un similar esquema de reparto de carbono durante el crecimiento del fruto.

Objectives

The rise in population across the world, and particularly in developing countries, means that there is a need to increase food production. In this sense, it should be noted that irrigated agriculture, which represents only 17% of arable land, produces 34% of the world's food total. The situation is considerably more notable in areas currently undergoing development, for example, the Middle East, where 75% of the food corresponds to only 30% of irrigated agriculture.

However, water is not only essential for food production; it is also needed to preserve the environment, for use by industries, urban and recreational areas, and, most importantly, for human use. It is this last sector which faces a dramatic situation in some parts of the world where, despite the progress made in recent years, there are still 884 million people who lack clean drinking water and 2600 million people who cannot access sanitation. Furthermore, it must be added that in the not too distant future, as a consequence of climate change, there will be an increase in potential evapotranspiration with an expected increase in water deficit situations and, consequently, in the demand for water resources (Houghton et al., 1995).

Therefore, water management is an issue of vital importance, where short and long-term solutions need to be addressed, assuring the protection and integrity of water resources (Katerji et al., 2008), due to the fact that most of the agrosystems dedicated to food production have to or will have to face the need to coexist with a limited or even a highly reduced availability of water resources in the medium term, thus needing to maintain optimal productivity with minimal environmental impacts. In this sense, it is of the greatest importance to save water through an optimal determination of crop water requirements by using new and innovative physical and biological criteria (Katerji, 1997), which generate innovative and concise irrigation management practices (Goldhamer and Fereres, 2001; Naor, 2006; Katerji et al., 2008).

In recent years, studies on irrigation management which use criteria based on knowledge of crop water status have become increasingly important. This idea derived from the fact that the plant itself is the best indicator of its water status, due to integrating the effects of not only soil water supply, but also of climatic conditions (Jones, 2004). In contrast, the traditional measurements of soil moisture for irrigation scheduling require adequate knowledge of the distribution and relative density of roots, which becomes considerably more complex when soil moisture varies in three dimensions, as in drip irrigation. Also, the uncertainties related to calculating crop evapotranspiration (ET_c) (Allen et al., 1998) are significant due to the effects of tree canopy architecture, the degree of soil canopy cover and soil surface management.

The use of trunk diameter sensors, which are able to accurately report on their fluctuations throughout the day, has opened up the possibility of proposing several parameters, for example, maximum daily trunk shrinkage (MDS), which are directly related to crop water status, and which have allowed for better management of irrigation scheduling (Goldhamer and Fereres, 2004; Conejero et al., 2007; García-Orellana et al., 2007; Vélez et al., 2007; Ortuño et al., 2009a,c).

The magnitude of MDS, even under non-limiting soil water conditions, varies depending on other factors, essentially evaporative demand (Zweifel and Häslar, 2001). Hence, the use of absolute values for plant-based water status indicators (Bussi et al., 1999) may be confusing, and so a more suitable approach would be to use normalized values with respect to those corresponding in non-limiting soil water conditions, and which have come to be called signal intensity (IS).

In order to obtain plant-based water status indicator reference values, measurements on plants in non-limiting soil water conditions are performed (Conejero et al., 2007; García-Orellana et al., 2007). The result is that there is a risk of inducing flood problems and changes in water

relations in the same way as drought stress, thus increasing MDS values (Ortuño et al. 2007), which adds uncertainty to irrigation scheduling. For these reasons, there is greater interest in the development of MDS baseline or reference equations obtained through relations of this indicator under non-limiting soil water conditions with climatic variables (Fereres and Goldhamer, 2003; Moreno et al., 2006; Ortuño et al., 2006, 2009b), determined, in addition, by factors such as carbon balance on these equations.

Moreover, in relation to water management, it should be noted that there are contrasting results based on the possibility of continuous deficit irrigation scheduling in woody crops using exclusively MDS data (Goldhamer and Fereres, 2004; García-Orellana et al., 2007; Vélez et al., 2007; Ortuño et al., 2009c). However, there is no information in the bibliography on scheduling regulated deficit irrigation (RDI) with trunk diameter sensors. In this sense, a precise control and the real-time of crop water status may be crucial in RDI scheduling to avoid a moderate level of drought stress from becoming too severe, thus affecting fruit yield and quality (Domingo et al., 1996; Johnson et al., 1992).

For all of the above reasons, the objectives of this study were i) to review the state of the art as regards the use of trunk diameter fluctuations (TDF) derived parameters for irrigation scheduling in woody crops, ii) to study the interannual variability of the MDS reference equations, iii) to assess the effect of crop load on these equations, and iv) to evaluate the possibility of scheduling regulated deficit irrigation (RDI) using exclusively MDS measurements, thus saving considerable water without affecting fruit yield and quality.

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Chapter 1:

Could trunk diameter sensors be used in woody crops for irrigation scheduling? A review of current knowledge and future perspectives

Abstract

The use of trunk diameter fluctuations and their derived parameters for irrigation scheduling in woody crops is reviewed. The strengths and weaknesses of these continuously measured plant-based water stress indicators compared with other discretely measured indicators for diagnosing plant water status in young and mature trees are discussed. Aspects such as sensor reading variability, signal intensity and the relationship between trunk diameter fluctuations and plant water status are analyzed in order to assess their usefulness as water stress indicators. The physiological significance of maximum and minimum daily trunk diameter and maximum daily trunk shrinkage (MDS) are also considered. Current knowledge of irrigation protocols and baselines for obtaining maximum daily trunk shrinkage reference values is discussed and new research objectives are proposed. We analyze the response of woody crops to continuous deficit irrigation scheduled by maintaining MDS signal intensity at threshold values to generate mild, moderate and severe water stress and assess the possibility of using linear variable displacement transducer (LVDT) sensors in trunk as a precision tool for regulated deficit irrigation scheduling. Finally, the possibility of using MDS signal intensity as a tool to match the irrigation regime to tree water requirements is also reviewed.

Key words: Deficit irrigation, Maximum daily trunk shrinkage, Irrigation requirements, Plant water relations, Sensors, Stem water potential, Trunk growth rate.

1. Introduction

The aridity of the climate and the scarcity of water resources is a historical and recurring characteristic in southern Europe. The impacts of water scarcity are likely to be exacerbated in the future, with predicted

increases in the frequency and severity of droughts, driven by climate change (Houghton et al., 1995; Collins et al., 2009). The major challenge represented by water scarcity and droughts has been recognised in a communication from the European Commission (2007), which estimated that at least 11% of Europe's population and 17% of its territory had been affected by water scarcity to date of publication and put the cost of drought in Europe over the past thirty years at EUR 100 billion.

Agrosystems, which are the main consumers of fresh water in the Mediterranean region, currently face the challenge of developing new approaches to water management that will insure the protection of water resources and their integrity for their future use (Katerji et al., 2008). Among the strategies that can be applied to attain this objective is, first and foremost, the saving of water through the improved determination of crop water requirements and the development of biological and physical criteria that lead to improved, innovative and precise irrigation management practices (Katerji, 1997; Goldhamer and Fereres, 2001; Naor, 2006; Katerji et al., 2008).

Irrigation scheduling based on soil water measurements requires good knowledge of root distribution and relative density, with the limitation that uncertainty increases when the wetted soil volume varies in three dimensions, as it does in trickle irrigation. For irrigation scheduling procedures involving high-frequency irrigation systems, information about crop evapotranspiration (ET_C) is required (Allen et al., 1998). Here, too, uncertainties abound due to the effects of tree canopy architecture, the degree of soil canopy cover and soil surface management. Also, the estimation of ET_C in young tree plantations, where it is necessary to use empirical factors or reduction coefficients or where there are actively growing weeds, involves uncertainty when irrigation scheduling is based on this parameter. In addition, there are still some woody crops of increasing interest in the Mediterranean region, such as loquat (*Eryobotria japonica*

(Thunb.) Lindl), pomegranate (*Punica granatum* L.) and persimmon (*Diospyros kaki* L. f.), whose water needs have not been determined and hence it is currently not possible to schedule irrigation properly.

For these reasons, the use of plant-based water status indicators has become very popular in recent years for studying plant-water relations and for planning more precise irrigation programmes, because it is recognized that the tree itself is the best indicator of its water status. Since the plant water status controls many physiological processes and crop productivity, this information can be highly useful in irrigation scheduling (Goldhamer and Fereres, 2001; Goldhamer et al., 2003). Particularly under deficit irrigation conditions, the continuous control of tree water status is crucial in order to prevent a moderate, potentially beneficial, water stress from becoming too severe and ending in a reduction of the yield (Domingo et al., 1996; Johnson and Handley, 2000).

There is no agreement as to who first discovered that trees undergo daily trunk shrinkage and swelling (Goldhamer et al., 2000). However, it has long been known that plant growth is one of the most sensitive indicators of water stress. Early on it was demonstrated that trends in trunk growth over weeks were indicative of the adequacy of irrigation (Hendrickson and Veihmeyer, 1941). Subsequently, the appearance of electronic devices permitted accurate measurements of daily trunk diameter fluctuations (TDF) (Kozlowski, 1967), which related the changes in trunk diameter with transpiration (Klepper et al., 1971; Molz and Klepper, 1972). This led to the proposal to use dendrometers for continuous monitoring of plant water status (Huck and Klepper, 1976), which is useful in irrigation decision-making (Huguet, 1985; Goldhamer and Fereres, 2001).

The aim of this review is to present the state of the art as regards the use of TDF-derived parameters for irrigation scheduling, especially in woody crops and including ornamental plantations. The following aspects

were considered: i) the strengths and weaknesses of these continuously measured plant-based water status indicators, ii) their agronomic and physiological significance, iii) the possibility of obtaining baselines or reference equations, iv) the crop response to irrigation scheduled according to plant-based water status indicator measurements, and v) the perspectives of the use of maximum daily trunk shrinkage (MDS) as a precision tool in full irrigation regimes and regulated deficit irrigation scheduling.

2. List of abbreviations for terms, definition and units

- CV** Coefficient of Variation. It is the ratio of the standard deviation (σ) to the mean (μ) (dimensionless number).
- ET_c** Crop evapotranspiration. It is the evapotranspiration from disease-free, well fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions (mmd^{-1}).
- LVDT** Linear Variable Displacement Transducer. It is the sensor that transducers the movement of the trunk/stem in electrical signal. The trunk moves an electromagnetic rib that is between two electrical circuits, one charge with continuous power and other which is off. The movement of the rib produces and induced electrical power that is linearly related with the displacement.
- MDS** Maximum Daily Trunk Shrinkage. The difference between the maximum daily trunk diameter value (just before sunrise) and the minimum daily trunk diameter value (sometime during the

afternoon) (mm or μm).

MNTD Minimum Daily Trunk Diameter. The minimum value of daily trunk diameter, which is reached sometime during the afternoon (mm or μm).

MXTD Maximum Daily Trunk Diameter. The maximum value of daily trunk diameter, which is reached just before sunrise (mm or μm).

REDI Regulated Deficit Irrigation. Deficit irrigation strategy in which irrigation water amounts are reduced during phenological periods non critical for yield or fruit quality.

SF Sap Flow. Estimation of the transpiration flow in a plant (l s^{-1} or l d^{-1}).

SI Signal Intensity. It is used to avoid the effect of meteorological conditions on a plant based water status indicator. It is calculated normalizing their values with respect to values under non-limiting soil water conditions (actual value/reference value) (dimensionless number).

TDF Trunk Diameter Fluctuations. The daily cycle of swelling and shrinking of the trunk/stem.

TGR Trunk Growth Rate. The difference between two consecutive maximum daily trunk diameters (mm or μm).

T_m Mean daily air temperature ($^{\circ}\text{C}$).

T_{md} Midday air temperature ($^{\circ}\text{C}$).

VPD Air Vapor Pressure Deficit. The difference between the amount of moisture in the air and how much moisture the air

can hold when it is saturated (kPa).

VPD_m Mean air vapour pressure deficit (kPa).

VPD_{md} Midday air vapour pressure deficit (kPa)

Ψ_m Soil matric potential. It is the portion of the water potential that can be attributed to the attraction of the soil matrix for water (kPa).

Ψ_{stem} Midday stem water potential. The water potential measured with a pressure chamber at midday in a leaf or shoot enclosed in plastic bag covered with aluminium foil for at least 2 h before measurements (MPa).

3. TDF-derived parameters as plant water status indicators

Coinciding with improvements in the robustness of the sensors used to measure TDF, there has been renewed interest in using their derived parameters as plant water status indicators, since this technique might provide for a real time automated registers of the plant water status. This implies fewer trips to the field and a significant saving of manpower compared with discretely measured plant-based indicators. Moreover, another advantage of using continuously measured TDF-derived parameters is the possibility of using them for fully automating irrigation scheduling. This could be achieved by means of suitable software that should be able to analyze sensor signals and to calculate the derived indices. In addition, this tool must also be capable of operating the irrigation controller devices.

Micrometric TDF measurements are generally performed using LVDT sensors attached to the trunk by a special bracket made of Invar

(Pictures 1A and 1B), an alloy with a thermal expansion coefficient close to zero, and aluminium (Katerji et al., 1994; Zweifel et al., 2000). The linear variable differential transducer is a sensor that converts a linear displacement or position from a mechanical reference (or zero) into a proportional electrical signal containing phase (for direction) and amplitude information (for distance). Brackets can be made to measure TDF of very different trunk sizes, from small stem typical of herbaceous crops (Gallardo et al., 2006a and 2006b) up to very large trunk size as in mature olive trees (Moreno et al., 2006). In addition TDF measurements can be also performed with a strain gauge type of sensor (Picture 1C) (Kirkham, 2005), a device whose electrical resistance varies in proportion to the amount of strain in the sensor.

The linear variable differential transducer, despite being a robust type of sensor, requires maintenance during field applications, particularly in case of fast trunk growing plants, or due to obstructions of the cavity where the needle moves inside the transformer. In addition needles attached to the trunk can get detached from the trunk, particularly in case of heavy rain events.

The TDF measurements reflect the combination of four components: irreversible radial growth, reversible living-cell dehydration/rehydration, thermal expansion and contraction, and expansion of dead conducting elements due to the increase and relaxation of internal tensions (Daudet et al., 2005). The daily TDF cycle provides three different common indices; maximum daily trunk diameter (MXTD), minimum daily trunk diameter (MNTD) and maximum daily trunk shrinkage (MDS), the last calculated as the difference between MXTD and MNTD (Figure 1). Trunk growth rate (TGR) can be calculated taking into account values of MXTD on two consecutive days (Figure 1) or over longer periods of time in order to reduce the day-to-day trunk growth variability.

Picture 1. Photographs of different devices for measuring trunk diameter fluctuations in trunks. LVDT sensor attached to a citrus tree (A), LVDT sensor attached to a grapevine (B), Strain gauge installed in a citrus tree (C) (Photograph courtesy of Dr. F. Intrigliolo, ACIREALE, Italy).

The daily values of MXTD and MNTD are reached just before sunrise and sometime during the afternoon, respectively. This pattern reflects the combined effects of soil water supply and evaporative demand on maximum shrinkage and the rehydration process, which depends primarily on soil water supply and may be only indirectly affected by the previous day's evaporative demand (Goldhamer and Fereres, 2001). In this

sense, Zweifel et al. (2000) concluded that, in addition to soil water availability and plant transpiration, the degree to which plant storage tissues were saturated was also a factor that affected the diurnal course of stem radius changes, because stored water plays an important role not only during periods of drought, but whenever water transport occurs within the tree. Daudet et al. (2005) indicated that the daily variations in plant stem diameter, which are related to the difference in total water potential between living bark cells and xylem vessels, and structural radial growth are the two main components of the observed daily variations of stem diameter and that carbon and water limitations can occur concurrently in the process of radial growth.

Figure 1. Indices provided by daily trunk diameter fluctuations: maximum (MXTD) and minimum (MNTD) daily trunk diameter, maximum daily trunk shrinkage (MDS) and trunk growth rate (TGR). Data shown correspond to two days of different evaporative demand (ET_o) in well watered and deficit irrigated plum trees.

According to the results obtained by Simonneau et al. (1993) in peach trees (*Prunus persica* (L.) Batsch), the changes in stem diameter

are closely related to changes in water content in the whole plant. MDS values are considered a good indicator of transpiration intensity when the soil water content is not strongly depleted (Huguet et al., 1992; Herzog et al., 1995; Ortuño et al., 2004b, 2005, 2006a). MDS values usually increase (Figure 2) and MXTD and MNTD values decrease in response to soil water deprivation (Klepper et al., 1971).

al., 2006a; Intrigliolo and Castel, 2007a; A. Pérez-Pastor, unpublished data) (Figure 3). Moreover, Ginestar (1995) and Ortuño et al. (2004b) found predawn and midday leaf water potential threshold values of -1.0 and -2.5 MPa, respectively, for young citrus plants. Also, other authors found predawn and midday leaf water potential threshold values of -0.74 and -2.5 MPa in potted apple trees (*Pyrus malus* L.) (Doltra, 2003) and -1.1 and -2.0 MPa in peach trees (Cohen et al., 2001). The change in MDS behaviour may be attributed to several factors: (i) the end of water recruitment from the bark, including phloem and cambium, when the water stored in the trunk is reduced (Garnier and Berger, 1986; Huguet et al., 1992; Remorini and Massai, 2003), (ii) the increase in the transversal resistance to the water movement from bark to xylem (Huck and Klepper, 1976), and (iii) the reduction in stomatal conductance and, therefore, transpiration (Hinckley and Bruckerhoff, 1975).

However, as shown in Figure 1, the magnitude of stem contraction even in a well watered tree is not constant over a period of days with different environmental conditions (Zweifel and Häsler, 2001). Hence the absolute MDS values registered without considering the evaporative demand might be meaningless. For instance the same MDS value could predict well watered conditions during a day of high evaporative demand, but might well suggest a tree that is water stressed if the evaporative demand is low (Figure 1). For this reason, for irrigation scheduling it is better to use the concept of *signal intensity* (SI), normalizing the absolute values with respect to values in non-limiting soil water conditions (Goldhamer and Fereres, 2001; Naor and Cohen, 2003; Ortuño et al., 2005, 2006a). This MDS SI, is a similar concept to what is commonly done for computing the crop water stress index from canopy temperature measurements, where a well watered control is often needed (Kirkham, 2005). MDS SI is a dimensionless variable, where values above unity indicate water stress levels, while SI values of unity indicate the absence of irrigation-related stress (Goldhamer and Fereres, 2004). In addition, SI

values clearly below unity could be used to predict the presence of trees suffering very severe water stress, because MDS values could have decreased as a consequence of Ψ_{stem} values falling below their threshold value (Figure 4). Also, an increase in MDS in reference trees as a consequence of flooding stress may induce a decrease in SI values.

