Universidad Politécnica de Cartagena

Departamento de Producción Vegetal

Programación de riego y déficit hídrico controlado en frutales de hueso

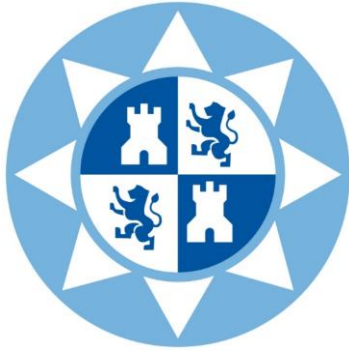**Tesis Doctoral**

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Directores: Dr. Emilio Nicolás Nicolás

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Tutor: Dr. Rafael Domingo Miguel

2015

Technical University of Cartagena

Plant Production Department

Irrigation scheduling and regulated deficit irrigation in stone fruit trees

Doctoral Thesis

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CONFORMIDAD DE DEPÓSITO DE TESIS DOCTORAL POR LA COMISIÓN ACADÉMICA DEL PROGRAMA

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Que la Tesis Doctoral titulada, "**PROGRAMACIÓN DE RIEGO Y DÉFICIT HÍDRICO CONTROLADO EN FRUTALES DE HUESO**", ha sido realizada, dentro del mencionado programa de doctorado, por D. **FRANCISCO PÉREZ SARMIENTO**, bajo la dirección y supervisión de los Dres. **EMILIO NICOLÁS NICOLÁS Y OUSSAMA MOUNZER.**

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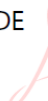
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Agradecimientos

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INTRODUCCIÓN/INTRODUCTION

1. Introducción

La actual y creciente presión sobre los recursos hídricos causada por la competencia por el agua entre agricultura, industria y población, crea una necesidad urgente de aumentar la productividad del agua de riego y desarrollando nuevas herramientas y métodos de ahorro de agua en la agricultura. Por tanto, resulta necesario el desarrollo de nuevas estrategias para optimizar el agua.

Una de las técnicas más prometedoras para lograr este objetivo es el Riego Deficitario Controlado (RDC), cuyo concepto es controlar el crecimiento vegetativo del cultivo sin afectar a su producción posibilitando incluso obtener otras ventajas, como la mejora de la calidad del fruto. En este contexto, es de vital importancia determinar el estado hídrico de la planta con el fin de detectar rápidamente cualquier estrés hídrico y, de esta manera, poder gestionar de forma adecuada el riego durante el desarrollo del cultivo. Para lograrlo, se necesitan herramientas precisas que determinen el estado hídrico de la planta. En este sentido, el uso de indicadores del estado hídrico basados en medidas en planta se ha convertido en una buena herramienta para la planificación del riego de precisión, ya que controla muchos procesos fisiológicos y la productividad de los cultivos.

El método más utilizado para evaluar el estado hídrico de los árboles para la programación del riego es el potencial hídrico de tallo al mediodía (Ψ_t). Sin embargo, la principal desventaja de Ψ_t es que no se puede automatizar y, por lo tanto, son necesarios viajes frecuentes al campo y mano de obra. Por otro lado, el uso de las fluctuaciones diámetro del tronco ha demostrado también su utilidad como indicadores del estado hídrico de la planta ya que, entre otras ventajas, permiten registros continuos y automatizados con la consiguiente reducción de la mano de obra necesaria para su medida.

El melocotonero [*Prunus persica* (L.) Batsch] es uno de los cultivos frutales más extendidos en todo el mundo, siendo la segunda especie frutal en producción después del manzano. Su gran aceptación por parte de los consumidores se debe a su gran variedad de usos, incluyendo el consumo en fresco. Su principal país productor es China, mientras España ocupa el cuarto lugar. En la Región de Murcia, el melocotonero es el primer frutal de hueso en rendimiento y el segundo en superficie cultivada tras el almendro. La Región de Murcia, con una superficie cultivada de 10.713 hectáreas y una

producción de 171.526 t ocupa el tercer lugar en la producción de melocotón en el país, tras Aragón y Cataluña (MAGRAMA, 2015).

El albaricoquero (*Prunus armeniaca* L.) es una de las especies frutales más importantes a nivel mundial ya que su fruto es muy apreciado por los consumidores (Roussos et al., 2011). La producción mundial de albaricoque es de, aproximadamente, 2,5 millones de toneladas por año siendo Turquía el país productor líder, según la Organización para la Agricultura y la Alimentación, con aproximadamente 676.000 t (FAO, 2013). España produce alrededor de 132.000 t de una zona de cultivo de 20.000 hectáreas. En la Región de Murcia (SE España) casi toda la superficie cultivada ($\approx$10,000 ha en 2014) se encuentra bajo regadío. Esta zona de cultivo produjo 79.000 t en 2014 (60% de la producción de albaricoque en España) (MAGRAMA, 2015). El cultivar más importante de albaricoquero es el 'Búlida', el cual representa el 66% de la producción total en la Región de Murcia (CARM, 2009).

En el presente estudio, se tomaron medidas de potencial hídrico del tallo al mediodía (Ψ_t) y máxima contracción diaria del tronco (MCD) durante un período de 3 años en melocotonero [*Prunus persica* (L.) Batsch cv. 'Catherine'] y albaricoquero [*Prunus armeniaca* L. cv. 'Búlida'] con el fin de evaluar el uso de estos indicadores del estado hídrico basados en la planta para la programación del Riego Deficitario Controlado (RDC).

Esta tesis doctoral se estructuró en 10 capítulos, de la siguiente forma:

En primer lugar (capítulo 2), se presenta un resumen de los contenidos de esta tesis incluyendo los objetivos, los materiales y métodos usados y los resultados obtenidos. En el apartado siguiente (capítulo 3) se enumeran los objetivos de esta investigación. Seguidamente, se expone brevemente el estado actual de conocimientos sobre el tema (capítulo 4).

Los capítulos 5, 6, 7 y 8 describen las cuatro experiencias que se han llevado a cabo, divididos en un breve resumen, introducción, materiales y métodos utilizados, resultados, discusión, conclusiones (en algunos casos), agradecimientos y bibliografía consultada.