Figure 3. Relationship between maximum daily trunk shrinkage (MDS) and midday stem water potential (Ψ_{stem}) in olive (green circles, $\text{MDS} = -0.53 - 1.78\Psi_{\text{stem}} - 0.79\Psi_{\text{stem}}^2 - 0.10\Psi_{\text{stem}}^3$, $r^2 = 0.54$), lemon (yellow circles, $\text{MDS} = -0.24 - 0.77\Psi_{\text{stem}} - 0.22\Psi_{\text{stem}}^2$, $r^2 = 0.43$), Fortune mandarin (red triangles, $\text{MDS} = -0.33 - 0.87\Psi_{\text{stem}} - 0.29\Psi_{\text{stem}}^2$, $r^2 = 0.75$) trees and grapevines (sky-blue squares, $\text{MDS} = -0.16 - 0.83\Psi_{\text{stem}} - 0.48\Psi_{\text{stem}}^2$, $r^2 = 0.51$). Moriana et al. (2000), Ortuño et al. (2006a), A. Pérez-Pastor (unpublished data), Intrigliolo and Castel (2007b).

The wide tree-to-tree variability in TDF-derived parameters regardless of the irrigation programme is well documented (Kozłowski, 1967; Ginestar and Castel, 1996; Naor, 2000; Naor et al., 2006). Consequently, for measurements to be accurate, it would be necessary to measure TDF in many trees within an orchard, increasing the measurement costs in the process (Naor et al., 2006). To assess the usefulness of plant-based water stress indicators for irrigation scheduling, it

is important to characterize the *signal:noise* ratio, defining *noise* as the coefficient of variation of the mean (CV). Therefore, the uncertainty associated with a high noise value may not be as crucial when the signal strength is sufficient (Goldhamer and Fereres, 2001).

For example, in Table 1 the behaviour of two continuously recorded plant-based indicators, sap flow (SF) (Picture 2) and MDS, is compared with a discretely measured plant-based indicator (Ψ_{stem}) in response to a period of soil water stress (June 20 to July 9, 2008) in 6 year-old peach trees, which presented a mean ground cover and trunk cross-sectional area of about 79% and 157 cm², respectively. The SF average noise value (CV) was higher than those of the MDS and Ψ_{stem} , which were similar, whereas the mean MDS signal value was higher than that of SF and similar to that of Ψ_{stem} . The MDS signal:noise ratio was the highest, indicating that MDS was more sensitive than the other indicators in detecting plant water stress.

Table 1. Maximum daily trunk shrinkage (MDS), sap flow (SF) and stem water potential (Ψ_{stem}) mean signal intensity, mean noise and signal/noise ratio values in peach trees during 9 days when irrigation was withheld. Means within the two first columns that do not have a common letter are significantly different according to the LSD_{0.05} range test.

Indicator	Mean signal	Mean noise	Signal/noise
MDS	1.15a	0.067a	17.2
SF	1.07b	0.123b	8.7
Ψ_{stem}	1.10ab	0.090a	12.2

The selection of a TDF-derived indicator to be used in irrigation scheduling is particularly important. The most common indicator of the TDF-parameters is the MDS, which, under high trunk growth, presents very low values and is of no use as a water stress indicator (Goldhamer and Fereres, 2001). Also, MXTD and MNTD have a cumulative nature, their values being strongly related with the initial value or the previous history of the trees. TGR has been proposed as water stress indicator because a

decrease in trunk growth is one of the earliest responses in plant water stress, particularly in young trees (Ginestar and Castel, 1996; Moriana and Fereres, 2002; Nortes et al., 2005). Also, in young plantations, maximizing tree growth is normally the agronomic objective, and so a continuous measurement of trunk growth can provide an indication of tree performance in real-time. However, other factors such as phenological stage, crop load (Berman and DeJong, 2003; Moriana and Fereres, 2004) and tree age (Intrigliolo and Castel, 2005) can affect trunk growth, independently of water status, indicating that TGR does not provide an independent measure of plant water status (Intrigliolo and Castel, 2007b; Egea et al., 2009).

Picture 2. Sap flow sensor attached to a lemon tree (A) and a peach tree (B).

As indicated above, Goldhamer and Fereres (2001) showed that MDS is not an accurate indicator for irrigation scheduling in conditions of fast trunk growth. Other authors, too, compared the behaviour of MDS, MNTD and MXTD in response to water stress. For example, Goldhamer et al. (1999) reported that in peaches MDS, MNTD and MXTD were more sensitive than stem and leaf water potentials, and showed that MNTD was the earliest indicator for detecting the beginning of water deficit, whereas

MDS more adequately reflected the magnitude of the water stress. In young citrus trees, Ortuño et al. (2004b) showed that the sensitivity of TDF-derived indicators varied as a function of the trunk growth rate: when trunk growth was very low, MDS was the best indicator, while MNTD and MXTD were the most reliable indicators when trunk growth was faster. Moreover, Ortuño et al. (2005) indicated that MDS and MNTD are more sensitive indicators than SF measurements for detecting water stress in young citrus trees. Also, Remorini and Massai (2003) indicated that in peach trees TDF-derived parameters are more sensitive indicators than SF and Ψ_{stem} in detecting water stress.

In contrast, in young olive trees, Moriana and Fereres (2002) showed that MDS values were not able to detect the water stress conditions and that MXTD was more sensitive than Ψ_{stem} for detecting the beginning of stress in a water deprivation cycle. Also, Intrigliolo and Castel (2006a), Nortes (2008) and Doltra et al. (2007) showed that in plum trees (*Prunus salicina* L.), almond trees (*Prunus dulcis* (Mill.) Webb) and apple trees, respectively, Ψ_{stem} is more sensitive to water deficit than TDF-derived parameters. All these aspects indicate that, in addition to tree age, the species or the degree of soil water deficit may also be factors that must be taken into consideration when selecting a water stress indicator for irrigation scheduling.

Even though the sensitivity of a plant-based water status indicator is very important for detecting the occurrence of a water deficit situation, high sensitivity in the indicator is also necessary for detecting the plant's recovery from water stress. In this sense, according to Ortuño et al. (2004a,b, 2006a), SF and MDS measurements are very sensitive detectors of water stress, although, the response of SF to water stress recovery is slower due to the 'refilling' of plant capacitances (plant water storage) (Alarcón et al., 2005; Ortuño et al., 2005).

Figure 4. Maximum daily trunk shrinkage (MDS) in control (dark circles) and flooded (red circles) young lemon trees. Vertical dotted lines indicate the beginning and the end of a flooding period. Asterisks indicate significant differences between treatments. Ortuño et al. (2007).

Some authors have suggested that trunk growth is also affected by pest and pathogens (Cohen et al., 1997), fertilizers (Brun and Tournier, 1992) and other stresses (Zweifel and Häslar, 2000; Cohen et al., 2001; Fujita et al., 2003). In this sense, Vanniere (1992) and Ortuño et al. (2007) showed that heavy rainfall can induce transient soil flooding conditions and that the responses to flooding of continuously (MDS and SF) and discretely measured plant-based water status indicators are very similar to those observed in response to drought stress (Figure 4). In contrast, in some species, after heavy rainfall, some authors observed that the trunk diameter expansion phase lasted more than one day (34 - 40 h), leading to the absence of trunk contraction or very low trunk contraction (Deslauriers et al., 2007). The same behaviour has been observed in plane trees (*Platanus x hispanica* Mill. ex Muenchh) (C. Biel, unpublished data). For this reason, for automatic irrigation scheduling purposes, it is advisable to

incorporate to the irrigation automatic device information about rainfall and/or soil water status into discriminate between the causes of modification in plant-based water status indicator values.

4. Reference equations

Because plants are in the middle of the soil-plant-atmosphere continuum, any measurement of plant water status, if taken during sunlight hours, will depend not only on the soil water status but also on the environmental conditions. Hence, before plant-based water stress indicators can be used for irrigation scheduling, a reference value must be obtained in plants under non-limiting soil water conditions. One option could be to previously define the effects of the evaporative demand on the plant water status indicator and later to use this relationship or “baseline” as a reference (Table 2) to correct the actual MDS values obtained.

In this sense, Ortuño et al. (2006b), Pagán et al. (2008) and Ortuño et al. (2009b) showed that it was possible to predict MDS reference values in citrus trees when meteorological variables measured on a whole-day basis were used, and suggested that the best predictor of MDS was mean daily air temperature (T_m). Also, Moreno et al. (2006) showed that the MDS in olive trees reflected changes in the evaporative demand variables, even though the MDS behaviour was best correlated with midday vapour pressure deficit (VPD_{md}) and air temperature (T_{md}). Although temperature is not an accurate indicator of the evaporative demand of the atmosphere (Hatfield and Fuchs, 1990), it should be borne in mind that mean daily air temperature is the easiest and cheapest meteorological variable to measure. Moreover, Velez (2004) indicated that MDS in *Citrus clementina* trees was more directly associated with changes in solar radiation and reference evapotranspiration than vapour pressure deficit and air temperature. Egea et al. (2009) reported that VPD_{mx} (VPD averaged during

the period 10.00–15.00 h solar time) was the best predictor of MDS in almond trees. Also, these authors showed that the relationship obtained during early stages (II-III), corresponding to rapid fruit and embryo growth and grand period of shoot growth, did not statistically differ from that for the whole season and could be used for the rest of the year.

As above indicated, Moreno et al (2006) suggested two reference equations for canning olive trees, one related with VPD_{md} ($MDS (mm) = -0.07 + 0.13 \cdot VPD_{md} (kPa), r^2 = 0.83$) and the other one with T_{md} ($MDS (mm) = -0.78 + 0.04 \cdot T_{md} (°C), r^2 = 0.79$) (Table 2). Then, for a specific day in which midday air temperature reaches 30°C, MDS reference value under non-limiting soil water conditions can be easily estimated using the second equation ($MDS (mm) = -0.78 + 0.04 \cdot 30 = 0.42$).

Some findings have shown that other factors can also affect MDS independently of environmental conditions, such as tree age (Moriana and Fereres, 2004), tree size (Intrigliolo and Castel, 2006b), the phenological period (Marsal et al., 2002; Fereres and Goldhamer, 2003; Intrigliolo and Castel, 2004; Moriana and Fereres, 2004; Conejero et al., 2007a) and crop load in olive and plum trees (Moriana and Fereres, 2004; Intrigliolo and Castel, 2007a), but not in citrus (Ortuño et al., 2009b) (Table 2).

Table 2. List of best fit reference equations for maximum daily trunk shrinkage (MDS) in function of selected environmental variables for several woody crops (ET_o , daily crop reference evapotranspiration; R_d , global radiation; T_m , daily mean air temperature; T_{md} , daily midday air temperature; VPD_m , daily mean air vapour pressure deficit; VPD_{md} , daily midday air vapour pressure deficit; VPD_{mx} , daily mean during 10 – 15 h (solar time) air vapour pressure deficit).

Tree species	Tree age	Phenological period	Reference equation	r^2	Source
Almond (<i>Prunus dulcis</i>) cv Fritz	Young	April-May	$MDS = 0.01 + 0.07 VPD_m$	0.77	Goldhamer and Federes (2004)
Almond (<i>Prunus dulcis</i>) cv Marta	Young	Season	$MDS = 0.16 VPD_{mx}$	0.80	Egea et al. (In press)
		Phenological stages II-III	$MDS = 0.17 VPD_{mx}$	0.78	
		Phenological stages IV	$MDS = 0.17 VPD_{mx}$	0.74	
		Phenological stages V	$MDS = 0.14 VPD_{mx}$	0.68	
Almond (<i>Prunus dulcis</i>) cv Price	Young	June-November	$MDS = -0.02 + 0.05 VPD_m$	0.64	Feres and Goldhamer (2003)
			$MDS = -0.11 + 0.01 T_m$	0.59	
Apple (<i>Malus communis</i>) cv Golden Delicious	Young	Season	$MDS = 0.03 + 0.07 ET_o$	0.79	C. Biel (unpublished data)
Lemon (<i>Citrus limon</i>) cv Fino	Adult	Season	$MDS = -0.04 + 0.01 T_m$	0.77	Ortuño et al. (2009b)
Mandarin (<i>Citrus clementina</i>) cv Clementina de Nules	Adult	Season	$MDS = 0.11 + 0.01 R_d$	0.52	Velez et al. (2007)
Olive (<i>Olea europaea</i>) cv Arbequina	Young	August-September	$MDS = -0.18 + 0.27 VPD_m$	0.80	Moriana and Fereres (2004)
Olive (<i>Olea europaea</i>) cv Manzanillo	Adult	June-September	$MDS = -0.07 + 0.13 VPD_{md}$	0.83	Moreno et al. (2006)
			$MDS = -0.78 + 0.04 T_{md}$	0.79	
Olive (<i>Olea europaea</i>) cv Picual	Adult	Season	$MDS = 0.03 + 0.16 VPD_m$ (Low crop load)	0.84	Moriana and Fereres (2004)
		August-September	$MDS = 0.05 + 0.22 VPD_m$ (High crop load)	0.71	
Peach (<i>Prunus persica</i>) cv Flordastar	Young	June	$MDS = -0.55 + 0.03 T_{md}$	0.75	Conejero et al. (2007a)
		July	$MDS = -1.07 + 0.05 T_{md}$	0.79	
		August-October	$MDS = -0.19 + 0.02 T_{md}$	0.72	
Plane (<i>Platanus x hispanica</i>)	Young	Season	$MDS = -0.02 + 0.03 ET_o$	0.38	C. Biel (unpublished data)
Plum (<i>Prunus salicina</i>) cv Black Gold	Adult	Season	$MDS = 0.01 + 0.11 VPD_m$	0.65	Intrigliolo and Castel (2006b)
		Fruit growth	$MDS = 0.01 e^{0.01 ET_o}$	0.73	
		Post-harvest	$MDS = 0.04 + 0.09 VPD_m$	0.54	
Plum (<i>Prunus salicina</i>) cv Black Gold	Adult	May-harvest	$MDS = 0.04 + 0.11 VPD_m$ (Low crop load)	0.58	Intrigliolo and Castel (2007a)
			$MDS = 0.04 + 0.15 VPD_m$ (High crop load)	0.68	

This behaviour may be related with the idea that stem diameter variations should be considered not only in the context of the water balance of the plant but also in the tree carbon balance (Sevanto et al., 2003; Daudet et al., 2005), because in some woody crop species the sugar content of woody tissues changes as a function of the presence or absence of sinks, including fruits (Flore and Layne, 1997). For this, even in adult trees with very low TGR, it is of paramount importance to consider crop load when attempting to use MDS as a water stress indicator. As a consequence, specific reference equations must be used to adjust for tree crop load when using MDS to determine plant water status and irrigation requirements (Intrigliolo and Castel, 2007b). Furthermore, in young early maturing peach trees, Conejero et al. (2007a) showed that MDS values in the post-harvest period were closely related to the presence or absence of other sugar-demanding sinks, such as active root growth. In any case, these last results suggest that the use of reference equations in irrigation management could be more complex than previously supposed, implying that a reference equation obtained under certain conditions might not be applicable in subsequent years, if the tree characteristics change.

To avoid this problem, another suitable approach is to relate the actual MDS values of a given treatment to the reference MDS values obtained in well irrigated trees in the same plot (Ferreeres and Goldhamer, 2003; Conejero et al., 2007a; García-Orellana et al., 2007). The actual MDS/well irrigated MDS ratio can then be used as an indication of the water status of the trees to schedule irrigation. This method implies greater management complexity (e.g., different irrigation schedules within the same orchard) than when reference lines are used, as well as increased investment costs (e.g., a higher number of sensors). However, at a field scale, the trees to be used as a reference can be “better irrigated” by increasing either the number of drippers or their discharge rate, without the need for different irrigation plots. However, special care should be taken in their selection, as the irrigation management of the whole orchard would

indeed depend on seasonal variation in their MDS. In addition, when trees are irrigated clearly above their water requirements in order to obtain non-limiting soil water conditions, oxygen status may be affected. As indicated above, flooding stress modifies plant-based water stress indicators in the same way as drought stress, including increased MDS values (Domingo et al., 2002; Ortuño et al., 2007), which can also complicate the information needed for irrigation scheduling.

5. Crop response to irrigation scheduling

For precise irrigation scheduling procedures, it is necessary to determine what the exact crop water requirements are at any moment, and to this end, measurements of the plant water status could provide a promising technique for irrigation management because of its dynamic nature, which is directly related with meteorological and soil conditions, as well as with crop productivity (Goldhamer et al., 2003; Remorini and Massai, 2003). The operational advantages of TDF measurements, such as the possibility of connecting remotely operated irrigation automatic device, and the ability to adjust schedules in very short periods in response to the daily signal, make MDS a very suitable tool for precise irrigation scheduling (Goldhamer and Fereres, 2001) (Picture 3).

Continuous records of stem diameter have been widely proposed as a management tool for irrigation scheduling (Huguet et al., 1992; Cabibel and Isberie, 1997; Cohen et al., 2001; Goldhamer and Fereres, 2001). Li et al. (1989), Li and Huguet (1990), Huguet et al. (1992) and Bussi et al. (1999) proposed the use of MDS absolute values for this purpose. Also, recently, Mercier et al. (2009) compared different irrigation schedules during the second period of rapid fruit growth (stage III of peach growth), using MDS absolute values ranging between 10 and 300 μm .

Picture 3. An informatization and telemonitoring system (via radio) controlled the moments of irrigation and fertilization and their duration.

Nevertheless, the fact that the plant water status was seen to integrate the effect of the soil water available to the plant and the weather conditions has induced the use of MDS SI for irrigation scheduling (Goldhamer and Fereres, 2001). To our knowledge, Goldhamer and Fereres (2004) were the first to demonstrate that it is feasible to develop an irrigation schedule based only on MDS SI measurements in almond trees. Subsequently, García-Orellana et al. (2007), Velez et al. (2007) and Ortuño et al. (2009c) confirmed that in citrus MDS measurements are indeed suitable for adjusting the deficit irrigation schedule.

These authors used irrigation protocols based on that proposed by Goldhamer and Fereres (2001) for mature trees under high frequency irrigation. This protocol consists of maintaining MDS SI at around a threshold value, decreasing the irrigation rate by 10% when MDS SI does not exceed the MDS SI threshold value on three consecutive days, and

increasing the irrigation rate by 10% when the MDS SI exceeds the threshold value on three consecutive days.