En el capítulo 9 se recogen las principales conclusiones derivadas de este trabajo de investigación, incluyendo tanto unas generales como parciales. En el capítulo 10 (anexos), se adjunta como indicador de calidad de esta Tesis el artículo "**Effects of regulated deficit irrigation on physiology and fruit quality in apricot trees",** publicado en la revista Spanish Journal of Agricultural Research 2010 Vol 8 (S2) S86-S94 ISSN 1695-971-X, revista perteneciente al JCR y encuadrada en el Q2 dentro del área científica 'Agriculture Multidisciplinary'.

1. Introduction

The current increasing pressure on water resources caused by the competition for water between agriculture, industry and population, creates an urgent need to increase irrigation water productivity and to develop and provide new tools and water conservation methods in agriculture. This requires the development of new strategies to optimize water.

One of the most promising techniques to achieve this objective is Regulated Deficit Irrigation (RDI), whose concept was to control excessive vegetative growth and enhance fruit growth, besides other advantages such as improvements of fruit quality and taste. In this context, it is of paramount importance to determine plant water status in order to rapidly detect any water stress and correctly manage irrigation over the growing season. To achieve this, precise tools for assessing plant water status are needed; in this sense, the use of plant-based water status indicators has become very popular for planning precise irrigation, because it controls many physiological processes and crop productivity.

The most widely used approach for evaluating tree water status for irrigation scheduling is the midday stem water potential (Ψ_s). However, the main disadvantage of Ψ_s is that it cannot be automated and thus frequent trips to the field and manpower are needed. The use of trunk diameter fluctuations has renewed the interest in usingthese measurements as a plant water status indicator. This technique permits continuous and automated registers with a reduction in the labour needed for the measurement procedure.

Peach [*Prunus persica* (L.) Batsch] is one of the most extended fruit crops worldwide, being the second fruit species in production after apple. Its great acceptance by consumers is due to its variety of uses, including fresh consumption. Its main producing country is China, whereas Spain ranks fourth. In the Murcia Region, peach is the first stone fruit in yield and the second one in cultivated surface after almonds. Murcia region, with a cultivated area of 10,713 ha and a production of 171,526 t ranks third in peach production within the country, after Aragon and Catalonia (MAGRAMA, 2015).

Apricot (*Prunus armeniaca* L.) is one of the most important fruit species worldwide since its fruit is highly appreciated by consumers (Roussos et al., 2011). Apricot world production is about 2.5 million t per year and Turkey is the leading producing country, according to the Food and Agriculture Organization, with approximately 676,000 t (FAO, 2013). Spain produces about 132,000 t from a cultivation area of 20,000 ha. In the Murcia Region (SE Spain) almost all the cultivated area (≈10,000 ha in 2014) is irrigated. This cultivation area yielded 79,000 t in 2014 (60% of apricot production in Spain) (MAGRAMA, 2015). The most important Spanish apricot cultivar is "Búlida", which represents 66% of the total production in the Murcia Region (CARM, 2009).

In the current study, measurements of midday stem water potential (Ψ_s) and maximum daily trunk shrinkage (MDS) were taken over a 3-year period in peach trees [*Prunus persica* (L.) Batsch cv. 'Catherine'] and in apricot trees [*Prunus armeniaca* L. cv. 'Búlida'] in order to assess the use of these plant-based indicators for regulated deficit irrigation (RDI) scheduling.

This doctoral thesis was structured in 10 chapters, as follows:

First (chapter 2), a summary of the contents of this thesis is presented including the aims, the materials and methods used and the results obtained. In the next section (Chapter 3), the objectives of this research are enumerated. Afterwards, the current state of the art on the subject is briefly described (Chapter 4).

Chapters 5, 6, 7 and 8 described the four experiments that have been carried out. These chapters are clearly and concisely presented, with a brief summary, introduction, materials and methods, results, discussion, conclusions (in some cases), acknowledgments and references.

Chapter 9 collects the main conclusions from this thesis, including both general and partial conclusions. In chapter 10 (annexes), attached to this thesis as a quality indicator, the article entitled "**Effects of regulated deficit irrigation on physiology and fruit quality in apricot trees**" is presented. It was published in the Spanish Journal of Agricultural Research in 2010 Vol 8 (S2) S86-S94 ISSN 1695-971-X, journal included in the JCR and ranked within the 2nd quartile in the 'Agriculture Multidisciplinary'category.

RESUMEN/SUMMARY

2. Resumen

La escasez y baja calidad de los recursos hídricos junto a la presión del desarrollo turístico, industrial y residencial hace que la agricultura en las regiones semiáridas afronte situaciones limitantes de modo casi permanente. Este sector consume más del 70% de los recursos hídricos disponibles ocasionando, en algunos casos, la sobreexplotación de los recursos hídricos subterráneos y la pérdida de calidad del agua. A pesar de ello, resulta difícil abordar esta problemática debido a varias razones entre las que se incluyen:

- Las consecuencias del uso excesivo del agua y fertilizantes en una agricultura intensiva no son tenidas en cuenta a medio y largo plazo.

- La gestión eficaz del recurso hídrico es una tarea colectiva ya que su implementación requiere la participación de todos los agentes implicados, tanto los gestores de los recursos hídricos como los agricultores o usuarios finales.

- La poca sensibilización de los usuarios sobre las dimensiones del problema de escasez de agua y sus consecuencias, en algunos casos.

- La baja utilización de herramientas/técnicas que permitan ahorrar agua en el sector agrícola.

Para mejorar esta situación se requiere un esfuerzo colectivo entre quién gestiona los recursos hídricos y quién los utiliza. Los primeros deben buscar nuevas políticas de gestión y sistemas de gobernanza participativa mientras que los segundos deben cambiar sus prácticas de modo que consigan producciones más elevadas y de mejor calidad con una menor utilización de recursos hídricos.

Los agricultores, apoyados por los estudios de investigación y la introducción de nuevas tecnologías, pueden paliar las consecuencias de escasez de agua mediante varias opciones complementarias:

1) Riego de precisión: esta estrategia pretende minimizar las pérdidas de agua que suelen producirse durante los eventos de riego. Requiere de un sistema eficiente y una metodología de programación de riego que tome en cuenta las relaciones hídricas en el sistema suelo-planta-atmósfera.

2)   Riego deficitario: el hecho de que la respuesta de los cultivos al déficit hídrico es variable en función del estado fenológico de la planta permite, durante las fases fenológicas no críticas, reducir los aportes de riego por debajo de las necesidades hídricas máximas sin provocar mermas en la producción final.