García-Orellana et al. (2007) and Ortuño et al. (2009c) reported that MDS measurements can be used for adjusting the deficit irrigation scheduling according to the daily information obtained, because adjustments in the irrigation water amounts applied can be made accurately (Figure 5). However, during rainy periods of low evaporative demand, some changes in the irrigation protocol should be introduced in order to improve the precision of irrigation management, using, for example, higher MDS SI threshold values and/or lower irrigation frequency (García-Orellana et al., 2007; Ortuño et al., 2009c) (Figure 5). In this sense, Conejero (2008) showed that daily irrigation scheduling using changes in the irrigation rate of 3% particularly improves the irrigation precision in early maturing peach trees. In order to solve these problems, other authors have used irrigation protocols based on the combination of soil matric potential (Ψ_m) and MDS values to adjust irrigation frequency and dose. Whenever Ψ_m values are above a threshold value (usually below field capacity) irrigation is stopped, and when Ψ_m values are below the threshold value irrigation is scheduled by taking into account MDS threshold values (Bonany et al., 2000; Biel et al., 2008). For example, irrigation scheduling in apple trees using -15 kPa and 200 μm as soil water potential and MDS threshold values, respectively, was able to save 38% of the water used in a water balance irrigation treatment without affecting yield or fruit quality (J. Bonany, unpublished data). Also, Biel et al. (2008) in plane trees using -20 kPa and 200 μm as Ψ_m and MDS threshold values, respectively, achieved a 7% water saving compared with the treatment in which irrigation was scheduled to maintain Ψ_m at values of -20 kPa, without affecting tree growth.

Figure 5. Maximum daily trunk shrinkage (MDS) signal intensity (SI) values in lemon trees in which irrigation was scheduled in order to maintain MDS SI at threshold values of 1.15 (green triangles), 1.25 (dark circles) and 1.35 (red triangles). Vertical bars from x-axis indicate amounts of irrigation water applied as percentage of daily ET_c during the measurement periods. Ortuño et al. (2009c).

Goldhamer and Fereres (2004) tested almond tree response to an irrigation schedule based primarily on Ψ_{stem} measurements but also considering ET_c information, and two irrigation schedules with MDS SI values of 1.75 and 2.75. The MDS-based treatments generated mild and moderate water stress, respectively, hastening fruit maturation (hull

splitting), while the less severe deficit irrigation regime did not affect kernel size and other important almond fruit parameters.

Ortuño et al. (2009c) assessed the lemon tree response to continuous deficit irrigation scheduling, maintaining MDS SI at threshold values of 1.15, 1.25 and 1.35, which generated mild, moderate and severe water stress, respectively (Figure 5). Deficit irrigation treatments scheduled using MDS SI threshold values of 1.25 and 1.35 led to a lower yield at the first harvest and a modification of fruit characteristics. In contrast, when mild deficit irrigation was scheduled, using MDS SI threshold values of 1.15, the yield at the first harvest was not affected and fruit characteristics were hardly affected.

In contrast, Velez et al. (2007) showed that during two consecutive seasons in *Citrus clementina* trees, irrigation scheduling that maintained MDS SI at around threshold levels of 1.25 during the period from the June fruit drop to October allowed seasonal water saving without affecting yield or average fruit weight, there being only a slight modification in fruit quality. As a consequence, these differences lead us to think that the response of a given species to irrigation based on a specific MDS SI threshold value may not be transferable to other species even within the same genus.

In this sense, Intrigliolo and Castel (2007a) showed that in grapevines after veraison, when the control of vine water status might be especially important for fruit quality (Williams and Matthews, 1990), there is no relationship between plant water status and MDS or TGR, which throws doubt on the practical use of MDS and TGR as variables to automate grapevine irrigation scheduling. Moreover, in olive trees, Michelakis (1997) indicated that MDS alone could not be considered as a reliable indicator for irrigation scheduling. Also, no apparent relationship between plant water status and MDS was found in young and mature olive trees under water stress conditions, although Ψ_{stem} was significantly lowered by the stress effect (Moriana and Fereres, 2002; Moriana et al., 2003; F. Moreno,

unpublished data). However, in severely water stressed mature olive trees ($\Psi_{\text{stem}} < -4.0$ MPa and stomatal closure) MDS values were significantly lower than in fully irrigated trees (Moriana et al., 2003). Such a response is probably related with the extremely high drought resistance of this species, and especially with the hydraulic architecture of the olive trees. This latter characteristic could be typified by the low storage of water in the trunk and a fast end to water recruitment from the bark (including phloem and cambium) (Garnier and Berger, 1986; Huguet et al., 1992; Remorini and Massai, 2003), and/or a high transversal resistance to the water movement from bark to xylem (Huck and Klepper, 1976).

Fernández and Moreno (1999) indicated that the olive is a diffuse-porous tree having a dense wood with abundant fibres and little parenchyma, sapwood depth highly heterogeneous and low xylem vessels diameter in comparison with other diffuse-porous species. The presence of abundant fibres, which makes olive wood so hard, accounts for the low vessel lumina of the species in comparison with other diffuse-porous Mediterranean trees. Also, these authors showed that in well-irrigated olive trees, in which the soil water potential could be assumed to be similar to that of the absorbing roots, the water potential gradient from leaves to roots was easily greater than 2 MPa, with a maximum difference of about 4 MPa. These large gradient water potential between leaves and roots might reflect a strong resistance to water movement in olive trees.

In addition, and as mentioned above, several authors have reported that the behaviour of MDS changes below a Ψ_{stem} threshold value (Moriana et al., 2000; Ortuño et al., 2004b; Ortuño et al., 2006a). The fact that Ψ_{stem} values in fully irrigated olive trees may frequently fall within a range of values around the Ψ_{stem} threshold value at which the decrease of MDS begins, could induce the absence of significant changes in MDS values as an effect of water stress until the conditions are extremely severe.

Recently, De Swaef et al. (2009) proposed an alternative approach to obtain MDS threshold values with which actual measured values could be compared and beyond which irrigation would be necessary (Fereres and Goldhamer, 2003; Jones, 2004; Steppe et al., 2008). For this, relationships between MDS and three measured plant responses to water deficit (sap flow rate, maximum photosynthesis rate and daily radial stem growth) were obtained in young apple trees. The MDS reference values obtained varied between 0.17 and 0.28 mm, with the characteristic that when the maximum photosynthesis approach was used the lowest reference values for MDS were obtained.

6. Perspectives for using MDS in regulated deficit irrigation management

Recently, in preliminary assessments, some promising results have been obtained in woody crops on the use of TDF-derived parameters in the regulated deficit irrigation (RDI) scheduling. Pagán et al. (2006) proposed the use of a decrease in TGR for detecting the beginning of the critical period (second half of the rapid fruit growth period) in Fortune mandarin, which implies a change from deficit to full irrigation. Also, in early maturing peach trees, it has been shown that it is possible to develop RDI by maintaining MDS SI at threshold values of 1, 1.3 and 1.6 from flowering to harvest, from harvest to the end July, and from the end July to the end of the season, respectively, saving 35–42% of irrigation water requirements with minimum impact in yield and fruit parameters (Conejero et al., 2011).

In mid-season maturing Japanese plum trees, it was possible to save up to 30% of annual water applications by maintaining SI values around 1.5 during phase II of fruit growth and up to 1.8 during post-harvest (D.S. Intrigliolo and J.R. Castel, unpublished data). However, it should be noted that similar results in terms of water savings and yield responses

were obtained with a deficit irrigation treatment where water restrictions were applied considering a fixed reduction of crop evapotranspiration without the need of continuously monitoring plant water status.

In almonds trees, Pagán et al. (2007) described an RDI strategy, maintaining MDS SI at a threshold value between 1 and 1.1 all season, except during the stage IV (kernel-filling), in which a MDS SI of 1.4 was used. The results pointed to an irrigation water saving of 54% and no effect on yield, although kernel size decreased in the RDI treatment due to the water deficit reached in mid-summer ($\Psi_{\text{stem}} \approx -2.45$ MPa).

In addition to the use of a MDS SI above unity for scheduling deficit irrigation, recent results have showed that maintaining MDS SI around the unity could be successfully employed for scheduling full irrigation, avoiding the absence of soil water deficit (Conejero et al., 2007b; Ortuño et al., 2009a). This irrigation management will be very useful to precisely match the irrigation applied with the actual amount of crop water used. In addition, in situations where drainage can be avoided, and in the absence of rainfall, this strategy could be considered as a tool for estimating crop evapotranspiration.

7. Summary and conclusions

Nowadays LVDT sensors are able to measure daily trunk diameter fluctuations with great precision, generating sensitive parameters which, in general, strongly correlate with established plant water status parameters. Moreover, the ease with which LVDT sensors can be computerised and their remote connection to automatic irrigation control systems is another positive features of TDF for irrigation management.

The results of research into the selection of suitable TDF-derived indicators to diagnose changes in plant water status are not uniform, pointing to the convenience of using specific indicators not only as a

function of tree age but also of plant material. In this sense, in young woody crops under conditions of fast trunk growth, MDS is not always a robust indicator of plant water status, and others indicators as MXTD and MNTD are more reliable. In adult trees, most authors have indicated the convenience of using MDS as a plant water status indicator for irrigation scheduling. However, in some cases such as olive trees and grape vines MDS does not seem a suitable soil water deficit indicator. Also, some authors have pointed to other factors, in addition to soil water availability and environmental conditions, such as tree age, phenological period or crop load, that may affect MDS values, which leads to the idea that stem diameter variations should be considered not only in the context of the water balance of the plant but also in the carbon balance of the plant. Moreover, it is necessary to look carefully at other related aspects, such as cultivar and rootstock effects on TDF-derived indicators.

In spite of the difficulty involved in interpreting plant water measurements due to the highly dynamic nature of the plant water status, the proposals to use the concept of *signal intensity (SI)* rather than absolute values for evaluating plant water status, is a turning point in irrigation decision-making development. MDS reference values can be obtained in well irrigated trees located in the same plot or by means of previously obtained reference, base-line equations, by relating the values obtained in plants under non-limiting soil water conditions with climatic variables, mainly those measured on a whole day basis. However, the fact that MDS baselines are influenced by other factors means that MDS measurements may need adjustment before they can be used in irrigation scheduling, making their use slightly more complicated than earlier believed.

The possibility of using RDI strategies, capable of reducing seasonal ET without affecting fruit yield and quality by means of MDS measurements is supported by the fact that continuous deficit irrigation can be reliably

scheduled using only MDS measurements, and that by maintaining MDS signal intensities at values close to unity, it is possible to fulfil the crop water requirements. Nevertheless, for automatic RDI management it is necessary to develop research concerning the use of fruit or trunk sensors for diagnosing the beginning and end of critical crop periods, possibly synchronized with the use of soil water availability sensors. Any proposed irrigation protocol can be considered as a general guideline that should be modified in order to improve the precision of irrigation management in specific situations. For example, in rainy periods of low evaporative demand or during specific phenological periods, such as the active fruit growth period of early maturing fruit trees, irrigation frequency and/or MDS SI threshold values need to be adjusted. Also, the use of automatic irrigation control systems could permit daily irrigation scheduling, improving the precision of irrigation scheduling.

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Chapter 2:

Establishing maximum daily trunk shrinkage and midday stem water potential reference equations for irrigation scheduling of early maturing peach trees

Abstract

Measurements of midday stem water potential (Ψ_{stem}) and maximum daily trunk shrinkage (MDS) were taken over a four year period in early maturing peach trees (*Prunus persica* (L.) Batsch cv. Flordastar) grafted on GF-677 rootstock. Plants were irrigated daily above their water requirements in order to obtain non-limiting soil water conditions. The results indicated that seasonal reference equations can be obtained for MDS and Ψ_{stem} using crop reference evapotranspiration (ET_o), daily mean vapour pressure deficit (VPD_m) and mean daily air temperature (T_m) in the case of MDS, and ET_o and VPD_m in the case of Ψ_{stem} . In this way, VPD_m was seen to be the best predictor of MDS and Ψ_{stem} , without both were influenced significantly by yield or crop load variations between years. When the postharvest regression between MDS or Ψ_{stem} and the meteorological parameters mentioned were broken down into early and late postharvest periods, the correlation coefficients improved and were closely related to the presence or absence of sugar-demanding sinks, such as active root growth. A negative linear relationship between MDS and Ψ_{stem} was found, pointing to unchanging radial hydraulic conductivity in the bark tissues and suggesting that MDS depends to a great extent of the water potential.

Key words: Maximum daily trunk shrinkage, Stem water potential, Meteorological variables, Reference equations, Irrigation scheduling, Plant water relations.

1. Introduction

In recent years, the use of plant-based water status indicators has become very trendy for planning more precise irrigation programmes, because it is recognized that the tree itself is the best indicator of its own

water status. Since plant water status controls many physiological processes and crop productivity, this information can be of great practical interest for irrigation scheduling (Goldhamer and Fereres, 2001; Goldhamer et al., 2003; Naor, 2006; Ortuño et al., 2010). Moreover, under deficit irrigation conditions, the continuous control of tree water status is crucial in order to prevent a moderate, potentially beneficial, water stress from becoming too severe, with adverse effects on yield (Domingo et al., 1996; Johnson and Handley, 2000).

Even though stem water potential (Ψ_{stem}) measurements require frequent trips to the field and a significant input of labour, the parameter is a reliable plant-based water status indicator and has been used for irrigation scheduling in fruit trees (Shackel et al., 1997; Naor, 2000; Choné et al., 2001; Intrigliolo and Castel, 2007). Maximum daily trunk shrinkage (MDS), the difference between maximum trunk diameter early in the morning and minimum trunk diameter early in the afternoon, provides continuous and automatic information of the plant water status (Goldhamer and Fereres, 2001; Ortuño et al., 2004a,b; Naor, 2006; Ortuño et al., 2006a). Also, MDS has been successfully used as a management tool for irrigation scheduling (Goldhamer and Fereres, 2004; Conejero et al., 2007b; García-Orellana et al., 2007; Velez et al., 2007; Ortuño et al., 2009a,c).

Because plants grow in the middle of the soil-plant-atmosphere continuum, any measurement of plant water status, if taken during sunlight hours, will depend not only on the soil water status but also on the environmental conditions. Hence, before plant-based water stress indicators can be used for irrigation scheduling, their absolute values must be normalized with respect to reference values obtained in plants under non-limiting soil water conditions (plant-based water status indicator signal intensity (SI), actual value/reference value). SI values above unity indicate

increasing water stress, while signal intensity values of unity indicate the absence of irrigation-related stress (Goldhamer and Fereres, 2004).

In general, plant-based water stress indicator reference values are obtained by maintaining reference plants in conditions of non-limiting soil water supply (Conejero et al., 2007b; García-Orellana et al., 2007). However, when trees are irrigated clearly above their water requirements in order to obtain non-limiting soil water conditions, oxygen status may be affected. In this sense, flooding stress modifies plant-based water stress indicators in the same way as drought stress, including higher MDS values (Ortuño et al., 2007), which can also complicate the information needed for irrigation scheduling.

Another option would be to previously define the effects of the evaporative demand on the plant water status indicator and to use this reference equation or baseline as a reference to normalize the actual plant-based water status indicator values obtained (Moreno et al., 2006; Ortuño et al., 2009a,c). In accordance with Sevanto et al. (2003) and Daudet et al. (2005), trunk diameter variations have to be considered not only in the context of the water balance of the plant but also in the context of the tree carbon balance, because in some woody crop species the sugar content of woody tissues changes as a function of the presence or absence of sinks, including fruits (Flore and Layne, 1997). For this, other factors, independently of environmental conditions or soil water status can affect MDS, such as tree age (Moriana and Fereres, 2004), tree size (Intrigliolo and Castel, 2006), the phenological period (Marsal et al., 2002; Fereres and Goldhamer, 2003; Intrigliolo and Castel, 2004; Moriana and Fereres, 2004; Conejero et al., 2007a) and crop load (Moriana and Fereres, 2004; Intrigliolo and Castel, 2007; Conejero et al., 2010).

For these reasons, the objective of this paper was to study the inter and intra season constancy of the MDS and Ψ_{stem} reference equations in early maturing peach trees, in order to obtain robust and transferable

reference equations based on appropriate meteorological variables for use in irrigation scheduling.

2. Materials and methods

2.1. Site description

Measurements were performed over four consecutive growing seasons, 2006 (from day of year (DOY) 81 to DOY 254), 2007 (from DOY 67 to DOY 233), 2008 (from DOY 71 to DOY 265) and 2009 (from DOY 79 to DOY 256), in a plantation of 5 year old (in 2006) early maturing (mid-May) peach trees (*Prunus persica* (L.) Batsch cv. Flordastar) grafted on *P. persica* x *P. amygdalus* GF-677 peach rootstock and trained to an open-centre canopy. Tree spacing followed a 5 m x 5 m square pattern. Hand-thinning was used to space fruitlets along the fruit bearing stems by 25 cm for the commercial crop load (Picture 1). The trees were located in the CEBAS-CSIC experimental field station (38° 06' N, 1° 02' W) near Santomera (Murcia), Spain, under Mediterranean climate. Pest control was that commonly used by local growers, and no weeds were allowed to develop within the orchard. Fertilization practices followed the principle of re-establishing nutrients taken up by the plants, and then all trees received the same amount of nutrients.

The soil, classified as a Lithic xeric haploxeroll (Soil Survey Staff, 2006), is stony (33% w/w) and shallow, with a clay-loam texture. Analytical data showed a high lime content (56% calcium carbonate), very low organic matter content (0.34%), low cationic exchange capacity (12.6 meq 100 g⁻¹), and low available potassium and phosphorus levels. Available soil water and bulk density were 200 mm m⁻¹ and 1.58 g cm⁻³, respectively. The volumetric soil water content at saturation, field capacity (-0.3 MPa) and permanent wilting point (-1.5 MPa) were 0.49, 0.35 and

0.15 m³ m⁻³, respectively. These values were measured at the laboratory in undisturbed soil samples and compared with field measurements to avoid overestimation. The irrigation water had a mean EC of 1.1 dS m⁻¹ and an average Cl⁻ concentration of 26 mg l⁻¹.

Picture 1. View of peach trees in the CEBAS-CSIC experimental field station.