3)   Uso de aguas no convencionales: las aguas municipales regeneradas representan un volumen considerable del consumo total agrícola, por ello suelen producirse en las cercanías de zonas agrícolas. Además, contienen una alta concentración en minerales y materias orgánicas que podrían cubrir parte de las necesidades nutritivas de las plantas.

Por estos motivos, en los últimos años han cobrado gran importancia los estudios que abordan la aplicación de estrategias de riego deficitario controlado (RDC), las cuales además del ahorro hídrico que suponen, pueden incluso resultar en mejoras de algunos aspectos cualitativos de las cosechas obtenidas (Fereres y Soriano, 2007).

En base a ello, ha aumentado el interés por las medidas del estado hídrico basadas en la planta ya que ésta integra el efecto tanto de la disponibilidad de agua en el suelo, como de la demanda evaporativa y, por ello, proporcionan una información más adecuada para determinar el efecto de las restricciones de agua sobre la actividad fisiológica de la planta y para la programación del riego (Jones, 2004). Cabe diferenciar estos indicadores del estado hídrico en dos grupos, según permitan la obtención de datos de forma continua (máxima contracción diaria de tronco, MCD), o no (potencial hídrico de tallo, Ψ_t), a fin de poder automatizar el riego.

En el contexto mundial, el melocotonero [*Prunus persica* (L.) Batsch] es uno de los cultivos frutales más extendidos, siendo la segunda especie frutal en producción tras el manzano. Su gran aceptación por parte del consumidor se debe a su diversidad de usos, entre ellos su consumo en fresco. Su principal país productor es China, mientras que España ocupa la cuarta posición. En la Región de Murcia el melocotonero es el primer frutal de hueso en producción y el segundo en superficie de cultivo tras el almendro. La Región de Murcia, con una superficie cultivada de 10.713 ha y una producción de 171.526 t, ocupa el tercer lugar en producción de melocotón dentro del territorio nacional, tras Aragón y Cataluña (MAGRAMA, 2015).

En el caso del albaricoquero (*Prunus armeniaca* L.) su producción mundial supera las 2,5 millones de toneladas, siendo Turquía el principal productor, seguido de Irán, mientras que España ocupa la 9ª posición (FAO, 2013). En España, la Región de Murcia, con aproximadamente un 60% de la producción nacional, ocupa el primer lugar, tanto en producción como en superficie cultivada, con una gran diferencia respecto al resto de Comunidades Autónomas (MAGRAMA, 2015).

Por todo ello, los objetivos generales de esta tesis fueron:

- Obtener ecuaciones de referencia a partir de medidas continuas de las fluctuaciones del diámetro del tronco con sensores en planta para su uso en la programación de riego en melocotoneros adultos [*Prunus persica* (L.) Batsch cv "Catherine"], calculando la máxima contracción diaria del tronco (MCD) y relacionándola con variables climáticas y el potencial hídrico de tallo.

- Cuantificar las necesidades hídricas de la planta en base a medidas de la MCD como herramienta de precisión en la programación de riego manteniendo los valores de intensidad de señal (IS$_{MCD}$, definido como MCD referencia/MCD Control) cercanos a la unidad durante toda la estación de crecimiento.

- Evaluar el uso de la MCD como indicador en planta para la programación del RDC, estableciendo para ello un umbral de la IS de 2 durante los períodos de crecimiento no críticos para esta estrategia de riego, evaluando para ello la producción y calidad de cosecha en melocotoneros adultos [*Prunus persica* (L.) Batsch cv "Catherine"].

- Evaluar el uso del potencial hídrico de tallo como indicador en planta para la programación del riego deficitario controlado (RDC), estableciendo para ello umbrales del mismo para melocotoneros adultos [*Prunus persica* (L.) Batsch cv "Catherine"].

- Evaluar el efecto del RDC en las relaciones hídricas de la planta, producción y calidad del fruto en albaricoqueros adultos [*Prunus armeniaca* (L.) cv. "Búlida"] durante tres años consecutivos.

Para alcanzar estos objetivos, se realizaron ensayos durante 3 años consecutivos en una finca comercial situada en el valle de Mula (Murcia) (37°55'N, 1°25'W, 360 m

sobre el nivel del mar). La climatología fue típicamente mediterránea con inviernos suaves, veranos secos y calurosos y baja pluviometría (entre 188 y 304 mm anuales durante los 3 años de estudio). Se seleccionaron dos parcelas dentro de la misma finca. Una de ellas de 0,5 ha de melocotonero [*Prunus persica* (L.) Batsch] cv. "Catherine" (variedad de media-tardía estación), injertado sobre patrón híbrido de melocotonero x almendro GF-677, de 9 años de edad al inicio de la experiencia (2008) y con un marco de plantación de 4 x 6 m. El suelo de la parcela es calcáreo, pedregoso, posee una textura franco-arenosa, baja materia orgánica y una capacidad de campo de 0,25 m^3 m^{-3}, aproximadamente.

Por otro lado, una parcela de 1 ha de albaricoquero [*Prunus armeniaca* L.] cv. "Búlida", injertado sobre patrón franco de 'Real Fino', con una edad de 9 años al inicio de los experimentos y con un marco de plantación de 6 x 8 m. El suelo de la parcela es altamente calcáreo, con una textura franco arcillosa, bajo en materia orgánica y una capacidad de campo de 0,31 m^3 m^{-3}, aproximadamente.

En ambos casos, el agua de riego procedía de un pozo cercano con valores de conductividad eléctrica en torno a 0,6 dS m^{-1}.

Las medidas realizadas a lo largo del periodo experimental fueron:

- Los datos climáticos se registraron en una estación meteorológica automatizada situada en el huerto experimental.

- El contenido volumétrico de agua en el suelo (θ_v, m^3 m^{-3}) se determinó mediante la técnica de la reflectometría en el dominio de tiempo (RDT) (Tektronix device, Model 1502C, Tektronix Inc., OR) de acuerdo con Moreno et al. (1996) y con una sonda de neutrones (Model 4300, Troxler Electronic Laboratories Inc., NC), tomando las medidas por la mañana, cada 7 a 15 días, durante el período experimental.