Drip irrigation was carried out during the night using one lateral pipe per tree row and eight emitters (each delivering 2 l h⁻¹) per plant. A computerized and telemonitored system (via radio) controlled the moments of irrigation and fertilization and their duration. Also, information was obtained on the applied volumes of water by means of flow meters integrated in the system. Crop irrigation requirements (ET_C) were estimated according to daily crop reference evapotranspiration (ET_o), calculated using the Penman-Monteith equation (Allen et al., 1998) and a crop factor based on the time of the year (Ayars et al., 2003) and the percentage of ground area shaded by the tree canopy (Fereres and Goldhamer, 1990). Total estimated ET_C was 589.8, 486.7, 797.2 and 777.5 mm during the 2006, 2007, 2008 and 2009 experimental periods, respectively. Peach trees were irrigated daily above ET_C in order to obtain

non-limiting soil water conditions. A total of 741, 676.8, 1058 and 1031.6 mm of water was applied in the 2006, 2007, 2008 and 2009 experimental periods, respectively. Although the amount of irrigation water applied to the plants during the experimental period was clearly above ET_C , the plant water relations and visual appearance indicated the absence of waterlogging (data not shown).

2.2. Measurements

Meteorological data, namely air temperature, solar radiation, air relative humidity, rainfall and wind speed 2 m above the soil surface, were collected every 15 min by an automatic weather station located near the experimental site (Picture 2), which was integrated in the same irrigation telemonitoring system. ET_o and mean daily air vapour pressure deficit (VPD_m) were calculated according to Allen et al. (1998).

Picture 2. View of the weather station located at CEBAS-CSIC experimental station field.

The soil volumetric water content (θ_v , $m^3 m^{-3}$) of the top 0.15 m of the soil profile was measured by time domain reflectrometry (TDR) using a Tektronik device (Model 1502C, Tektronix Inc., OR), as described by

Moreno et al. (1996). The θ_v content of the soil from 0.2 m down to a maximum depth of 0.80 m was measured every 0.1 m using a neutron probe (Model 4300, Troxler Electronic Laboratories Inc., NC) (Picture 3), in access tubes installed 1.0 m from the trees and beside the emitters.

Picture 3. Time domain reflectometry (TDR) (A) and Neutron probe (B) to measure soil volumetric water content (θ_v).

Midday (12.00 h solar time) stem water potential (Ψ_{stem}) was measured in two mature leaves per plant, taken from close to the trunk. Leaves were inserted into a small black hermetic plastic bag covered with aluminium foil for at least 2 h before detaching from the tree and measurements were made in a pressure chamber (Picture 4).

Picture 4. Leaf covered with aluminium foil (A) and Pressure chamber to measure stem water potential (Ψ_{stem}) (B).

Trunk diameter fluctuations (TDF) were measured throughout the experimental period on four trees, using a set of linear variable displacement transducers (LVDT) (Model DF $\pm$ 2.5 mm, Solartron Metrology, Bognor Regis, UK) attached to the trunk, with a special bracket made of Invar, an alloy of Ni and Fe with a thermal expansion coefficient close to zero (Katerji et al., 1994), and aluminium. Sensors were placed on the north side and were covered with silver thermoprotected foil to protect the device from direct radiation and rain (Picture 5). Measurements were taken every 2 s and the datalogger (Model CR10X with AM25T multiplexer, Campbell Scientific Ltd, Logan, USA) was programmed to report 15 min means. Maximum daily trunk shrinkage (MDS) was calculated as the difference between maximum and minimum daily trunk diameter.

Picture 5. LVDT sensor attached to a peach tree.

Peach fruits were harvested according to market demand, and the number of fruit per tree was obtained from the number of boxes and by counting the fruit per box in at least three randomly selected boxes per replicate at each harvest time.

2.3. Statistical design and analysis

Only one well irrigated treatment was considered. Four replicates of this treatment were distributed randomly within the field, with each replication consisting of three adjacent rows, each of them with 13 trees. Measurements were taken in the inner tree of the central row of each replicate, all of which were of very similar appearance (leaf area, trunk cross sectional area, height, ground shaded area, etc.), and the other trees served as border trees. Ψ_{stem} values for each day and replicate were averaged before the mean and the standard error were calculated. A one-way ANOVA was performed and means were separated by $\text{LSD}_{0.05}$ range test. Linear regression analysis was carried out to explore relationships between variables, and linear regression differences were determined using covariance analysis.

3. Results

Total rainfall was very scarce, amounting to 110.9, 161.4, 141.8 and 113.2 mm in 2006, 2007, 2008 and 2009, respectively (Figure 1A), and falling mainly in April and May (Figure 1A). θ_v values from 0 to 0.80 m depth were nearly constant, with values always very close to field capacity (average values of 97.3, 100.5, 101.6 and 105.4% of field capacity θ_v in 2006, 2007, 2008 and 2009, respectively) (Figure 1B). The Ψ_{stem} values showed a similar seasonal trend during each season, decreasing progressively from the beginning of the observation periods, reaching minimum values around late July - early August and increasing afterwards (Figure 1C). Also, MDS values showed some differences on its seasonal trend during each season. Nevertheless, the MDS values increased from the beginning of each seasonal measurement period to late July-early August and decreased afterwards (Figure 1D).

Figure 1. Daily crop reference evapotranspiration (ET_0 , solid line) and daily rainfall (vertical bars) during the experimental period (A), volumetric soil water content (θ_v) down to 0.80 m depth (B), midday stem water potential (Ψ_{stem}) (C) and maximum daily trunk shrinkage (MDS) (D). Each data point is the mean of four values. Vertical bars are twice the overall mean SE. Horizontal lines, from top to bottom, represent soil volumetric water content at field capacity and at permanent wilting point, respectively. Vertical lines, from left to right, represent the days of harvest and the change moment between the 1st and 2nd postharvest period.

Average ground cover and trunk cross sectional area increased during the experiment (2006-2009), although minimum ground cover values were obtained in 2007 as a consequence of severe winter pruning accounted previously. Yield and mean fruit weight were constant during the four seasons of the experiment. However, crop load and fruit load efficiency showed significant differences between seasons, mainly due to the low values obtained in the 2007 season as a consequence of the previous pruning (Table 1).

Table 1. Vegetative and yield components (average ground cover (GC, %), trunk cross sectional area (TCSA, cm²), crop load (CL, number of fruits tree⁻¹), fruit load efficiency (FLE, number of fruits per tree divided by trunk cross sectional area (cm²), yield (kg tree⁻¹) and mean fruit weight (FW, g)) during the experimental period.

Season	GC	TCSA	CL	FLE	Yield	FW
2006	53.8b	86.98d	221bc	2.54a	26.44a	125.8a
2007	44.5b	127.76c	142c	1.11b	18.04a	137.7a
2008	78.5a	158.63b	273ab	1.72ab	32.84 ^a	123.5 ^a
2009	80.2a	188.11a	399 ^a	2.12ab	49.09 ^a	136.7 ^a

Means for each year within a column that do not have a common letter are significantly different by LSD_{0.05} test.

The seasonal relations of MDS and Ψ_{stem} with ET_o , VPD_m , midday vapour pressure deficit (VPD_{md}), mean daily air temperature (T_m) and midday air temperature (T_{md}), indicated that both plant-based water status indicators could be associated with the measured meteorological variables (Tables 2, 3). Increases in the meteorological variables were connected with increases in MDS and decreases in Ψ_{stem} . The corresponding determination coefficients for these seasonal relations were higher for MDS than for Ψ_{stem} , except when T_m was considered as meteorological variable. Also, the scatter of the data around the regression lines was always lower for MDS than for Ψ_{stem} , as indicated by the lower mean square error (MSE) values (Tables 2, 3).

Table 2. Intercept (a), slope (b), coefficient of determination (r^2), number of data points (n) and mean square error (MSE) of best fit first-order linear equations ($y = a + bx$) between maximum daily trunk shrinkage (MDS, mm) and selected environmental variables for 2006, 2007, 2008 and 2009 seasons.

Season	a	b	r^2	n	MSE
MDS vs. ET_o (mm)					
2006	0.0253	0.0337	0.35***	174	0.0030
2007	0.0084	0.0371	0.55***	167	0.0030
2008	0.0164	0.0403	0.39***	195	0.0056
2009	-0.0279	0.0461	0.61***	175	0.0028
MDS vs. VPD_m (kPa)					
2006	0.0223	0.1108	0.68***	174	0.0015
2007	0.0233	0.1210	0.74***	167	0.0018
2008	0.0241	0.1370	0.60***	195	0.0037
2009	0.0358	0.1181	0.77***	175	0.0016
MDS vs. VPD_{md} (kPa)					
2006	0.0354	0.0591	0.71***	174	0.0013
2007	0.0249	0.0712	0.81***	167	0.0013
2008	-0.1135	0.1294	0.64***	195	0.0033
2009	0.0496	0.0685	0.84***	175	0.0011
MDS vs. T_m (°C)					
2006	-0.1104	0.0132	0.60***	174	0.0019
2007	-0.0766	0.0129	0.76***	167	0.0017
2008	-0.1143	0.0153	0.51***	195	0.0045
2009	-0.0803	0.0132	0.65***	175	0.0024
MDS vs. T_{md} (°C)					
2006	-0.1389	0.0116	0.73***	174	0.0013
2007	-0.1084	0.0115	0.84***	167	0.0011
2008	-0.1677	0.0147	0.63***	195	0.0034
2009	-0.1174	0.0122	0.77***	175	0.0016

ET_o daily crop reference evapotranspiration, VPD_m daily mean air vapour pressure deficit, VPD_{md} daily midday air vapour pressure deficit, T_m daily mean air temperature, T_{md} daily midday air temperature.

*** Significant at $P < 0.001$

Table 3. Intercept (*a*), slope (*b*), coefficient of determination (r^2), number of data points (*n*) and mean square error (MSE) of best fit first-order linear equations ($y = a + bx$) between midday stem water potential (Ψ_{stem} , MPa) and selected environmental variables for 2006, 2007, 2008 and 2009 seasons.

Season	<i>a</i>	<i>b</i>	r^2	<i>n</i>	MSE
Ψ_{stem} vs. ET_o (mm)					
2006	-0.3431	-0.0578	0.19**	44	0.0212
2007	-0.1082	-0.0854	0.38***	42	0.0216
2008	-0.2003	-0.0609	0.34***	50	0.0125
2009	0.1425	-0.1159	0.29***	50	0.0506
Ψ_{stem} vs. VPD_m (kPa)					
2006	-0.3210	-0.1968	0.33***	44	0.0175
2007	-0.1832	-0.2497	0.53***	42	0.0170
2008	-0.2224	-0.1961	0.62***	50	0.0072
2009	0.0414	-0.3327	0.56***	50	0.0312
Ψ_{stem} vs. VPD_{md} (kPa)					
2006	-0.3834	-0.0903	0.27***	44	0.0192
2007	-0.2094	-0.1375	0.52***	42	0.0173
2008	0.0534	-0.2136	0.80***	50	0.0037
2009	-0.0429	-0.1739	0.52***	50	0.0347
Ψ_{stem} vs. T_m (°C)					
2006	0.2062	-0.0359	0.66***	44	0.0089
2007	0.1478	-0.0325	0.78***	42	0.0077
2008	0.0855	-0.0268	0.74***	50	0.0048
2009	0.5413	-0.0454	0.82***	50	0.0123
Ψ_{stem} vs. T_{md} (°C)					
2006	0.1374	-0.0263	0.51***	44	0.0128
2007	0.1521	-0.0261	0.70***	42	0.0109
2008	0.1461	-0.0244	0.77***	50	0.0043
2009	0.6058	-0.0393	0.77***	50	0.0160

ET_o daily crop reference evapotranspiration, VPD_m daily mean air vapour pressure deficit, VPD_{md} daily midday air vapour pressure deficit, T_m daily mean air temperature, T_{md} daily midday air temperature.

** and *** significant at $P < 0.01$ and 0.001 , respectively

The covariance analysis of the MDS seasonal reference equations indicated that differences in slopes and intercepts between the four experimental seasons were not statistically significant in the case of the linear regression equations of MDS versus meteorological variables measured on a whole-day basis (ET_o , VPD_m and T_m). This suggests that it was possible to evaluate MDS by means of a first order fit and by pooling data across the four experimental seasons (Figure 2). The pooled data over the four experimental seasons showed a tighter correlation for the regression of MDS versus VPD_m than those of MDS versus ET_o and T_m (Figure 2).

Figure 2. Relationships between maximum daily trunk shrinkage (MDS) and (A) crop reference evapotranspiration (ET_o), (B) mean daily air vapour pressure deficit (VPD_m) and (C) mean daily air temperature (T_m), using all data pooled (2006, sky-blue triangles; 2007, green diamonds; 2008, yellow squares; 2009, red circles). Each data point is the mean of four values.

The covariance analysis of the Ψ_{stem} baselines obtained during the four experimental seasons showed that differences in slopes and intercepts were not statistically significant for the linear regression equations between Ψ_{stem} and ET_o and VPD_m (Figure 3). Pooled data of Ψ_{stem} versus VPD_m became a tighter first order regression than that for Ψ_{stem} versus ET_o (Figure 3). Also, the relation between Ψ_{stem} versus VPD_m showed a lower coefficient of determination and a higher MSE than observed for MDS (Figures 2, 3).

Figure 3. Relationship between midday stem water potential (Ψ_{stem}) and (A) crop reference evapotranspiration (ET_o) and (B) mean daily air vapour pressure deficit (VPD_m), using all data pooled. Each data point is the mean of four values. Symbols as in Figure 2.

When the seasonal regressions between MDS and selected environmental variables (ET_o , VPD_m , VPD_{md} , T_m and T_{md}) were broken down into two time periods (fruit growth and postharvest), the correlations obtained worsened considerably (Tables 4, 5, 6). In this sense, when the postharvest regression between MDS and T_m and T_{md} were broken down into early postharvest period (from harvest (DOY 136, 130, 121 and 132 in 2006, 2007, 2008 and 2009, respectively) to DOY 190 in every year) and late postharvest period (from DOY 191 to when the leaves fall (DOY 254, 233, 265 and 256 in 2006, 2007, 2008 and 2009, respectively)), the correlations obtained also worsened, except in 2009 (Table 6). In contrast, when the postharvest regression between MDS and ET_o , VPD_m and VPD_{md} were broken down into early and late postharvest periods, the correlations obtained showed a clear tendency to improve (Tables 4, 5).

Table 4. Intercept (a), slope (b), coefficient of determination (r^2), number of data points (n) and mean square error (MSE) of best fit first-order linear equations ($y = a + bx$) between maximum daily trunk shrinkage (MDS, mm) and daily crop reference evapotranspiration (ET_o , mm) for the different phenological periods in 2006, 2007, 2008 and 2009 seasons.

Phenological period		a	b	r^2	n	MSE
MDS vs. ET_o						
2006	Fruit growth	0.0172	0.0320	0.33***	55	0.0019
	Postharvest	0.0768	0.0255	0.18***	119	0.0033
	Early postharvest	0.0366	0.0252	0.32***	55	0.0019
	Late postharvest	0.0738	0.0329	0.34***	64	0.0016
2007	Fruit growth	0.0240	0.0286	0.45***	63	0.0019
	Postharvest	0.0915	0.0247	0.15***	104	0.0033
	Early postharvest	0.0018	0.0354	0.28***	61	0.0034
	Late postharvest	0.1298	0.0239	0.29***	43	0.0012
2008	Fruit growth	-0.0692	0.0535	0.41***	50	0.0054
	Postharvest	0.0517	0.0353	0.36***	145	0.0054
	Early postharvest	0.0475	0.0257	0.63***	70	0.0012
	Late postharvest	0.0533	0.0444	0.52***	75	0.0034
2009	Fruit growth	0.0235	0.0285	0.60***	52	0.0009
	Postharvest	-0.0028	0.0433	0.42***	123	0.0031
	Early postharvest	0.0124	0.0374	0.40***	59	0.0024
	Late postharvest	-0.0670	0.0582	0.60***	64	0.0027

*** Significance at $P < 0.001$

Table 5. Intercept (*a*), slope (*b*), coefficient of determination (r^2), number of data points (*n*) and mean square error (MSE) of best fit first-order linear equations ($y = a + bx$) between maximum daily trunk shrinkage (MDS, mm) and daily mean (VPD_m, kPa) and midday (VPD_{md}, kPa) air vapour pressure deficit for the different phenological periods in 2006, 2007, 2008 and 2009 seasons.

Phenological period		<i>a</i>	<i>b</i>	r^2	<i>n</i>	MSE
MDS vs. VPD _m						
2006	Fruit growth	0.0329	0.1017	0.36***	55	0.0018
	Postharvest	0.0182	0.1132	0.66***	119	0.0014
	Early postharvest	0.0116	0.1014	0.84***	55	0.0005
	Late postharvest	0.0753	0.0942	0.60***	64	0.0010
2007	Fruit growth	0.0339	0.1025	0.39***	63	0.0021
	Postharvest	0.0442	0.1113	0.61***	104	0.0016
	Early postharvest	0.0225	0.1158	0.63***	61	0.0018
	Late postharvest	0.1084	0.0866	0.70***	43	0.0005
2008	Fruit growth	-0.0592	0.1899	0.42***	50	0.0053
	Postharvest	0.0465	0.1263	0.65***	145	0.0029
	Early postharvest	0.0705	0.0846	0.61***	70	0.0013
	Late postharvest	0.0845	0.1212	0.68***	75	0.0023
2009	Fruit growth	0.0355	0.1066	0.54***	52	0.0011
	Postharvest	0.0604	0.1071	0.68***	123	0.0017
	Early postharvest	0.0804	0.0933	0.65***	59	0.0014
	Late postharvest	0.0448	0.1176	0.70***	64	0.0019
MDS vs. VPD _{md}						
2006	Fruit growth	0.0493	0.0514	0.44***	55	0.0016
	Postharvest	0.0313	0.0606	0.70***	119	0.0012
	Early postharvest	0.0376	0.0491	0.82***	55	0.0005
	Late postharvest	0.0577	0.0593	0.74***	64	0.0006
2007	Fruit growth	0.0317	0.0645	0.55***	63	0.0015
	Postharvest	0.0325	0.0694	0.73***	104	0.0011
	Early postharvest	-0.0054	0.0796	0.75***	61	0.0012
	Late postharvest	0.1153	0.0472	0.78***	43	0.0004
2008	Fruit growth	-0.3232	0.2449	0.60***	50	0.0037
	Postharvest	-0.1555	0.1411	0.70***	145	0.0025
	Early postharvest	-0.0278	0.0833	0.62***	70	0.0013
	Late postharvest	-0.2598	0.1805	0.72***	75	0.0020
2009	Fruit growth	0.0473	0.0645	0.66***	52	0.0008
	Postharvest	0.0661	0.0640	0.77***	123	0.0013
	Early postharvest	0.0752	0.0595	0.77***	59	0.0009
	Late postharvest	0.0613	0.0668	0.76***	64	0.0015

*** Significance at $P < 0.001$

Table 6. Intercept (a), slope (b), coefficient of determination (r^2), number of data points (n) and mean square error (MSE) of best fit first-order linear equations ($y = a + bx$) between maximum daily trunk shrinkage (MDS, mm) and daily mean (T_m , °C) and midday (T_{md} , °C) air temperature, for the different phenological periods in 2006, 2007, 2008 and 2009 seasons.