- El potencial hídrico de tallo al mediodía (Ψ_t, MPa) y el potencial hídrico foliar (Ψ_h, MPa) se midieron usando una cámara de presión tipo Scholander (Soil Moisture Equip. Corp., model 3000, Santa Barbara, CA, USA) y siguiendo los procedimientos descritos por Turner (1981).

- Las fluctuaciones micrométricas del diámetro del tronco (FDT) se registraron durante el periodo experimental con la ayuda de transductores de

desplazamiento linear variable (sensores TDLV, Solartron Metrology, Bognor Regis, UK, model DF ± 2.5 mm, precisión ± 10 μm). Las mediciones se registraron cada 30 s en un datalogger y un multiplexor (modelo CR1000, Campbell Scientific, Inc., Logan, EE.UU.), los cuales fueron programados para grabar valores medios cada 15 minutos. La máxima contracción diaria del tronco (MCD) se calculó diariamente como la diferencia entre el máximo y mínimo diámetro del tronco (Goldhamer y Fereres, 2001).

- La fotosíntesis neta (P_n) y la conductancia estomática (g_s) se midieron sobre hojas directamente expuestas a la radiación solar en los mismos días que el Ψ, usando para ello un sistema portátil de medida de fotosíntesis (LI-6400, Li-Cor, Lincoln, NE, USA).

- El diámetro del fruto se midió cada 7-10 días usando un calibre digital (Powerfix model Nr Z22855F, Milomex Ltd, Bedfordshire, UK), y el crecimiento de brotes se obtuvo cada 7-10 días midiendo su longitud.

- El tamaño del fruto se evaluó mediante su producción comercializable o no comercializable, según Regulación Europea (EC) nº 1861/2004.

- El diámetro del tronco se midió anualmente con un pie de rey para estimar el área de la sección transversal del tronco.

- El peso de madera de poda se registró en la poda de invierno en ambos cultivos usando una balanza Scaltec Mod. SSH91, capacidad 150 kg y precisión ± 5g.

- En cosecha, la firmeza, el pH, el contenido en sólidos solubles y la acidez titulable (AT) se evaluaron como índices de calidad del fruto en una muestra representativa de cada tratamiento estudiado (100 frutos por tratamiento). Los análisis de firmeza, pH y contenido en sólidos solubles se realizaron de acuerdo con Artés et al. (1993), mientras que la acidez titulable se determinó mediante el método de AOAC (1984).

- Los valores de color, en la superficie (color de la piel) y tras pelar (color de pulpa), se midieron con un colorímetro (CR-300, Minolta, Ramsey, NJ). El número de frutos que se usó por tratamiento fue de 200 (50 por parcela experimental) y se realizaron 3 medidas en cada fruto, tanto en la piel como en la pulpa.

La presente tesis se ha dividido en cuatro capítulos independientes pero relacionados, cuyos objetivos y resumen se exponen a continuación:

Capítulo 5 (REFERENCE VALUES OF MAXIMUM DAILY TRUNK SHRINKAGE FOR IRRIGATION SCHEDULING IN MID-LATE MATURING PEACH TREES) enviado a la revista "Agricultural Water Management".

En este capítulo, se obtuvieron medidas de potencial hídrico de tallo (Ψ_t) y máxima contracción diaria del tronco (MCD) en melocotoneros [*Prunus persica* (L.) Batsch cv. "Catherine"] durante 3 años consecutivos con el objetivo de obtener ecuaciones de referencia que permitan la programación del riego a partir de medidas automáticas de MCD como herramienta de gestión.

En este ensayo, los árboles se regaron por encima de sus necesidades hídricas (120% de la ET_c) para obtener condiciones no limitantes de agua en el suelo. Se determinaron las relaciones entre la MCD y distintos parámetros climáticos como la ET_0, temperatura y déficit de presión de vapor (DPV) (máxima y al mediodía) así como con el Ψ_t, un indicador del estado hídrico de la planta ampliamente reconocido.

Nuestros resultados indicaron que los registros de MCD presentaban una mayor correlación con la temperatura, tanto al mediodía como máxima diaria, durante el período de crecimiento del fruto que con las otras variables estudiadas; mientras que en post-cosecha, la mejor relación se obtuvo con el DPV. Las relaciones entre la MCD y Ψ_t difirieron interanualmente, aunque se encontraron ecuaciones de referencia similares entre estaciones de crecimiento para los distintos períodos post-cosecha. Sin embargo, estas relaciones variaron mucho con el estado fenológico del árbol y la carga de frutos de cada año. En conclusión, los agricultores deben ser conscientes de estos factores al utilizar valores MCD para obtener ecuaciones de referencia de cara a su utilización en la programación del riego.

Capítulo 6 (USEFULNESS OF MAXIMUM DAILY TRUNK SHRINKAGE FOR ESTIMATING WATER NEEDS AND REGULATED DEFICIT IRRIGATION SCHEDULING IN PEACH TREES) enviado a la revista "Agricultural Water Management".

A pesar de la facilidad de uso y robustez de las medidas de Ψ_t, el inconveniente de tener que desplazarse hasta la finca en numerosas ocasiones es un hecho a tener en cuenta, por ello, en este capítulo, se evaluó la aplicabilidad de la determinación del estado hídrico de la planta mediante sensores de medida de las fluctuaciones del diámetro de los troncos (sensores TDLV), utilizando los valores de la máxima contracción diaria del tronco (MCD) durante 3 años consecutivos en melocotonero [*Prunus persica* (L.) Batsch cv. "Catherine"].

El objetivo fue, en primer lugar, cuantificar las necesidades hídricas de la planta, a partir de las medidas de MCD, y normalizarlo respecto al control (MCDtrat/MCDControl) como intensidad de señal de la MCD (IS_{MCD}), a fin de eliminar el efecto climatológico, manteniéndola en valores cercanos a la unidad durante todo el ciclo de cultivo. Por otro lado, se programó un tratamiento de Riego Deficitario Controlado (RDC) en base a la $IS_{MCD,}$ manteniendo valores cercanos a 2 durante los períodos no críticos para el desarrollo del cultivo. Así, los tratamientos aplicados fueron:

a)   Un control sobrerregado (C_{ETc}) por encima de las necesidades hídricas del cultivo (aproximadamente un 120% de la ET_c de media para los 3 años).

b)   Un tratamiento de precisión o control ajustado (C_{MCD}) donde se mantuvieron los valores de IS_{MCD} en torno a la unidad durante todo el ciclo de cultivo.

c)   Un tratamiento RDC donde se mantuvo un valor de IS_{MCD} en torno a la unidad en todos los estados fenológicos del cultivo excepto en los periodos no críticos (Fase II de crecimiento del fruto y período post-cosecha) donde el valor de la IS_{MCD} se mantuvo en torno a 2.