Phenological period		a	b	r^2	n	MSE
MDS vs. T_m						
2006	Fruit growth	-0.2196	0.0199	0.44***	55	0.0018
	Postharvest	-0.2382	0.0181	0.61***	119	0.0016
	Early postharvest	-0.1344	0.0132	0.54***	55	0.0013
	Late postharvest	-0.3062	0.0210	0.44***	64	0.0014
2007	Fruit growth	-0.1169	0.0162	0.67***	63	0.0011
	Postharvest	-0.2460	0.0195	0.60***	104	0.0016
	Early postharvest	-0.2594	0.0202	0.53***	61	0.0023
	Late postharvest	-0.3258	0.0223	0.58***	43	0.0007
2008	Fruit growth	-0.2394	0.0245	0.36***	50	0.0059
	Postharvest	-0.2314	0.0198	0.62***	145	0.0032
	Early postharvest	-0.0579	0.0111	0.48***	70	0.0017
	Late postharvest	-0.5478	0.0323	0.58***	75	0.0030
2009	Fruit growth	-0.0820	0.0140	0.50***	52	0.0012
	Postharvest	-0.2382	0.0192	0.49***	123	0.0027
	Early postharvest	0.0171	-0.1723	0.60***	59	0.0016
	Late postharvest	-0.6457	0.0339	0.60***	64	0.0026
MDS vs. T_{md}						
2006	Fruit growth	-0.1153	0.0111	0.51***	55	0.0014
	Postharvest	-0.2520	0.0150	0.77***	119	0.0009
	Early postharvest	-0.1520	0.0111	0.77***	55	0.0007
	Late postharvest	-0.3478	0.0183	0.76***	64	0.0006
2007	Fruit growth	-0.1106	0.0121	0.73***	63	0.0009
	Postharvest	-0.3261	0.0183	0.83***	104	0.0007
	Early postharvest	-0.3746	0.0201	0.80***	61	0.0010
	Late postharvest	-0.2518	0.0159	0.85***	43	0.0003
2008	Fruit growth	-0.3284	0.0234	0.58***	50	0.0039
	Postharvest	-0.2223	0.0163	0.68***	145	0.0027
	Early postharvest	-0.0611	0.0094	0.62***	70	0.0013
	Late postharvest	-0.4126	0.0231	0.72***	75	0.0020
2009	Fruit growth	-0.0657	0.0103	0.70***	52	0.0007
	Postharvest	-0.3303	0.0189	0.73***	123	0.0014
	Early postharvest	-0.2296	0.0159	0.78***	59	0.0009
	Late postharvest	-0.5906	0.0268	0.82***	64	0.0012

*** Significance at $P < 0.001$

When the seasonal regressions between Ψ_{stem} and selected environmental variables (ET_o , VPD_m , VPD_{md} , T_m and T_{md}) were broken down into fruit growth and postharvest periods the correlations obtained worsened considerably, frequently presenting non-significant determination coefficients (Tables 7, 8, 9). In the same way, when the postharvest regression between Ψ_{stem} and T_m and T_{md} were broken down into early and late postharvest periods, the correlations obtained showed a clear tendency to worsen, showing frequently, non-significant determination coefficients (Table 9). In the contrast, when the postharvest regression between Ψ_{stem} and ET_o , VPD_m and VPD_{md} were broken down into early and late postharvest periods, the correlations obtained showed a clear tendency to improve (Tables 7, 8).

Table 7. Intercept (*a*), slope (*b*), coefficient of determination (r^2), number of data points (*n*) and mean square error (MSE) of best fit first-order linear equations ($y = a + bx$) between midday stem water potential (Ψ_{stem}) and daily crop reference evapotranspiration (ET_o) for the different phenological periods in 2006, 2007, 2008 and 2009 seasons.

Phenological period		<i>a</i>	<i>b</i>	r^2	<i>n</i>	MSE
Ψ_{stem} vs. ET_o						
2006	Fruit growth	-0.2937	-0.0338	0.23 ns	11	0.0043
	Postharvest	-0.7352	0.0046	0.00 ns	33	0.0128
	Early postharvest	-0.6613	0.0081	0.03 ns	15	0.0028
	Late postharvest	-0.4720	-0.0603	0.41**	18	0.0041
2007	Fruit growth	-0.2152	-0.0347	0.49**	14	0.0019
	Postharvest	-0.645	-0.0023	0.00 ns	28	0.0182
	Early postharvest	-0.2996	-0.0472	0.22*	19	0.0048
	Late postharvest	-0.7332	-0.0150	0.05 ns	9	0.0052
2008	Fruit growth	-0.2908	-0.0228	0.39*	11	0.0013
	Postharvest	-0.2497	-0.0562	0.29***	39	0.0127
	Early postharvest	-0.1845	-0.0528	0.59***	19	0.0046
	Late postharvest	-0.3131	-0.0591	0.36**	20	0.0073
2009	Fruit growth	0.0184	-0.0470	0.34**	17	0.0034
	Postharvest	-0.6829	0.0087	0.00 ns	33	0.0352
	Early postharvest	-0.1629	-0.0504	0.26*	16	0.0095
	Late postharvest	-0.7965	0.0029	0.00 ns	17	0.0093

*, ** and *** Significance at $P < 0.05$, 0.01 and 0.001, respectively.

ns not significant

Table 8. Intercept (*a*), slope (*b*), coefficient of determination (r^2), number of data points (*n*) and mean square error (MSE) of best fit first-order linear equations ($y = a + bx$) between midday stem water potential (Ψ_{stem}) and daily mean (VPD_m) and midday (VPD_{md}) air vapour pressure deficit, for the different phenological periods in 2006, 2007, 2008 and 2009 seasons.

Phenological period		<i>a</i>	<i>b</i>	r^2	<i>n</i>	MSE
Ψ_{stem} vs. VPD_m						
2006	Fruit growth	-0.3283	-0.0866	0.18 <i>ns</i>	11	0.0046
	Postharvest	-0.5910	-0.0673	0.06 <i>ns</i>	33	0.0121
	Early postharvest	-0.5463	-0.0388	0.13 <i>ns</i>	15	0.0025
	Late postharvest	-0.6029	-0.1051	0.19 <i>ns</i>	18	0.0056
2007	Fruit growth	-0.2410	-0.1154	0.40*	14	0.0023
	Postharvest	-0.4683	-0.1097	0.12 <i>ns</i>	28	0.0166
	Early postharvest	-0.3792	-0.1158	0.41**	19	0.0038
	Late postharvest	-0.6205	-0.1121	0.41 <i>ns</i>	9	0.0032
2008	Fruit growth	-0.3159	-0.0646	0.24 <i>ns</i>	11	0.0016
	Postharvest	-0.2598	-0.1848	0.63***	39	0.0066
	Early postharvest	-0.2252	-0.1708	0.78***	19	0.0025
	Late postharvest	-0.3860	-0.1428	0.62***	20	0.0043
2009	Fruit growth	0.0120	-0.1878	0.39**	17	0.0032
	Postharvest	-0.3168	-0.1714	0.25**	33	0.0263
	Early postharvest	-0.2331	-0.1412	0.42**	16	0.0074
	Late postharvest	-0.6146	-0.0843	0.26*	17	0.0069
Ψ_{stem} vs. VPD_{md}						
2006	Fruit growth	-0.3399	-0.0437	0.21 <i>ns</i>	11	0.0045
	Postharvest	-0.6249	-0.0275	0.04 <i>ns</i>	33	0.0123
	Early postharvest	-0.5465	-0.0219	0.17 <i>ns</i>	15	0.0024
	Late postharvest	-0.6579	-0.0427	0.13 <i>ns</i>	18	0.0060
2007	Fruit growth	-0.2690	-0.0522	0.33*	14	0.0025
	Postharvest	-0.4653	-0.0655	0.13 <i>ns</i>	28	0.0162
	Early postharvest	-0.3995	-0.0618	0.40**	19	0.0039
	Late postharvest	-0.6250	-0.0636	0.39 <i>ns</i>	9	0.0033
2008	Fruit growth	-0.2328	-0.0791	0.35 <i>ns</i>	11	0.0014
	Postharvest	0.1328	-0.2402	0.79***	39	0.0038
	Early postharvest	0.0189	-0.1875	0.81***	19	0.0021
	Late postharvest	0.1134	-0.2414	0.66***	20	0.0039
2009	Fruit growth	0.0429	-0.1473	0.57***	17	0.0022
	Postharvest	-0.4045	-0.0754	0.17*	33	0.0294
	Early postharvest	-0.2710	-0.0707	0.40**	16	0.0077
	Late postharvest	-0.6537	-0.0402	0.20 <i>ns</i>	17	0.0075

*. ** and*** = significance at $P < 0.05$, 0.01 and 0.001, respectively.

ns not significant

Table 9. Intercept (*a*), slope (*b*), coefficient of determination (r^2), number of data points (*n*) and mean square error (MSE) of best fit first-order linear equations ($y = a + bx$) between midday stem water potential (Ψ_{stem} , MPa) and daily mean (T_m , °C) and midday (T_{md} , °C) air temperature, for the different phenological periods in 2006, 2007, 2008 and 2009 seasons.

Phenological period		<i>a</i>	<i>b</i>	r^2	<i>n</i>	MSE
Ψ_{stem} vs. T_m						
2006	Fruit growth	-0.0795	-0.0185	0.17 <i>ns</i>	11	0.0047
	Postharvest	-0.0956	-0.0244	0.33***	33	0.0087
	Early postharvest	-0.4064	-0.0087	0.27 <i>ns</i>	15	0.0021
	Late postharvest	-0.1835	-0.0232	0.22 <i>ns</i>	18	0.0054
2007	Fruit growth	-0.2528	-0.0063	0.11 <i>ns</i>	14	0.0034
	Postharvest	0.3959	-0.0427	0.66***	28	0.0064
	Early postharvest	0.0346	-0.0260	0.63***	19	0.0024
	Late postharvest	-0.0560	-0.0285	0.41 <i>ns</i>	9	0.0032
2008	Fruit growth	-0.2533	-0.0082	0.25 <i>ns</i>	11	0.0016
	Postharvest	0.2374	-0.0329	0.74***	39	0.0046
	Early postharvest	0.0919	-0.0256	0.81***	19	0.0022
	Late postharvest	0.4325	-0.0409	0.48***	20	0.0059
2009	Fruit growth	0.2603	-0.0279	0.44**	17	0.0029
	Postharvest	0.7123	-0.0520	0.52***	33	0.0169
	Early postharvest	0.4640	-0.0381	0.85***	16	0.0019
	Late postharvest	-0.3548	-0.0157	0.10 <i>ns</i>	17	0.0083
Ψ_{stem} vs. T_{md}						
2006	Fruit growth	-0.1901	-0.0097	0.24 <i>ns</i>	11	0.0043
	Postharvest	-0.2543	-0.0146	0.17*	33	0.0107
	Early postharvest	-0.4688	-0.0048	0.14 <i>ns</i>	15	0.0025
	Late postharvest	-0.2224	-0.0177	0.20 <i>ns</i>	18	0.0056
2007	Fruit growth	-0.2239	-0.0063	0.20 <i>ns</i>	14	0.0030
	Postharvest	0.1565	-0.0268	0.40***	28	0.0112
	Early postharvest	-0.0776	-0.0170	0.54***	19	0.0030
	Late postharvest	-0.1709	-0.0202	0.43 <i>ns</i>	9	0.0031
2008	Fruit growth	-0.2213	-0.0080	0.36 <i>ns</i>	11	0.0014
	Postharvest	0.2790	-0.0288	0.78***	39	0.0040
	Early postharvest	0.1069	-0.0215	0.78***	19	0.0024
	Late postharvest	0.3626	-0.0323	0.67***	20	0.0038
2009	Fruit growth	0.2054	-0.0190	0.51*	17	0.0026
	Postharvest	0.5321	-0.0372	0.38***	33	0.0218
	Early postharvest	0.3666	-0.0278	0.65***	16	0.0044
	Late postharvest	-0.2819	-0.0154	0.20 <i>ns</i>	17	0.0075

*, ** and *** Significance at $P < 0.05$, 0.01 and 0.001, respectively.

ns not significant

The regression analysis between MDS and Ψ_{stem} during each season indicated clear associations, while the covariance analysis indicated that these relationships were not statistically different (data not shown), suggesting that it is possible to represent the relationship between MDS and Ψ_{stem} for all seasons by one line (Figure 4). Moreover, when the MDS versus Ψ_{stem} seasonal regressions were broken down into fruit growth and postharvest periods, and postharvest into early and late postharvest periods, the determination coefficients did not improve (data not shown).

Figure 4. Relationship between maximum daily trunk shrinkage (MDS) and midday stem water potential (Ψ_{stem}), using all data pooled. Each data point is the mean of four values. Symbols as in Figure 2.

4. Discussion

Even though the amount of irrigation water applied was above the crop water requirement during the experiment, θ_v values were always

close to field capacity (Figure 1B), indicating that the trees were under non-limiting soil water conditions.

The high sensitivity of MDS to changes in evaporative demand indicators (Table 2) agrees with previous observations in other fruit tree species (Intrigliolo and Castel, 2006; Moreno et al., 2006; Ortuño et al., 2009b). In this sense, the changes in stem size during the day are a consequence of the withdrawal and refilling of water storage components (Cermák et al., 2007), which can occur even in well-watered plants (Zweifel et al., 2001). Also, the finding that the relationships between MDS and the environmental variables were linear (Table 2; Figure 2), even in situations of high evaporative demand, can be attributed to efficient water movement from storage sites within the tree when evaporative demand increased.

Given that MDS encompasses a daily time scale, the results indicated that it was possible to predict MDS reference values by pooling data across the four studied seasons only when meteorological variables measured on a whole-day basis (ET_o , VPD_m and T_m) were used (Figure 2). The association between overall MDS in non-limiting soil water conditions data and ET_o and VPD_m (Figure 2) can be considered a consequence of the fact that MDS indicates the transpiration stream intensity when the soil water content is not strongly depleted (Huguet et al., 1992; Ortuño et al., 2006b). However, taking into consideration that air temperature is a poor indicator of atmospheric evaporative demand (Hatfield and Fuchs, 1990), it is difficult to explain why T_m is an adequate predictor of MDS (Figure 2). Nonetheless, others papers in almond (Ferreles and Goldhamer, 2003), plum (Intrigliolo and Castel, 2006), olive (Moreno et al., 2006) and lemon (Ortuño et al., 2009b) demonstrated that air temperature is a good predictor of MDS. In any case, it must be considered that T_m is a meteorological variable that is easier and less costly to measure than VPD and ET_o .

Despite the fact that Ψ_{stem} values are obtained at point measurements, the covariance analysis indicated that it was only possible to predict Ψ_{stem} reference values when ET_o and VPD_m are used by pooling data across the whole experimental period (Figure 3). Nevertheless, the scatter of the Ψ_{stem} vs ET_o relationship avoids its use to predict Ψ_{stem} reference values for precise irrigation scheduling.

Independently of environmental and soil water conditions, some authors have suggested that other factors can also affect MDS, such as the phenological period (Marsal et al., 2002; Fereres and Goldhamer, 2003; Intrigliolo and Castel, 2004; Moriana and Fereres, 2004; Conejero et al., 2007a) and crop load (Moriana and Fereres, 2004; Intrigliolo and Castel, 2007; Ortuño et al., 2010). These behaviours indicate that MDS values should be considered not only in the context of the water balance of the plant but also in the tree carbon balance (Sevanto et al., 2003; Daudet et al., 2005), because the sugar content of woody tissues changes as a function of the presence or absence of sinks (Flore and Layne, 1997).

In contrast, our result indicated that, despite the significant differences existing between seasons in crop load and fruit load efficiency, there is inter seasonal constancy in the reference equations to estimate MDS and Ψ_{stem} as a function of ET_o , VPD_m and T_m , and ET_o and VPD_m , respectively (Figures 2, 3). That these yield components have no effect on MDS and Ψ_{stem} reference equations could be attributed to the fact that the inter seasonal differences in these yield components, while being statistically significant, are within the range of the typical alternate bearing pattern of this species. In this sense, in a recent paper, Conejero et al. (2010) showed that MDS reference equations for peach trees, in which fruitless were not thinned, were statistically different from those for trees from which all the fruitless were removed. However, in the cases of trees in which fruits were hand-thinned to obtain commercial crop load (547

fruits tree⁻¹) and trees in which fruits were not thinned (3114 fruits tree⁻¹), no significant differences in MDS reference equations were obtained.

In contrast to the finding of Intrigliolo and Castel (2006) that in plum trees different reference equations are required for the fruit growth and postharvest periods, our results indicated that when the regressions between MDS or Ψ_{stem} and ET_o , VPD_m , VPD_{md} , T_m and T_{md} are broken down into fruit growth and postharvest periods the coefficients of determination obtained (Tables 4, 5, 6, 7, 8, 9) are lower than those for the seasonal relationships (Tables 2, 3). This behaviour could be attributed to the very short fruit growth period (52-56 days from fruit thinning), and to the fact that MDS values under non-limiting soil water conditions in the postharvest period are closely related to the presence or absence of sugar-demanding sinks, such as active root growth (Conejero et al., 2007a; Abrisqueta et al., 2008). In this sense, the improved correlation coefficients obtained when the postharvest regressions between MDS or Ψ_{stem} and ET_o , VPD_m and VPD_{md} were broken down into early and late postharvest periods, could also be related to the presence or absence of sugar-demanding sinks (Conejero et al., 2007a).

Marsal et al. (2002), Fereres and Goldhamer (2003) and Intrigliolo and Castel (2004) showed weak correlations between MDS and Ψ_{stem} on a seasonal basis in deciduous trees, although they improved when they were broken into different phenological periods, probably due to changes in trunk growth rate and tissue elasticity during the season. In contrast, the steady relationship between MDS and Ψ_{stem} (Figure 4) is in agreement with the result obtained in lemon trees by Ortuño et al. (2009b) and the idea of Génard et al. (2001), who suggested that this behaviour is probably related to the unchanging radial hydraulic conductivity in the bark tissues. Also, the significant correlation found between MDS and Ψ_{stem} (Figure 4) confirmed that one of the main factors controlling MDS was the water potential (Molz and Klepper, 1973).

The above mentioned results indicate that in early maturing peach trees with an alternate crop load pattern, MDS and Ψ_{stem} baselines or reference values can be obtained by pooling data across several seasons for ET_o , VPD_m and T_m , and ET_o and VPD_m , respectively. This means that the use of MDS and Ψ_{stem} baselines for irrigation scheduling may be less complex than was previously supposed. The inter and intra season constancy of the relation between MDS and Ψ_{stem} underlines the constancy of the radial hydraulic conductivity of bark tissues and confirms the idea that the main factor controlling MDS is the water potential.

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Chapter 3:

Influence of crop load on maximum daily trunk shrinkage reference equations for irrigation scheduling of early maturing peach trees

Abstract

The effects of high crop load (unthinned trees, 22-23 fruits cm⁻² of trunk cross sectional area (TCSA)), commercial crop load (3-4 fruits cm⁻² of TCSA), and no crop load (all fruitlets removed) on maximum daily trunk shrinkage (MDS), trunk growth rate (TGR) and stem water potential (Ψ_{stem}) were studied during the fruit growth period and 20 days following harvest in fully irrigated early maturing peach trees, *Prunus persica* (L.) Batsch, cv. Flordastar. Even though crop load did not affect plant water status, the MDS and TGR values increased and decreased, respectively, as a result of the crop load effect. In this sense, for the same Ψ_{stem} value, there was a linear increase in MDS with crop load, with a slope of 6.6 $\mu\text{m MPa}^{-1}$ per unit of crop load increment. The effects of environmental conditions on daily MDS values were also dependent on crop load, suggesting that MDS reference values should be obtained by representing the relations between MDS and the climatic variables (daily mean air temperature, daily mean vapour pressure deficit and daily crop reference evapotranspiration) for a given crop load. The constancy of the relation between MDS and Ψ_{stem} across crop load underlined the constancy of the elastic properties of the bark tissues.

Key words: Maximum daily trunk shrinkage, Trunk growth rate, Stem water potential, Crop load, Reference equations, Plant water relations.

1. Introduction

To determine what the exact crop water requirements are at any moment, measurements of the plant water status could provide a promising technique for irrigation management because of its dynamic nature, which is directly related with meteorological and soil conditions, as

well as with crop productivity (Goldhamer et al., 2003; Remorini and Massai, 2003).

Continuous records of stem diameter have been widely 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 this sense, recently, Ortuño et al. (2009c) have reviewed the state of the art as regards the use of trunk diameter fluctuations derived parameters for irrigation scheduling in woody crops. To our knowledge, Goldhamer and Fereres (2004) were the first to demonstrate that it is feasible to develop a deficit irrigation schedule based only on maximum daily trunk shrinkage (MDS) measurements in almond trees. Subsequently, García-Orellana et al. (2007), Velez et al. (2007) and Ortuño et al. (2009d) confirmed that in citrus MDS measurements are indeed suitable for adjusting the deficit irrigation schedule.

Recent results have showed that maintaining MDS signal intensity (SI, actual MDS/well irrigated MDS) around the unity could be successfully employed for scheduling full irrigation, avoiding the absence of soil water deficit (Conejero et al., 2007b; Ortuño et al., 2009a). This irrigation management will be very useful to precisely match the irrigation applied with the actual amount of crop water used. In addition, in situations where drainage can be avoided, and in the absence of rainfall, this strategy could be considered as a tool for estimating crop evapotranspiration (Ortuño et al., 2009c).

The concept of MDS SI arises taking into account that the plant water status is the result of the effects of the soil water available to the plant and the climatic conditions. Then, the use of absolute values for plant-based water status indicators is meaningless and it is more meaningful to use the concept of signal intensity, normalizing the absolute values with respect to values in non-limiting soil water conditions

(Goldhamer and Fereres, 2001, Naor and Cohen, 2003, Ortuño et al., 2006).

Plant-based water status indicators reference values can be obtained by maintaining trees in conditions of non-limiting soil water supply (Conejero et al., 2007a; García-Orellana et al, 2007). Nevertheless, when trees are irrigated much above their water requirements in order to obtain non-limiting soil water conditions, oxygen status may be affected. Moreover, under flooding stress conditions, MDS values increase in the same manner as observed in response to drought stress (Ortuño et al., 2007), which complicates the information needed for irrigation scheduling. It would therefore be useful to develop reference equations to interpret the values of a plant-based water status indicator. These reference values can be obtained by relating their values in trees under non-limiting soil water conditions with the evaporative demand of the atmosphere (Moreno et al., 2006, Conejero et al., 2007b, Ortuño et al., 2009b).

Some authors have indicated that crop load may increase transpiration rates (Chalmers et al., 1983), stomatal conductance (DeJong, 1986), leaf photosynthesis (Gucci et al., 1994), and tree water use (Mpelasoka et al., 2001). In contrast, Williamson and Coston (1989) pointed to a reduction in water uptake as a result of the crop load effect, while other authors showed that the effect of crop load on tree water status is not obvious (Naor et al., 1999) or is apparent only under deficit irrigation conditions (Naor, 2004).

It has been shown that MDS values can also be affected by other factors, such as tree age (Moriana and Fereres, 2004) or phenological period (Marsal et al., 2002; Intrigliolo and Castel, 2004; Moriana and Fereres, 2004; Conejero et al., 2007b). Moreover, Marsal et al. (2002) and Intrigliolo and Castel (2006) showed that the relationship between MDS and Ψ_{stem} is affected by the presence or absence of fruits, indicating that crop load might directly influence this relationship. However, Intrigliolo and

Castel (2007a) showed that despite a trend for MDS to increase with a heavy crop load, the slope of the MDS vs Ψ_{stem} relationship was not significantly affected by crop load.

Taking into account these considerations, the specific objectives of this paper were: (1) to evaluate the crop load effect on plant water status and TDF-derived parameters during the fruit growth period, (2) to determine the influence of climatic factors on MDS as a function of crop load, and (3) to evaluate the influence of crop load on the MDS vs Ψ_{stem} relationship.

2. Materials and methods

2.1. Experimental conditions, plant material and treatments

The experiment was performed in 2008, in a seven-year old early maturing peach orchard (*Prunus persica* (L.) Batsch, cv. Flordastar grafted on GF-677 peach rootstock) at the CEBAS-CSIC experimental station in Santomera (Murcia, Spain) (38° 06' N, 1° 02' W, elevation 110 m). The soil is stony (33% w/w) and shallow, with a clay-loam texture. Analytical data showed a high lime content, very low organic matter content, low cationic exchange capacity, and low available potassium and phosphorus levels. Available soil water and bulk density were 200 mm m⁻¹ and 1.58 g cm⁻³, respectively. The volumetric soil water content at saturation and field capacity were 0.49 and 0.35 m³ m⁻³, respectively. The irrigation water had a mean EC of 1.1 dS m⁻¹ and a mean Cl⁻ concentration of 26 mg l⁻¹. The trees were trained to an open-centre canopy. Tree spacing followed a 5 m x 5 m square pattern, with an average ground cover of about 78.5%. Pest control and fertilization practices were those commonly used by the growers, and no weeds were allowed to develop within the orchard.

From 11 March 2008 (day of year 71, DOY 71) to 19 May (DOY 140), peach trees were irrigated daily above the estimated crop evapotranspiration ($156\% ET_C$) in order to obtain non-limiting soil water conditions. Crop irrigation requirements were determined according to daily crop reference evapotranspiration (ET_o), calculated using the Penman-Monteith equation (Allen et al., 1998), and a crop factor based on the time of the year (FAO 56, Allen et al., 1998) and the percentage of ground area shaded by the tree canopy (Fereres and Goldhamer, 1990). Irrigation was carried out during the night using a drip irrigation system with one lateral pipe per tree row and eight emitters (each delivering 2 l h^{-1}) per plant. Total water amounts applied were measured with in-line water meters.

On 10 March (DOY 70) peaches were thinned in order to obtain three different crop load treatments. In the control treatment (T0) fruits were not thinned; in T1 fruitlets were hand-thinned to leave 25 cm between the fruits (commercial crop load), and in T2 all the fruitlets were removed by hand (Picture 1).

2.2. Measurements

Every 30 min micrometeorological data, namely air temperature, solar radiation, air relative humidity, rainfall and wind speed 2 m above the soil surface, were collected by an automatic weather station located near the experimental site. Daily mean vapour pressure deficit (VPD_m) was calculated according to Allen et al. (1998).

The soil volumetric water content (θ_v) of the top 150 mm of the soil profile was measured by time-domain-reflectometry (TDR) (model 1502C, Tektronix Inc., OR.), as described by Moreno et al. (1996). The θ_v content of the soil from 0.2 m down to a maximum depth of 0.80 m was measured every 0.1 m using a neutron probe (model 4300, Troxler Electronic

Laboratories, Inc. NC.) in access tubes installed 1.0 m away from the trees and besides the emitters. Measurements were taken in the morning during the experimental period.

At midday (12.00 h solar time), stem water potential (Ψ_{stem}) was measured in two mature leaves per plant (four trees per treatment), taken close from the trunk. Leaves were enclosed in a small black plastic bag covered with aluminium foil for at least 2 h before measurements were made in a pressure chamber.

The micrometric trunk diameter fluctuations (TDF) were measured throughout the experimental period in four trees per treatment, using a set of linear variable displacement transducers (LVDT) (model DF $\pm$ 2.5 mm, accuracy $\pm$ 10 μ m, Solartron Metrology, Bognor Regis, UK) attached to the trunk, with a special bracket made of Invar, an alloy of Ni and Fe with a thermal expansion coefficient close to zero (Katerji et al., 1994), and aluminium. Sensors were placed on the north side and were covered with silver thermoprotected foil to prevent heating and wetting of the device. Measurements were taken every 2 s and the datalogger (model CR10X with AM25T multiplexer, Campbell Scientific, Logan, UT) was programmed to report 15 min means. Maximum daily trunk shrinkage (MDS) was calculated as the difference between maximum and minimum daily trunk diameter, and trunk growth rate (TGR) was determined as the increment in maximum daily trunk diameter.

The effect of T0 and T1 treatments on fruit size was assessed by evaluating the proportions of marketable and non-marketable fruit production (fruits with a diameter above or below 56 mm, respectively). According to EEC directive 3596/90 (Ministerio de Agricultura, Pesca y Alimentación, 1995), 56 mm is the minimum diameter for a fruit to be considered in the extra category, which can be subdivided into different categories: A, 73 mm > diameter $\geq$ 67 mm; B, 67 mm > diameter $\geq$ 61 mm and C, 61 mm > diameter $\geq$ 56 mm.

Picture 1. Fruits were not thinned (A), fruitlets were hand-thinned to leave 25 cm between the fruits (commercial crop load) (B), and all the fruitlets were removed by hand (C).

2.3. Statistical design and analysis

The design of the experiment was completely randomized with four replications, each replication consisting of three adjacent tree rows of 13 trees. Measurements were taken in the central tree of the central row of each replicate, and the other trees served as border trees. All the trees presented a very similar appearance (leaf area, trunk cross sectional area,

height, ground shaded area, etc.), A two-way ANOVA was performed and means were separated by LSD_{0.05} range test. Percentage values were arc-sin-transformed before statistical analysis.

All the measurements were taken on the same tree in each replicate. Ψ_{stem} values for each day and replicate were averaged before the mean and the standard error of each treatment were calculated.

3. Results

During the experiment, average daily maximum and minimum air temperatures were 23.3 and 11.3 °C, respectively, and average mean relative humidity was 55% (data not shown). Total rainfall was very low (86 mm), falling mainly on DOY 129 and 139 (Figure 1). Daily VPD_m and daily mean air temperature (T_m) fluctuated, reaching average values of 1.17 kPa and 17.3 °C, respectively (Figure 1). Total daily ET_o reached 313.9 mm (Figure 1).

Figure 1. Daily crop reference evapotranspiration (ET_o, solid thin line in black), daily mean air temperature (T_m , solid thick line in red), daily mean air vapour pressure deficit (VPD_m, short dash line in red) and daily rainfall (sky-blue vertical bars) during the experimental period.

The mean crop load, fruit load efficiency and fruit yield differed substantially between T0 and T1, as expected (Table 1) (Picture 2). Moreover, the higher crop load of the T0 trees was responsible for a lower average fruit weight (Table 1), and all the fruits were included in the non-extra category (data not shown). However, fruits from T1 trees confirmed the efficacy of thinning to produce a commercial crop, 30.0%, 30.0% and 18.7% of fruits corresponding to A, B and C extra categories, respectively, and 21.3% to non-extra category (data not shown).

Table 1. Mean crop load (number of fruits tree⁻¹), fruit load efficiency (number of fruits per tree divided by trunk cross sectional area (cm²)), average fruit weight (g) and fruit yield (kg tree⁻¹) in T0 and T1 trees. Means within a column that do not have a common letter are significantly different at $P < 0.001$.

Treatment	Crop load	Fruit load efficiency	Fruit weight	Yield
T0	3114.0 a	22.74 a	30.23 a	95.2 a
T1	547.0 b	3.52 b	123.5 b	62.8 b

Picture 2. View of the peach production obtained at harvest.

The average θ_v from 0 to 0.80 m depth was nearly constant, with values always very close to field capacity (100.4% of θ_v value at field capacity) (Figure 2A). From the beginning of the experiment, θ_v values in

the soil not affected by irrigation (between two adjacent tree rows) gradually decreased, reaching values near permanent wilting point on DOY 126; however, this level increased afterwards as a consequence of the rainfall that occurred on DOY 129 and 139 (Figure 2A).

Minimum fluctuations in Ψ_{stem} values were observed in T0, T1 and T2 treatments (Figure 2B). In this sense, no differences in Ψ_{stem} values between T0 and T1 trees or between T0 and T2 trees were observed. Moreover, Ψ_{stem} values in T1 and T2 trees were similar except on DOY 109 and 112 (Figure 2B).

During the fruit growth period and the few first days after harvest, MDS values increased through the effect of crop load (Figure 2C). The differences in MDS values between T0 and T2 trees were statistically significant on most days during the fruit growth period, and from harvest to DOY 130. The differences in MDS values between T1 and T2 trees occurred during a part of fruit growth period (DOY 84-119), and on DOY 121 and 130 (postharvest). However, the differences between T0 and T1 trees were less frequent, occurring during the fruit growth period on DOY 72, 73, 94, 97 and from DOY 113 to 120, and only on DOY 125 and 126 during the postharvest period.

TGR values decreased through the effect of crop load, statistically significant differences existing between treatments from DOY 71 to 135 (Figure 2D). This behaviour was mainly due to the existence of statistically significant differences in TGR values between T0 and T2 trees, and T1 and T2 trees. TGR values in T0 and T1 were significantly different during the fruit growth period only on DOY 71, 72, 89, 95, 98, 101 and 102, and during the postharvest period only on DOY 122 and 130.

Figure 2. Volumetric water content down to 0.80 m depth in the soil affected (dark circles) and non-affected (yellow squares) by irrigation (A), midday stem water potential (Ψ_{stem}) values in T0 (red triangles), T1 (dark circles) and T2 (green circles) trees (B), maximum daily trunk shrinkage (MDS) in T0 (red triangles), T1 (dark circles) and T2 (green circles) trees (C), and daily trunk growth rate (TGR) in T0 (red triangles), T1 (dark circles) and T2 (green circles) trees (D) during the experimental period. The periods of time between vertical dotted lines from left to right represent phase I, II and III of the fruit growth. Horizontal lines, from bottom to top, represent soil volumetric water content at permanent wilting point and at field capacity, respectively. Vertical bars are twice the overall mean SE. Asterisks indicate statistically significant differences treatments at 5% level ($\text{LSD}_{0.05}$) range test. Each point is the mean of four values.

The associations of MDS with climatic variables during the fruit growth period showed a linear relationship between MDS and T_m , whereas MDS was better related with VPD_m and ET_o with both of which it showed an exponential rather than a linear relationship (Figure 3). The covariance analysis of the MDS vs T_m baselines obtained in the three treatments showed that differences in slopes and intercepts were not statistically significant, meaning that it was possible to evaluate MDS by pooling data from the three crop load treatments (Figure 3A). In contrast, there were statistically significant differences in the relationships between MDS versus ET_o and VPD_m as a function of crop load (Figures 3B and 3C). Thus, covariance analysis of the MDS vs ET_o and VPD_m baselines obtained in the three treatments indicated that differences in slopes were statistically significant in the case of T2 with respect to T0 and T1, whereas slopes in T0 and T1 were not significantly different.

Neither the slopes nor the intercepts of the linear regression equations of MDS vs Ψ_{stem} in the three treatment trees were significantly affected by crop load (Figure 4). The MDS/Ψ_{stem} ratio of each recorded tree was negatively related to its crop load (Figure 5), meaning that increases in tree crop load were related with a higher MDS for a given Ψ_{stem} value.

Figure 3. Relationships between maximum daily trunk shrinkage (MDS) and mean daily air temperature (T_m) (A), mean daily air vapour pressure deficit (VPD_m) (B), and crop reference evapotranspiration (ET_o) (C) during fruit growth period, using all data pooled. Each data point is the mean of four values. Symbols as in Figure 2.

Figure 4. Relationship between maximum daily trunk shrinkage (MDS) and midday stem water potential (Ψ_{stem}) during fruit growth period, using all data pooled. Each data point is the mean of four values. Symbols as in Figure 2.

Figure 5. Relationship between the mean MDS: Ψ_{stem} ratio, calculated over the fruit thinning at harvest, and tree crop load. Symbols as in Figure 2.

4. Discussion

The fact that average θ_v values were near constant and close to field capacity, and that the rainfall which occurred on DOY 129 and 139,

increasing θ_v values in the non-irrigated soil, did not affect plant water status (Ψ_{stem}) confirmed that trees were under non-limiting soil water conditions during the experimental period (Figures. 2A and B).

The presence of more frequent statistically significant differences in daily values of MDS and TGR between T0 and T2 trees and T1 and T2 trees, than between T0 and T1 trees, suggests that the presence or absence of fruits has more effect than fruit load on MDS and TGR values (Figures 2C, D and 5). Moriana and Fereres (2004) indicated that the increases in MDS through the crop load resulted from increased transpiration rates due to the presence of fruits. However, the absence of crop load effect on plant water status (Figure 2B) suggests that the MDS increase was not a consequence of lower Ψ_{stem} values (Goldhamer et al., 1999; Remorini and Massai, 2003; Ortuño et al., 2009b). Moreover, the absence of crop load effect on Ψ_{stem} suggests that xylem water potential at the point where stem shrinkage was measured was also unaffected by tree crop load. Therefore, it seems reasonable to think that the effect of crop load on MDS was not related with the effect of increasing transpiration rate on xylem water potential.