La estrategia para alcanzar y mantener estos niveles de estrés fue mediante el protocolo propuesto por Goldhamer y Fereres (2001).

Los resultados indicaron valores de MCD e IS_{MCD} similares para los tratamientos C_{MCD} y C_{ETc} durante los 3 años. El tratamiento RDC presentó valores más altos de estos indicadores durante los periodos en los que el déficit hídrico fue impuesto. Los valores de IS_{MCD} para el tratamiento C_{MCD} presentaron unos coeficientes de variación (CV) bajos, en torno a 0,082; 0,069 y 0,083 para cada uno de los 3 años de experimentación. Por otro lado, en el tratamiento de RDC, dentro de los periodos en los que se aplicó el déficit hídrico, el CV ascendió moderadamente a valores entre 0,119 y 0,324.

El ahorro hídrico del tratamiento deficitario se situó alrededor del 43-65% respecto a la ET_c durante los 3 años de la experiencia y no se observaron diferencias significativas en el crecimiento de los frutos, aunque sí en el crecimiento vegetativo. Los valores del índice de madurez de los frutos se vieron incrementados bajo RDC.

El hecho de que el tratamiento C_{MCD} presentara niveles de Ψ_t, intercambio gaseoso y MCD similares al control, además de una producción y calidad del fruto sin diferencias significativas, indicó que los melocotoneros bajo este tratamiento de precisión no fueron afectados por el protocolo de riego impuesto, por lo que, en ausencia de drenaje y manteniendo los niveles de IS_{MCD} cercanos a la unidad se puede considerar como una herramienta plausible para poder estimar los valores de K_c cuando éstos no se conozcan a nivel local. Por tanto, nuestros resultados confirmaron la viabilidad de programar el riego basándose en medidas de IS_{MCD}.

Capítulo 7 (USE OF MIDDAY STEM WATER POTENTIAL FOR DEFICIT IRRIGATION SCHEDULING IN PEACH ORCHARDS IN SOUTH-EAST SPAIN) enviado a la revista "Agricultural Water Management".

En este capítulo se procedió a evaluar el efecto del RDC en la respuesta fisiológica y productiva de melocotoneros de media-tardía estación [*Prunus persica* (L.) Batsch cv. "Catherine"] durante 3 años consecutivos. Para ello, el riego se programó mediante el empleo de valores umbrales establecidos para el potencial hídrico de tallo (Ψ_t) (medidas discontinuas del estado hídrico de la planta), debido a que estudios previos lo sitúan como un indicador robusto, fiable y sensible del estado hídrico de la planta.

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Se establecieron tres tratamientos:

Un control sobrerregado (aproximadamente un 120% ET_c de media entre las tres campañas estudiadas), a fin de no tener condiciones limitantes de agua en el suelo, y dos tratamientos deficitarios:

a) RDC I (Déficit moderado) las plantas se regaron a fin de mantener los valores de Ψ_t cercanos a -1,5 MPa durante la fase II de crecimiento del fruto y en el período postcosecha.

b) RDC II (Déficit severo) las plantas se regaron a fin de mantener los valores de Ψ_t cercanos a -1,8 MPa durante la fase II de crecimiento del fruto y a -2,0 MPa en el período postcosecha.

Para mantener estos niveles de déficit hídrico se siguió el protocolo propuesto por Goldhamer y Fereres (2001) para riegos de alta frecuencia. Así, si el valor observado era más alto que el umbral establecido, se reducía el riego un 10% y, en caso contrario, se aumentaba en el mismo porcentaje.

Nuestros resultados mostraron una reducción en el agua aplicada respecto a la ET_c de entre 38 y 68% en los tratamientos deficitarios, lo cual se tradujo en menores valores de contenido volumétrico del agua en el suelo y en valores más negativos de Ψ_t en estos tratamientos, causando también una reducción en los parámetros de intercambio gaseoso (P_n y g_s). El crecimiento vegetativo y la poda se vieron reducidos en ambos tratamientos de RDC respecto al control, efecto que no se observó en la evolución del tamaño del fruto y la cosecha. Asimismo, se observó una mejora en la calidad de los frutos bajo RDC asociada fundamentalmente a un aumento en el índice de madurez.

Nuestros resultados demostraron que el uso de valores umbrales de Ψ_t para programar el riego es una opción viable para ahorrar agua sin comprometer el rendimiento. La disminución del crecimiento vegetativo observada a lo largo del presente experimento puede ser de interés para los agricultores ya que se podrían ver reducidos los costes de operaciones de poda (menor tiempo de trabajo), así como se obtendría una mejor intercepción de luz en la copa de los árboles. Las características físico-químicas de los frutos indicaron una mejora en la calidad del fruto bajo los

tratamientos RDC. Sin embargo, estos efectos deben estudiarse a largo plazo para evaluar la sostenibilidad de estas estrategias, así como para adaptar los umbrales Ψ_t a otras condiciones de suelo y clima.

Capítulo 8 (EFFECTS OF REGULATED DEFICIT IRRIGATION ON PHYSIOLOGY, YIELD AND FRUIT QUALITY IN APRICOT TREES) enviado a la revista "Scientia Horticulturae".

En este último capítulo se evaluó el efecto del RDC en albaricoquero [*Prunus armeniaca* (L.) cv. "Búlida"] durante 3 años consecutivos, calculando los requerimientos hídricos semanalmente según la ecuación de Penman-Monteith (Allen et al., 1998) y un coeficiente local de cultivo (K_c), de 0,5 en Febrero; 0,75 en Marzo; 0,8 en Abril; 0,9 en Mayo; 0,6 en Junio y 0,5 desde Julio hasta Noviembre, según indicaron Abrisqueta et al. (2001).

Los tratamientos establecidos fueron dos: Un control regado al 100% de la ET_c durante todo el ciclo de cultivo y un tratamiento de riego deficitario controlado (RDC) regado al 100% de la ET_c durante los estados fenológicos críticos y cuyo porcentaje de reducción del riego respecto a la ET_c en los periodos no críticos fue función del estado fenológico de la planta.