The opposite responses of MDS and TGR to crop load (Fig. 2C and D) could be related with the suggestion of McBurney and Costigan (1984) that trunk shrinkage is greater for a given Ψ_{stem} when trunk growth is low. In this sense, Ryugo et al. (1977) and Buwalda and Lenz (1992) showed that high crop load decreases sugars content of woody tissues, thereby presumably increasing the osmotic potential of phloem tissues. Cochard et al. (2001) and Intrigliolo and Castel (2007a) suggested that this behaviour could lead to a larger water potential gradient between the xylem and the bark, and, in turn to larger trunk contractions for a given Ψ_{stem} in trees with a high crop load. Sevanto et al. (2003) and Daudet et al. (2005) indicated that daily stem diameter variations should be interpreted not only in the context of the water balance of the plant but also taking into consideration

the carbon balance of the plant. In this sense, for a given water status (Ψ_{stem}), in the range of crop load evaluated (0 to 27 fruit cm^{-2} TCSA), MDS increased by 6.6 μm per unit increment of crop load (Figure 5).

Some authors have mentioned the influence of crop load on the MDS vs Ψ_{stem} relationship (Marsal et al., 2002; Fereres and Goldhamer, 2003; Intrigliolo and Castel, 2006). According to Intrigliolo and Castel (2004), this may be due to changes in trunk growth rate and tissue elasticity. In contrast, our results showed a constant relationship between MDS and Ψ_{stem} (Figure 4), suggesting that during the fruit growth period of early maturing peach trees these explanations are not relevant, and, in agreement with Génard et al. (2001), the cause of this behaviour is probably related to the constancy in the radial hydraulic conductivity of bark tissues.

In contrast with Moriana and Fereres (2002) and Nortes et al. (2005), who proposed TGR as a suitable water stress indicator because, they suggested, a decrease in TGR is one of the earliest signals of plant water stress in young trees, our results showed that TGR does not offer an independent measure of plant water status in mature peach trees because it is affected by crop load (Figure 2D) and phenological stage (Berman and DeJong, 2003; Conejero et al., 2007b). The reduced availability of carbohydrates for trunk growth, as a result of increased competition for assimilates between fruits and trunk, may explain the decrease in TGR values caused by high crop load. The absence of statistically significant differences in TGR values from two weeks after harvest onward (Figure 2D) confirmed the inhibitory effect of fruits on TGR.

Taking into account the MDS time scale, it was to be expected that MDS would correlate with the evaporative demand indicators measured on a whole-day basis (T_m , VPD_m , and ET_o) (Figure 3). Moreover, according to Huguet et al. (1992) and Ortuño et al. (2006), the MDS data association

with changes in ET_o and VPD_m can be explained by taking into consideration that MDS is a versatile indicator of transpiration stream intensity when the soil water content is not strongly depleted. In agreement with the results provided by Moriana and Fereres (2004) for olive trees and Intrigliolo and Castel (2007a) for plum trees, the effects of environmental conditions on daily MDS values during fruit growth were dependent on crop load (Figure 3). This implies that, when using reference equations for irrigation scheduling, specific equations as a function of crop load should be used to avoid errors in the estimation of MDS values as a function of ET_o or VPD_m .

5. Conclusion

The above mentioned results indicated that the plant water status (Ψ_{stem}) was not influenced by yield or crop load factors. However, it is important to consider crop load when intending to use MDS or TGR as water stress indicators. Also, the effects of environmental conditions on daily MDS values were dependent on crop load, indicating that specific MDS reference equations as a function of crop load should be developed for use in irrigation scheduling. The finding that MDS is influenced by factors besides plant water status means that MDS measurements may need adjustment before they can be used in irrigation scheduling, meaning that their use is not so straightforward as earlier believed. The constancy of the relation between MDS and Ψ_{stem} and the goodness of the correlation underlined the constancy of the radial hydraulic conductivity of bark tissues.

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Chapter 4:

Using trunk diameter sensors for regulated deficit irrigation scheduling in early maturing peach trees

Abstract

The aim of this paper was to test the possibility of scheduling regulated deficit irrigation (RDI) using exclusively maximum daily trunk shrinkage (MDS) measurements, and that RDI strategies can be applied in early maturing peach trees reducing significantly the seasonal water use. During three growing seasons, 6-year-old peach trees (*Prunus persica* (L.) Batsch cv. Flordastar) grafted on *P. persica* x *P. amygdalus* GF-677 peach rootstock were submitted to different drip irrigation treatments. Control (T0) plants were irrigated above the estimated crop evapotranspiration level ($\approx 130\% ET_C$) and T1 plants were submitted to RDI, which were irrigated in order to maintain MDS signal intensity (SI) values close to unity (no irrigation-related stress) from the fruit thinning stage to 2 weeks after harvest, at MDS SI values close to 1.3 during the early postharvest period, and at MDS SI values of 1.6 during the late postharvest period. The RDI strategy assayed reduced the seasonal water applied by 35-42% with respect to estimated ET_C without affecting yield efficiency components or the distribution of different peach fruit categories, while improving water productivity. The only vegetative growth component affected by RDI was pruning weight, indicating that vigor regulation as a result of RDI may decrease the competition for assimilates between vegetative apices and reserve tissues. Also, the absence of any significant effect of RDI on the ratio between yield and the increase in trunk cross sectional area suggested similar carbon partitioning schemes during fruit growth. To improve the precision of MDS SI-driven schedule in RDI strategies changes in the irrigation protocol should be considered so that the scheduled water deficit levels are attained more rapidly. For this, when it is necessary to change from a MDS SI threshold value to a higher one, the daily irrigation rate should be decreased by more than 3%.

Keywords: Regulated deficit irrigation, Maximum daily trunk shrinkage, Stem water potential, Trunk diameter fluctuations, Plant water relations.

1. Introduction

Mediterranean agrosystems are characterised by the aridity of the climate and the persistent shortage of water resources. This situation is aggravated by the strong competition for the water that is available with other non-agricultural users that has arisen in recent years. Consequently, to cope with this water scarcity new and precise tools for accessing crop water requirements are needed, and biological and physical criteria need to be established to develop more adequate and precise deficit irrigation management practices (Goldhamer and Fereres, 2001; Pereira et al., 2002; Naor, 2006; Katerji et al., 2008).

Regulated deficit irrigation (RDI) is an irrigation strategy designed to save water with a minimum impact on yield and fruit quality (Chalmers, 1989; Goldhamer, 1989; Naor, 2006). RDI strategies require precise knowledge of the crop response to drought stress during different phenological phases, in order to identify phenological periods in which adverse effects on productivity are minimized (non-critical periods). In stone fruits trees two critical periods have been defined (Torrecillas et al., 2000). The first one corresponds to the second rapid fruit growth period (stage III), when drought stress induces a reduction in yield due to the smaller fruit size at harvest. The second critical period is the early postharvest period, in which drought stress affects flower bud induction and/or the floral differentiation processes that occur at this time. This leads to a lower germination potential in the pollen in the next bloom and encourages young fruit to drop in the following season (Uriu, 1964; Ruiz-Sánchez et al., 1999).

It is important to bear in mind that in peach trees RDI can reduce yield if the recovery of tree water status is delayed after deficit irrigation, particularly when the drought stress extends into the stage III of fruit development (Girona et al., 1993; Goldhamer et al., 2002). For this reason, in early maturing peach trees, with their very short period from fruit

set to harvest and a very long post-harvest phenological period, deficit irrigation should be applied only during the post-harvest period in order to avoid any effect on yield and fruit quality.

In recent years, the use of plant-based water status indicators has become very popular for planning more precise irrigation programmes, because it is recognized that the tree itself is the best indicator of its water status (Shackel et al., 1997; Fernández and Cuevas, 2010). Since the plant water status controls many physiological processes and crop productivity, this information can be highly useful in irrigation scheduling (Ortuño et al., 2010). Particularly under deficit irrigation conditions, the continuous control of tree water status is crucial in order to prevent a moderate, potentially beneficial, drought stress from becoming too severe and ending in a reduction of yield (Domingo et al., 1996; Johnson et al., 1992). In this sense, sensors like LVDTs are able to measure daily trunk diameter fluctuations (TDF) with great precision, generating sensitive parameters which strongly correlate with established plant water status parameters (Ortuño et al., 2010). The most common TDF parameter for the irrigation scheduling of stone fruit trees is the maximum daily trunk shrinkage (MDS) (Huguet et al 1990; Ortuño et al 2010). Moreover, the operational advantages of TDF measurements, such as the possibility of connecting remotely operated irrigation automatic devices, and the ability to rapidly adjust schedules in response to the daily signal, make MDS a very suitable tool for precise irrigation scheduling (Goldhamer and Fereres, 2001).

The magnitude of MDS even in a fully irrigated tree is not constant over a period of days with the same water status but different environmental conditions (Zweifel and Häslar, 2001). On the other hand, from earlier studies, it is known that MDS values increased in response to drought stress (e.g. Moriana et al., 2000; Deslauriers et al., 2003; Ortuño et al., 2006; Intrigliolo and Castel 2007; Klepper et al., 1971), though

severe conditions of drought stress decrease MDS values (Moriana et al., 2000; Ortuño et al., 2006; Intrigliolo and Castel, 2007). Because of this, absolute MDS values registered without considering the evaporative demand might be meaningless, and for irrigation scheduling it is better to use the concept of signal intensity (SI), normalizing the absolute MDS values with respect to those in non-limiting soil water conditions (actual MDS/reference MDS) (Goldhamer and Fereres, 2001; Naor and Cohen, 2003; Ortuño et al., 2005, 2006, 2010). These MDS values in non-limiting conditions may be obtained from over-irrigated trees (so called reference trees), or reference equations that can estimate these values from meteorological data, so called baselines (Goldhamer and Fereres, 2001). Therefore, MDS SI is a dimensionless variable, where values above unity indicate drought stress levels, while SI values of unity indicate the absence of irrigation-related stress (Goldhamer and Fereres, 2004; Ortuño et al., 2010). In addition, SI values clearly below unity could be used to predict the presence of trees suffering very severe drought stress, or a flooding stress in reference trees because this stress also induces an increase in MDS values (Vanniere, 1992; Ortuño et al., 2007).

The research reported in this paper was conducted to test the hypotheses that i) RDI scheduling can be based exclusively on MDS measurements, and ii) that by maintaining MDS SI values close to unity during fruit growth (absence of irrigation-related stress), a moderate water deficit during early postharvest period and a more severe drought stress during late postharvest period, it is possible to save water without affecting yield and fruit components.

2. Materials and methods

2.1. Experimental conditions, plant material and treatments

The experiment was performed in a plot of the CEBAS-CSIC experimental station in Murcia (Spain) (38° 06' N, 1° 02' W) during three growing seasons (2007, 2008 and 2009). The soil, classified as a Lithic xeric haploxeroll (Soil Survey Staff, 2006), is stony (33%, w/w) and shallow, with a clay-loam texture. Analytical data showed a high lime content (56% calcium carbonate), very low organic matter content (0.34%), low cationic exchange capacity (12.6 meq 100g⁻¹), and low available potassium and phosphorus levels. Available soil water and bulk density were 200 mm m⁻¹ and 1.58 g cm⁻³, respectively. The volumetric soil water content at saturation, field capacity and permanent wilting point were 0.49, 0.35 and 0.15 m³ m⁻³, respectively. The irrigation water had a mean EC of 1.1 dS m⁻¹ and an average Cl⁻ concentration of 26 mg l⁻¹.

The plant material consisted of 6 year old (in 2007) early maturing (mid-May) peach trees (*Prunus persica* (L.) Batsch cv. Flordastar) grafted on *P. persica* x *P. amygdalus* GF-677 peach rootstock and trained to an open-centre canopy. Tree spacing followed a 5 m x 5 m square pattern. Hand-thinning was used to space fruitlets along the fruit bearing stems to 25 cm for the commercial crop load. Pest control was that commonly used by the growers, and no weeds were allowed to develop within the orchard. Fertilization practices followed the principle of re-establishing nutrients taken up by the plants, and then all treatments received the same amount of nutrients. In order to avoid the use of more concentrated solutions in T1 during the deficit irrigation periods, fertilizers were applied in both treatments only during the timing of water application corresponding to T1 treatment.

Crop irrigation requirements (ET_C) were estimated according to daily crop reference evapotranspiration (ET_o), calculated using the Penman-Monteith equation (Allen et al., 1998), and a crop factor based on the time of the year (FAO 56, Allen et al., 1998) and the percentage of ground area shaded by the tree canopy (Fereres and Goldhamer, 1990). Control plants (treatment T0) were irrigated daily above the estimated crop evapotranspiration level ($\approx 130\% ET_C$) in order to obtain non-limiting soil water conditions. Before fruit thinning (day of the year (DOY) 67, 71 and 79 in 2007, 2008 and 2009, respectively), the regulated deficit irrigation (RDI) treatment (T1) was irrigated at $100\% ET_C$ values. The RDI plants were then irrigated to maintain MDS SI at three different plant water status levels. From fruit thinning to 2 weeks after harvest (DOY 141, 137 and 144 in 2007, 2008 and 2009, respectively), RDI plants were irrigated to maintain MDS SI at values close to unity (no irrigation-related stress). During the early postharvest period (from 2 weeks after harvest (DOY 142, 138 and 145 in 2007, 2008 and 2009, respectively), to DOY 195, 190 and 190 in 2007, 2008 and 2009, respectively), RDI plants were irrigated to maintain MDS SI values close to 1.3. Finally, during the late postharvest period (from DOY 196, 191 and 191 in 2007, 2008 and 2009, respectively, to when the leaves fall (DOY 233, 265 and 256 in 2007, 2008 and 2009, respectively)), RDI plants were irrigated to maintain MDS SI values close to 1.6 (Picture 1).

In T1, the irrigation rate was decreased by 3% when the MDS SI did not exceed the threshold value on the previous day, and increased by 3% when the MDS signal intensity exceeded the threshold value. This irrigation protocol was based on that proposed by Goldhamer and Fereres (2001) for mature trees under high frequency irrigation. The MDS signal intensity threshold values of 1.3 and 1.6, and the application period, were adopted because, according to previous experience (Conejero, 2008; Abrisqueta et al., 2008), they would induce different drought stress levels. For both the T0 and T1 treatments, irrigation was carried out during the

night using a drip irrigation system with one lateral pipe per tree row and eight emitters (each delivering 2 l h^{-1}) per plant. An informatization and telemonitoring system (via radio) controlled the moments of irrigation and fertilization and their duration. Also, information of the applied volumes of water was obtained by means of flow meters integrated in the system.

Picture 1. View at field of the phenological periods to peach tree. MDS SI values close to unity during fruit growth (absence of irrigation-related stress) (A), a moderate water deficit during early postharvest period (B) and a more severe drought stress during late postharvest period (defoliation) (C).

2.2. Measurements

A. Climate

Every 15 min micrometeorological data, namely air temperature, solar radiation, air relative humidity, rainfall and wind speed 2 m above the soil surface, were collected by an automatic weather station located near the experimental site, which was integrated in the same irrigation telemonitoring system.

B. Soil water content

The soil volumetric water content (θ_v) of the top 150 mm of the soil profile was measured by time-domain-reflectometry (TDR) (model 1502C, Tektronix Inc., OR.), as described by Moreno et al. (1996). The θ_v content of the soil from 0.2 m down to a maximum depth of 0.80 m was measured every 0.1 m using a neutron probe previously calibrated for the site (model 4300, Troxler Electronic Laboratories, Inc. NC.), in access tubes installed 1.0 m from the trees and next to the emitters (10 cm). Measurements (four replications per treatment) were taken during the experimental period in the early morning every 7, 9 and 8 days in 2007, 2008 and 2009, respectively.

C. Stem water potential

Midday (12.00 h solar time) stem water potential (Ψ_{stem}) was measured in two mature leaves per plant (four plants per treatment), taken close to the trunk. Leaves were enclosed in a small black plastic bag covered with aluminium foil for at least 2 h before measurements were made in a pressure chamber, according to the method described by Scholander et al. (1965), using a pressure chamber (Soil Moisture Equipment Co., Santa Barbara, CA, USA).

D. Trunk diameter fluctuations

The micrometric trunk diameter fluctuations (TDF) were measured throughout the experimental period in four trees per treatment, using a set of linear variable displacement transducers (LVDT) (model DF $\pm$ 2.5 mm, accuracy $\pm$ 10 μ m, Solartron Metrology, Bognor Regis, UK) attached to the trunk, with a special bracket made of Invar, an alloy of Ni and Fe with a thermal expansion coefficient close to zero (Katerji et al., 1994), and aluminium. Sensors were placed on the north side and were covered with silver thermoprotected foil to prevent heating and wetting of the device. In order to eliminate measurement noise, old bark was carefully eliminated with a sharpened knife. Then, TDF measurements included only the contributions of the phloem and xylem. Measurements were taken every 2 s and the datalogger (model CR10X with AM25T multiplexer, Campbell Scientific, Logan, UT) was programmed to report 15 min means. Maximum daily trunk shrinkage (MDS) was calculated daily as the difference between maximum and minimum daily trunk diameter.

E. Vegetative and yield components

Trunk diameter was determined with a forest caliper about 30 cm above the graft union during dormancy of each year. Trunk cross sectional area (TCA) was estimated as equivalent to a circle. Trees were pruned in winter each year and the pruning of trees was weighed (Picture 2). A sample was dried at 70°C to a constant weight. Ground cover area (GC) was estimated annually in summer. A large tarpaulin (4 m x 4 m) divided into 625-cm² squares, was placed under the tree around solar noon and the total number of shaded squares were digitally analyzed using the photo-software Corel PHOTO-PAINT X4.

The effect of the irrigation treatments on fruit size was studied evaluating marketable and non-marketable production, as the proportion of fruits with a diameter above or below 56 mm, respectively. According to

Commission Regulation (EC) n° 1221 (2008), 56 mm is the minimum diameter for a fruit to be considered in the 'extra' category, which can be subdivided into different categories: (A) 73 mm > diameter $\geq$ 67 mm; (B) 67 mm > diameter $\geq$ 61 mm and (C) 61 mm > diameter $\geq$ 56 mm.

Picture 2. Peach trees were pruned in winter each year and the pruning of trees was weighed.