Según estudios previos de Torrecillas (2000), estos porcentajes fueron de: a) 40% de ET_c desde floración hasta el final de la fase I del crecimiento del fruto; b) 60% de ET_c durante la fase II de crecimiento del fruto, c) 50% ET_c durante la post-cosecha tardía I, la cual tiene una extensión de 30 días y comienza 60 días después de la recolección y d) 25% ET_c hasta el fin de la defoliación (post-cosecha tardía II).

Los resultados indicaron que el albaricoquero es una especie apropiada para el establecimiento de estrategias de RDC debido a que presenta una clara separación entre el crecimiento vegetativo y reproductivo, así como su capacidad para recuperar la reducción de diámetro de fruto sufrida durante la aplicación del déficit hídrico. El estrés impuesto no redujo significativamente el crecimiento vegetativo ni el área de la sección transversal del tronco en el tratamiento RDC en comparación con el control. En cuanto a la calidad de los frutos, algunas características cualitativas como el índice de madurez

aumentaron bajo RDC, debido a un incremento en el contenido en sólidos solubles y a la ausencia de efectos sobre la acidez, lo que según estudios previos afecta la percepción del gusto (dulzura y acidez) por el consumidor, influyendo en sus decisiones de compra. Los parámetros de color del fruto también mejoraron en el tratamiento deficitario, siendo mayores los valores de ángulo HUE (matiz), croma (intensidad) y claridad bajo RDC. Estas razones, junto con ahorros en el agua aplicada al tratamiento de RDC de alrededor del 33% en promedio, demuestran que el RDC es una estrategia de manejo del agua de riego adecuada para las zonas con escasez de recursos hídricos como el sureste español.

2. Summary

Water resources scarcity and low quality, together with the pressure of tourist, industrial and residential developments, makes that agriculture in semiarid regions must deal with water-limiting situations almost permanently. Irrigated agriculture consumes more than 70% of available water resources causing, in some cases, overexploitation of groundwater resources and the loss of water quality. However, it is difficult to tackle the problem due to several reasons such as:

-        The consequences of excessive water use and fertilizers in intensive agriculture are not taken into account at the medium and long terms.

-        The effective management of water resources is a collective task since its implementation requires the involvement of all the agents, both water resource managers and farmers or end users.

-        User limited awareness about the dimensions of the problem of water scarcity and its consequences, in some cases.

-        Low utilization of tools / techniques to save water in agriculture.

In order to improve this situation, a collective effort between who manages water resources and who uses them is required. The first ones should seek new management policies and participatory governance systems, while the second ones must change their practices to get higher yields and better crop quality with a lower use of water resources.

Farmers, supported by research studies and the introduction of new technologies, can mitigate the consequences of water shortages through several complementary options:

1)   Precision irrigation: this strategy seeks to minimize water losses that usually occur during irrigation events. It requires an efficient system and an irrigation scheduling methodology that takes into account water relations in the soil-plant-atmosphere system.

2)   Deficit irrigation: the fact that crop response to water deficit is variable depending on the plant growth stage allows for reducing water application through

irrigation during non-critical phenological stages without causing losses in the final yield.

3) Use of unconventional water: municipal reclaimed water represents a considerable volume of total agricultural consumption, thus often occur in nearby agricultural areas. These water resources also contain a high concentration of minerals and organic matter that could partially cover plan nutritional needs.

For these reasons, in recent years the studies that address the implementation of regulated deficit irrigation strategies (RDI) have become very important, due to the water savings they entail, which can even result in qualitative improvements in some aspects of the harvests obtained (Fereres and Soriano, 2007). Based on this, plant based water status measurements have gained interest because they integrate the effect of both the soil water availability and the evaporative demand and, therefore, provide more suitable information for determining the water restrictions effect on plant physiological activity and irrigation scheduling (Jones, 2004). These water status indicators may be distinguished in two groups, if they allow for continuous data collection (maximum daily trunk shrinkage, MDS) or not (stem water potential, Ψ_s), in order to automate irrigation.

In the world context, peach [*Prunus persica* (L.) Batsch] is one of the most extended fruit crops, being the second fruit species in production after apple. Its great acceptance by consumers is due to its variety of uses, including fresh consumption. Its main producing country is China, whereas Spain ranks fourth. In the Murcia Region, peach is the first stone fruit in yield and the second one in cultivated surface after almonds. Murcia region, with a cultivated area of 10,713 ha and a production of 171,526 t ranks third in peach production within the country, after Aragon and Catalonia (MAGRAMA, 2015).

In the case of apricot (*Prunus armeniaca* L.), worldwide production exceeds 2.5 million tons, being Turkey the leading producer, followed by Iran, while Spain occupies the 9th place (FAO, 2013). In Spain, the Murcia region, with approximately 60% of the national production, ranks first in both production and cultivated area, with a great difference compared to other regions (MAGRAMA, 2015).

For these reasons, the general objectives of this doctoral thesis were to:

- Obtain reference equations from continuous measurements of trunk diameter fluctuations with plant sensors for irrigation scheduling in adult peach trees [*Prunus persica* (L.) Batsch cv "Catherine"], by calculating the maximum daily shrinkage (MDS) and relating it to climatic variables and stem water potential.

- Quantify the plant water needs based on the MDS measures as a precision tool for irrigation scheduling maintaining signal intensity values (IS_{MDS}, defined as $MDS_{reference} / MDS_{Control}$) close to unity for all the growing season.

- Assess the use of MDS as a plant-based indicator for regulated deficit irrigation (RDI) scheduling, establishing a signal intensity threshold value of 2 during non critical growth periods for this irrigation strategy, and evaluating production and crop quality in adult peach trees [*Prunus persica* (L.) Batsch cv "Catherine"].

- Assess the use of the midday stem water potential as a plant-based indicator for RDI scheduling, establishing threshold values for this parameter in adult peach trees [*Prunus persica* (L.) Batsch cv "Catherine"].

- Assess the RDI effect in plant water relations, yield and fruit quality in adult apricot trees [*Prunus armeniaca* (L.) cv. "Búlida"] during three consecutive years.

In order to achieve these objectives, experiments were performed over three consecutive years in a commercial orchard located in Mula (Murcia) (37°55'N, 1°25'W, 360 m above sea level). The climate is typically Mediterranean, with mild winters, hot dry summers and low rainfall amounts (between 188 and 304 mm per year over the three years of study). Two plots were selected within the same orchard. One of 0.5 ha of peach [*Prunus persica* (L.) Batsch] cv. "Catherine" (mid-late season), grafted on a hybrid pattern peach x almond GF-677 rootstock, 9 years old at the beginning of the experience (2008), spacings of 4 m x 6 m. The soil at the site is calcareous, stony, with a sandy-loam texture, low organic matter content and its available water capacity is 0.25 m^3 m^{-3}, approximately.

On the other hand, a 1-ha plot of apricot trees [*Prunus armeniaca* L.] cv. "Búlida", grafted on Real fino apricot rootstock, and 9 years old at the beginning of the experience, spacings of 8 m x 6 m. The orchard soil is highly calcareous with a clay-

loam texture, low organic matter content and available water capacity is about 0.31 m^3 m^{-3} aproximately.

In both cases, irrigation water came from a nearby water well and had electrical conductivity values around 0.6 dS m^{-1}.

The measurements carried out over the experimental period were:

- Climate data were recorded at an automatic weather station placed within the experimental orchard.

- The volumetric soil water content (θ_v, m^3 m^{-3}) was measured by time domain reflectometry (TDR) (Tektronix device (Model 1502C, Tektronix Inc., OR), as described by Moreno et al. (1996), and a neutron probe (Model 4300, Troxler Electronic Laboratories Inc., NC), measurements were taken in the morning, every 7 to 15 days, during the experimental period.

- Midday stem water potential (Ψ_s) and leaf water potential (Ψ_l) were measured using a pressure chamber (Soil Moisture Equip. Corp, model 3000, Santa Barbara, CA, USA) following the procedures described by Turner (1981).

- The micrometric trunk diameter fluctuations (TDF) were measured throughout the experimental period using a set of linear variable displacement transducers (LVDT) (Solartron Metrology, Bognor Regis, UK, model DF ± 2.5 mm, accuracy ± 10 μm,) Measurements were taken every 30 s with a datalogger and a multiplexor (model CR1000, Campbell Scientific, Inc., Logan, USA), which were programmed to report 15 min means. Maximum daily trunk shrinkage (MDS) was calculated daily as the difference between the maximum and minimum daily trunk diameter (Goldhamer and Fereres, 2001).

- Net photosynthesis (P_n) and stomatal conductance (g_s) were measured in sun-facing leaf in the same days that stem water potential was recorded, using a field-portable photosynthesis system (LI-6400, Li-Cor, Lincoln, NE, USA).

- Fruit diameter was measured every 7-10 days using a digital caliper (Powerfix model Nr Z22855F, Milomex Ltd, Bedfordshire, UK) and shoot length values were collected every 7-10 days by measuring their lengths.

- Fruit size was studied by evaluating marketable and non marketable production according to Commission Regulation (EC) nº 1861/2004

- Trunk diameter was measured annually with a sliding caliper and used to estimate trunk cross-sectional area.

- Pruning weight was recorded at winter pruning in both crops using a scale (Scaltec Mod. SSH91, capacity 150 kg and accuracy ± 5g).

- At harvest, firmness, pH, soluble solids content (SSC) and titratable acidity (TA) were evaluated as fruit quality indices in a representative sample of each treatment studied (100 fruits per treatment). Firmness, pH and SSC determinations were conducted according to Artés et al. (1993), while titratable acidity (TA) was determined by AOAC (1984).

- Colour values, on the surface (ground skin colour) and after peeling in the flesh, were measured with a Minolta chromameter (CR-300, Minolta, Ramsey, NJ). The number of fruits used per treatment was 200 (50 per experimental plot) and 3 measurements were taken per fruit, both in skin and pulp.

This thesis has been divided into four independent but related chapters, their objectives and summaries are presented below:

Chapter 5 (REFERENCE VALUES OF MAXIMUM DAILY TRUNK SHRINKAGE FOR IRRIGATION SCHEDULING IN MID-LATE MATURING PEACH TREES) submitted to "Agricultural Water Management".

In this chapter, measures of stem water potential (Ψ_s) and maximum daily trunk shrinkage (MDS) were obtained for peach [*Prunus persica* (L.) Batsch cv. "Catherine"] over 3 consecutive years aiming to obtain reference equations that allow for irrigation scheduling based on automatic measurements of MDS as a management tool. In this experiment, the trees were irrigated over their water needs (120% ET_c) for obtaining non-limiting water conditions on the soil. Relations between the MDS and several climatic parameters such as ET_0, temperature and vapor pressure deficit (VPD) (maximum and at midday) were obtained, as well as with the Ψs, an indicator of plant

water status widely recognized. Our results indicated that, during the fruit growth period, MDS records showed a higher correlation with temperature, either at midday or the daily maximum, than with the other variables studied; while at postharvest, the best correlation value was obtained with VPD. Relations between the MDS and Ψs differed between years, although similar reference equations between growing seasons were found for the different postharvest periods. However, these relationships varied considerably with the growth stage of the tree and fruit load each year. In conclusion, farmers must be aware of these factors when using MDS values for getting reference equations in order to use them in irrigation scheduling.

Chapter 6 (USEFULNESS OF MAXIMUM DAILY TRUNK SHRINKAGE FOR ESTIMATING WATER NEEDS AND REGULATED DEFICIT IRRIGATION SCHEDULING IN PEACH TREES) submitted to "Agricultural Water Management".

Despite the ease of use and robustness of Ψ_s measures, the inconvenience of having to go to the farm on a great number of occasions is a fact to consider. Therefore, in this chapter, the applicability of plant water status determination by means of trunk diameter fluctuations sensors (LVDT sensors) was evaluated over three years in peach [*Prunus persica* (L.) Batsch cv. "Catherine"] using maximum daily trunk shrinkage (MDS) records.