2.3. Statistical design and analysis

The design of the experiment was completely randomized with four replications, each replication consisting of three adjacent tree rows, each with 13 trees. Measurements were taken on the inner tree of the central row of each replicate, which presented very similar appearance (leaf area, trunk cross sectional area, height, ground shaded area, etc.), while the other trees served as border trees. In order to make percentage values more suitable for statistical analysis, their values were arc-sin-transformed before statistical analysis (Sokal and Rohlf, 1995). Statistical analysis was performed by two-way analysis of variance using general linear model (GLM) of SPSS v. 17.0 (SPSS Inc., 1996). Means were separated by the $LSD_{0.05}$ range test.

All the measurements were taken on the same tree in each replicate. Ψ_{stem} values for each day and replicate were averaged before the mean and the standard error of each treatment were calculated.

3. Results

During the experimental period, the volumetric soil water content (θ_v) from 0 to 0.80 m depth in T0 was nearly constant, with values slightly above field capacity (Figure 1A). θ_v values in T1 during early and late postharvest periods gradually decreased and showed significant differences with respect to those observed in T0 (Figure 1A). In T1 plants MDS and Ψ_{stem} values showed a tendency to increase and decrease, respectively, as a result of decreasing irrigation volumes. Significant differences between treatments in MDS and Ψ_{stem} values were observed mainly from the middle of the early postharvest period onwards (Figure 1B and C).

In 2007, Ψ_{stem} values of T0 ranged from -0.3 to -0.9 MPa, whereas in T1 plants it reached minimum values of -1.2 and -1.6 MPa during the early and late postharvest periods, respectively (Figure 1B). In 2008, Ψ_{stem} values of T0 fluctuated within a range of -0.3 to -0.8 MPa, while minimum values in T1 during early and late postharvest periods were -1.1 and -1.6 MPa, respectively (Figure 1B). In 2009, Ψ_{stem} values of T0 ranged from -0.1 to -0.9 MPa, and minimum values in T1 during early and late postharvest periods were -1.0 and -1.3 MPa, respectively (Figure 1B).

Figure 1. Volumetric soil water content down to 0.80 m depth (θ_v) and precipitation (sky-blue vertical bars) (A), midday stem water potential (Ψ_{stem}) (B) and maximum daily trunk diameter shrinkage (MDS) (C) values in T0 (dark circles) and T1 (red circles) trees during the experimental period. Vertical dotted lines from left to right represent the beginning of early and late postharvest periods, respectively. Horizontal lines, from bottom to top, represent soil volumetric water content at permanent wilting point and at field capacity, respectively. Vertical bars are twice the overall mean SE. Asterisks indicate statistically significant differences between treatments at 5% level (LSD_{0.05} range test). Each point is the mean of four values.

In the three seasons, the different volumes of irrigation water applied for every day period from fruit thinning to 2 weeks after harvest were able to maintain the MDS SI values in T1 plants close to unity (average values of 0.96, 1.09 and 1.03 with a coefficient of variation (CV) values of 0.13, 0.10 and 0.17 in 2007, 2008 and 2009 season, respectively) (Figure 2). During the early postharvest period MDS SI average values were 1.16, 1.27 and 1.39 with a CV of 0.16, 0.26 and 0.07 in the 2007, 2008 and 2009 season, respectively, and during late postharvest period, MDS SI average values were 1.44, 1.51 and 1.58 with

a CV of 0.13, 0.13 and 0.15 in the 2007, 2008 and 2009 season, respectively (Figure 2).

In 2008, at the end of early postharvest, after a rainy period, a continuous increase in MDS SI values was observed (Figure 2), indicating a decrease in the irrigation precision. This behaviour was due to the important reduction of the irrigation rate during the rainy period, in order to try achieving the new MDS SI threshold value for this period, and the increase in ET_0 .

Figure 2. Maximum daily trunk shrinkage (MDS) signal intensity (SI) values in T1 treatment plants during the experimental period. Horizontal lines indicate the MDS signal intensity threshold values (1, 1.30 and 1.60). Vertical dotted lines from left to right represent the beginning of early and late postharvest periods, respectively. Each data point is the mean of four values.

Estimated ET_C reached 504-797 mm between 2007 and 2009 (Table 1). During the period in which plants were irrigated to maintain MDS SI at values close to unity (from fruit thinning to 2 weeks after harvest) the amount of water applied was reduced by 11-59% with respect to the estimated ET_C . In the RDI treatment (T1) 26-49% less water respect to ET_C was applied during the early postharvest period, and 26-63% less during the late postharvest period (Table 1). Meanwhile, the deficit irrigation applied during both the early and late postharvest periods reduced the water applied by 36-48% respect to estimated ET_C (Table 1).

Table 1. Precipitation (mm), reference evapotranspiration (ET_o , mm), estimated crop evapotranspiration (ET_c , mm) and irrigation applied (mm) to T0 (control) and T1 (regulated deficit irrigation scheduled using different maximum daily trunk shrinkage signal intensity (MDS SI) threshold values) treatments during different phenological periods (DOY). Values in parenthesis indicate obtained average MDS SI values.

Year	Period	MDS SI	Precipitation	ET_o	ET_c	Irrigation applied	
						T0	T1
2007	67-141	1 (0.96)	156	300	148	196	118
	142-195	1.3 (1.16)	34	328	214	286	158
	196-233	1.6 (1.44)	2	219	143	195	53
2008	71-137	1 (1.09)	47	301	184	262	164
	138-190	1.3 (1.27)	77	296	257	335	148
	191-265	1.6 (1.51)	18	410	356	462	173
2009	79-144	1 (1.03)	104	283	195	262	80
	145-190	1.3 (1.39)	4	298	257	345	131
	191-256	1.6 (1.58)	5	360	326	425	242

RDI treatment (T1) did not affect average ground cover, trunk cross sectional area and the increase in trunk cross sectional area during the 3 years of the experiment (Table 2). However, pruning weight values in RDI plants were significantly lower than in T0 plants (Table 2).

Yields in both irrigation treatments increased during the experimental period (Table 3), even though no effect of irrigation treatments on yield, crop load, fruit load efficiency, yield efficiency or yield per increase in trunk cross sectional area during this period was observed (Tables 2 and 3). However, water use efficiency was higher in T1 plants than in control plants (Table 2).

Table 2. Effect of irrigation treatments on vegetative and yield efficiency components (ground cover (GC, %), pruning weight (kg tree⁻¹), trunk cross sectional area (TCA, cm²), increase in trunk cross sectional area (Δ TCA, cm²), fruit load efficiency (number of fruits per tree/TCA, n°/cm²), yield per increase in trunk cross sectional area (Yield/ Δ TCA, kg cm⁻²) and water use efficiency (WUE, kg m⁻³)) during the experimental period. Means for each year within a column that do not have a common letter are significantly different by LSD_{0.05} test.

Year	Treatment	GC	Pruning	TCA	Δ TCA	Fruit load efficiency	Yield/ Δ TCA	WUE
2007	T0	44.5a	13.4a	127.8a	22.6a	1.15a	0.80a	1.06a
	T1	42.8a	8.8b	114.3a	16.3a	1.12a	0.99a	1.96b
2008	T0	78.5a	18.7a	158.6a	24.4a	1.72a	1.34a	1.24a
	T1	68.7a	10.7b	139.3a	14.2a	1.62a	2.07a	2.41b
2009	T0	80.2a	22.6a	188.1a	34.0a	2.12a	1.45a	1.90a
	T1	68.5a	13.6b	167.0a	24.1a	1.88a	1.66a	3.54b

Table 3. Effect of irrigation treatments on yield (kg tree⁻¹) and crop load (number of fruits tree⁻¹) during the experimental period. Means for each year within a column that do not have a common letter are significantly different by LSD_{0.05} test.

Treatment	2007		2008		2009	
	Yield	Crop load	Yield	Crop load	Yield	Crop load
T0	18.1a	142a	32.8a	273a	49.1a	399a
T1	16.1a	130a	29.3a	225a	40.1a	315a

T0 and T1 plants yielded fruits of a similar average weight during the 3 harvests (Table 4). Also, fruit distribution into size classes, corresponding to A, B and C extra categories and non-marketable category, was not statistically affected by the irrigation treatment during the experimental period (Table 4).

Table 4. Effect of irrigation treatments on average fruit weight (g) and the distribution of different peach fruit categories (%) (CEE directive 3596/90) harvested (fruit extra categories: A, 73 mm > diameter $\geq$ 67 mm; B, 67 mm > diameter $\geq$ 61 mm and C, 61 mm > diameter $\geq$ 56 mm, and fruit non extra category, diameter < 56 mm). Data were arcsine $\sqrt{\%}$ transformed. Means for each year within a column that do not have a common letter are significantly different by LSD_{0.05} test.

Year	Treatment	Fruit weight	Fruit category			
			A	B	C	Non extra
2007	T0	137.7a	39.9a	46.1a	10.9a	3.1a
	T1	120.7a	41.4a	42.5a	13.9a	2.2a
2008	T0	123.5a	30.0a	30.0a	18.7a	21.3a
	T1	131.3a	33.7a	35.9a	14.5a	15.9a
2009	T0	136.7a	50.7a	35.4a	12.9a	1.1a
	T1	146.4a	51.3a	41.8a	5.2a	1.6a

4. Discussion

4.1. MDS SI for irrigation scheduling

The fact that MDS SI values from fruit thinning to 2 weeks after harvest in T1 plants showed low variability and remained close to the selected MDS SI threshold value (unity) and that their Ψ_{stem} values were similar to those of T0 plants (Figures 1 and 2) shows that the irrigation water amounts applied were suitably adjusted and able to satisfy the plant water requirements while saving irrigation water compared with the amount estimated by ET_C (Table 1) (Conejero et al., 2007; Ortuño et al., 2009). The difference between the applied water rate in the MDS signal intensity-driven schedule (T1) and peach evapotranspiration (ET_C) during this period could be attributed to the fact that the crop factors used to calculate ET_C (FAO 56, Allen et al., 1998) were not developed for an early maturing peach cultivar, with a very short fruit growth period and a long standing postharvest period, as the used in the experiment.

The moderate variability of MDS SI values during the early and late postharvest periods also indicated that the information generated in this way under RDI was sufficient to adjust the irrigation schedule to maintain MDS signal intensity close the selected threshold values and that peach tree irrigation scheduling can be based on MDS measurements alone (García-Orellana et al., 2007; Conejero et al., 2007; Ortuño et al., 2009). Nevertheless, the fact that the average MDS SI values during the early and late postharvest period of 2007, and during the late postharvest period of 2008, were lower than the threshold value suggests that it is necessary to modify the proposed irrigation protocol in order to obtain the new drought stress level faster. In addition, the MDS SI values behaviour observed in 2008 at the end of early postharvest, after a rainy period (Figures 1 and 2), also suggests that it is necessary to modify the proposed irrigation protocol when important rainfall occurs at the beginning of a deficit irrigation period. So, when an RDI schedule involves a change from one MDS SI threshold value to higher one, the decrease in the irrigation rate during the first days of this change should be greater than 3%, and when an important rainfall occurs at the beginning of a deficit irrigation period, the decrease in the irrigation rate during the rainy period should be lower than 3%.

The fact that the θ_v in T0 remained close to field capacity during the 3 years of the experimental period indicated that irrigation scheduling in this treatment kept the plants under non-limiting soil water conditions (Figure 1). The deficit irrigation during early and late postharvest (T1) resulted in a progressive reduction in θ_v values, which, in turn, induced a decrease in Ψ_{stem} values, reflecting a moderate drought stress during the early postharvest period and a more severe drought stress during late postharvest period (Figure 1).

4.2. Plant growth and carbon partitioning

The fact that the only vegetative growth component affected by deficit irrigation was pruning weight (Table 2) may be related with the fact that apex elongation is more sensitive than other physiological parameters to water deficit (Mills et al., 1996; Dichio et al., 2007). The relationship between yield and increased trunk cross sectional area absolute values has been used to express the degree of carbon partitioning between vegetative and productive growth (Ebel et al., 1995; González-Altozano and Castel, 1999). For this reason, the absence of a significant effect of RDI on the yield/ Δ TCA ratio (Table 2) could indicate similar carbon partitioning schemes during fruit growth. However, taking into consideration that vegetative apices are the main users of carbohydrates during the postharvest period, vigor regulation in RDI (T1) plants may decrease the competition for assimilates between vegetative apices and reserve tissues, reducing pruning (Boland et al., 2000; Pérez-Pastor et al., 2009). As Dichio et al. (2007) indicated, bearing in mind that pruning influences the vegetative growth vs. cropping balance, and reduces canopy shading, the application of RDI could facilitate peach orchard management.

Although the seasonal irrigation water applied in RDI was 35-42% lower than the estimated ET_C , no effect on total yield, yield efficiency components or the distribution of different peach fruit categories was observed (Tables 2, 3 and 4). This behaviour confirmed our hypothesis that it is possible to develop a moderate water deficit during flower bud induction and/or the floral differentiation period (early postharvest period) and a more severe drought stress during the non-critical period (late postharvest period), saving considerable water without affecting yield and fruit components.

5. Conclusion

The above mentioned results indicated that RDI scheduling in early maturing peach trees can be based exclusively on MDS measurements. In this sense, the RDI strategy assayed was able to reduce the seasonal water applied by 35-42% compared with the estimated ET_C without affecting yield efficiency components or the distribution of different peach fruit categories, while improving water productivity. Nevertheless, to improve the MDS SI-driven schedule precision in RDI strategies some changes in the irrigation protocol should be taken into consideration. These changes should be focused on obtaining the scheduled water deficit levels faster and avoid a decrease in irrigation precision when important rainfall occurs at the beginning of a new deficit irrigation period. For this, when it is necessary to change from an MDS SI threshold value to a higher one, the decrease in the daily irrigation rate should be higher than 3%, and when an important rainfall occurs at the beginning of a new deficit irrigation period, the decrease in the irrigation rate during the rainy period should be lower than 3%.

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General conclusions

1. Through the review of other articles, it became clear that the normalization of parameters derived from trunk diameter fluctuations with respect to their values in non-limiting soil water conditions has meant a true turning point in the improvement of irrigation scheduling with sensors.
2. In spite of the expectations about the use of baselines to estimate maximum daily trunk shrinkage (MDS) reference values, the multiple factors capable of modifying them, particularly the carbon balance, caused researchers to begin to question its usefulness, especially in stone fruit trees.
3. Articles have already been published regarding irrigation scheduling using trunk diameter sensors in which the authors tried to cover crop water requirements as well as the development of sustainable deficit irrigation. However, until now, publications have not developed the most significant strategies such as regulated deficit irrigation.
4. Known irrigation protocols that are based on the use of trunk diameter sensor data can only be considered as very general rules requiring specific rules in order to optimize accuracy of irrigation. Articles that have already been published point out some inaccuracies due to occasions such as rainy periods with low evaporative demand, changes in the irrigation frequency, and modifications of the maximum daily trunk diameter shrinkage signal intensity threshold value in the same season.

5. The results showed that it is possible to develop seasonal reference equations with interannual validity of the maximum daily trunk shrinkage and midday stem water potential as a function of climatic variables. Specifically, the first parameter can be estimated through the values of reference crop evapotranspiration, the daily mean vapor pressure deficit or daily mean air temperature, and the second parameter is based on the values of reference crop evapotranspiration or daily mean vapor pressure deficit. In both cases, the daily mean vapor pressure deficit is the independent variable that leads to more accurate estimates of both parameters.
6. The same-species crop load variations between years do not significantly influence the reference equation values. However, extreme crop load values do have an effect on these equations.
7. In contrast to the articles that have already been published, when the MDS reference equation values were broken down into fruit growth and postharvest periods, the correlation coefficients decreased. This fact may be due to the very short fruit growth period, making it possible to provide seasonal reference equations which allow for less complicated irrigation scheduling than initially thought, at least in the variety studied.
8. When the postharvest regressions between MDS and the meteorological parameters mentioned above were broken down into early and late postharvest periods, the correlation coefficient improved significantly, demonstrating that MDS values under non-limiting soil water conditions were closely related to the presence or absence of sugar-demanding sinks, such as active root growth.

9. In contrast to what some researchers have suggested, the trunk relative growth rates were not a reliable crop water status indicator, due to their clear dependence on the crop load values and phenological period.
10. The steady inter and intraseasonal relationship between MDS and midday stem water potential highlights the unchanging hydraulic conductivity in the bark tissues of peach trees and confirms that the main factors controlling MDS is the water potential.
11. The results showed that it is possible to develop regulated deficit irrigation strategies using exclusively MDS measurements. Nevertheless, some have suggested changes in the proposed irrigation protocol in order to improve the accuracy of irrigation scheduling.
12. In this sense, given the early maturing peach tree studied, by avoiding water deficit situations during the very short fruit growth period, developing moderate water deficits during flower bud induction and/or floral differentiation, and generating more severe water deficits, water productivity is improved with savings between 35 and 42% without affecting the yield or fruit size.
13. The only vegetative growth component affected by RDI was pruning weight. This vigor regulation can be considered a positive aspect by decreasing the competition for assimilates between vegetative apices and reserve tissues

Abbreviations and symbols

Alphabetales

ANOVA	Analysis of variance
CL	Crop Load
CV	Coefficient of variation
cv	Cultivar
DOY	Day of the year
ET _c	Crop evapotranspiration
ET _o	Crop reference evapotranspiration
FDT	Fluctuación del diámetro del tronco
FLE	Fruit Load Efficiency
FW	Fruit Weight
GC	Ground Cover area
IS	Intensidad de señal
K _c	Crop coefficient
LSD	Least Significant Difference
LVDT	Linear Variable Displacement Transducer
MCD	Máxima contracción diaria del tronco
MDS	Maximum Daily trunk Shrinkage
MNDT	Maximum Daily Trunk Diameter

MNTD	Minimum Daily Trunk Diameter
MSE	Mean Square Error
RDC	Riego deficitario controlado
RDI	Regulated Deficit Irrigation
SI	Signal Intensity
TCA	Trunk Cross Sectional Area
TCR	Tasa de crecimiento relativa del tronco
TCSA	Trunk Cross Sectional Area
TDF	Trunk Diameter Fluctuations
TGR	Trunk Growth Rate
VPD	Air Vapour Pressure Deficit
WUE	Water Use Efficiency

No alphabetables

R_d	Global radiation
T_m	Mean daily air temperature
T_{md}	Midday air temperature
VPD_m	Daily mean air Vapour Pressure Deficit
VPD_{md}	Midday air Vapour Pressure Deficit
VPD_{mx}	Daily mean during 10 – 15 h (solar time) air Vapour Pressure Deficit
Ψ_m	Soil matric potential
Ψ_{stem}	Midday stem water potential
θ_v	Soil volumetric water content