The aim of this study was, first, to quantify the plant water needs from MDS measures and standardize them respect to control (MDStreat / MDSControl) as MDS signal intensity (MDS SI), in order to eliminate the climatic effect, keeping its values close to unity throughout the growing season. Furthermore, regulated deficit irrigation treatment (RDI) was scheduled based on MDS SI, keeping its values close to 2 during non critical periods for crop development. Thus, the treatments were:

a)   A Control (C_{ETc}) irrigated over the crop water needs (120% of ET_c averaged for the three years, aproximately).

b)   A precision treatment or adjusted control (C_{MDS}) where MDS SI values around unity were maintained throughout the growing season.

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c)   A RDI treatment where MDS SI values were maintained around unity in all developmental stages of crop except for noncritical periods (stage II of fruit growth and postharvest period) where the MDS SI values were kept around 2.

The strategy to achieve and maintain these stress levels was based on that proposed by Goldhamer and Fereres (2001).

The results indicated similar MDS and MDS SI values for C_{ETc} C_{MDS} treatments during the 3 years. The RDI treatment showed higher values of these indicators during the periods when the water deficit was imposed. MDS SI values for the C_{MDS} treatment showed low coefficients of variation (CV), around 0.082; 0.069 and 0.083 for each of the three years of experimentation, respectively. On the other hand, in the RDI treatment, the CV moderately increased between 0.119 and 0.324 within the periods in which the water deficit was applied.

The water savings in the RDI treatment were around 43-65% respect to ET_c during the 3 years of experience and no significant differences were observed in fruit growth, although they were observed in vegetative growth. Fruit maturity index values increased under RDI. The fact that the C_{MDS} treatment present Ψ_s, gas exchange and MDS levels similar to those of the control treatment, as well as yield and fruit quality without significant differences, indicated that the peaches under this precision treatment were not affected by the irrigation protocol imposed, so that maintaining levels of MDS SI close to unity can be considered as a plausible tool, in the absence of drainage, to estimate the K_c values when they are not locally available. Therefore, our results confirmed the viability of irrigation scheduling based on MDS SI measurements.

Chapter 7 (USE OF MIDDAY STEM WATER POTENTIAL FOR DEFICIT IRRIGATION SCHEDULING IN PEACH ORCHARDS IN SOUTH-EAST SPAIN) submitted to "Agricultural Water Management".

In this chapter, we assessed the effect of the RDI in the physiological and yield response of mid-late season peach [*Prunus persica* (L.) Batsch cv. "Catherine"] during three consecutive years. For this, irrigation was programmed through stem water potential (Ψ_s) (discontinuous measurement of plant water status) threshold values, since

previous studies consider it a robust, reliable and sensitive indicator of plant water status.

Three treatments were established:

An over irrigated control (120% ET_c averaged among the three seasons studied), in order to obtain non-water-limiting conditions on soil, and two deficitary treatments:

a)   RDI I (moderate deficit) plants were irrigated to keep Ψ_s values close to -1.5 MPa during stage II of fruit growth and postharvest period.

b)   RDI II (severe deficit) plants were irrigated to keep Ψ_s values close to -1.8 MPa during stage II of fruit growth and -2.0 MPa at postharvest period.

To maintain these levels of water deficit the protocol proposed by Goldhamer and Fereres (2001) for high frequency irrigation was followed. Thus, if the value observed was higher than the threshold, irrigation was reduced by 10%, otherwise it was increased in the same percentage.

Our results showed a reduction in water applied between 38 and 68% in the RDI treatments as compared to the ET_c, which resulted in lower values of volumetric soil water content and Ψ_s more negative in these treatments, also causing a reduction in gas exchange parameters (P_n and g_s). Vegetative growth and pruning were reduced in both RDI treatments compared to the control, whereas no effects were observed in the fruit growth evolution and harvest. Moreover, an improvement was observed in fruit quality under RDI, fundamentally associated with a maturity index increase. Our results showed that the use of Ψ_s threshold values to schedule irrigation is a viable option for saving water without compromising crop yield. The decrease of vegetative growth observed throughout this experiment may be of interest to farmers since it could reduce costs of pruning (less working time), as well as allow for a better light interception in trees canopy. The physicochemical characteristics of the fruits indicated improvements in fruit quality under the RDI treatments. However, these effects should be studied in the long-term to assess the sustainability of these strategies, and to adapt Ψ_s thresholds to other soil and climate conditions.

Chapter 8 (EFFECTS OF REGULATED DEFICIT IRRIGATION ON PHYSIOLOGY, YIELD AND FRUIT QUALITY IN APRICOT TREES) submitted to "Scientia Horticulturae".

In this final chapter, the RDI effects on apricot [*Prunus armeniaca* (L.) cv. "Búlida"] were evaluated. Irrigation requirements were calculated weekly according to the Penman-Monteith equation (Allen et al., 1998), and a local crop coefficient (K_c), 0.5 February, 0.75 March, 0.8 April, 0.9 May, 0.6 June, 0.5 July-November as suggested by Abrisqueta et al. (2001).

Two irrigation treatments were applied: A Control irrigated to 100% ET_c during all crop growth stages and a regulated deficit irrigation treatment (RDI) irrigated at 100% ET_c during the critical phenological periods and with water restrictions respect to ET_c during the non-critical periods depending on plant growth stage. According to Torrecillas (2000) the percentages of applied water were: a) 40% of ET_c from flowering until the end of the first stage of fruit growth; b) 60% of ET_c during the second stage of fruit growth, c) 50% ET_c during the late postharvest I, with a duration of 30 days and that starts 60 days after harvesting and d) 25% of ET_c until the end of tree defoliation (late postharvest II).

The results indicated that the apricot is an appropriate species to establish RDI strategies because it presents a clear separation between vegetative and reproductive growth and its ability to recover from the suffered fruit diameter reduction during water shortage implementation. Our results showed that the stress imposed did not significantly reduce vegetative growth or trunk cross-sectional area when compared to control. Regarding fruit quality, some qualitative characteristics, such as the maturity index, which according to previous studies affects the taste perception (sweetness and acidity) by the consumer, influencing their buying decisions, improved due to an increase in soluble solids content and the absence of effects on acidity. The fruit colour parameters also improved under the deficit treatment, being the hue angle, chroma (intensity) and lightness values higher under RDI. These reasons, as well as average applied water savings about 33% show that RDI strategies are an adequate irrigation management tool in areas with water shortages, as the southeast of Spain.

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OBJETIVOS/OBJECTIVES

3. Objetivos

Los objetivos generales de esta tesis fueron los siguientes (entre paréntesis se indica el capítulo en el que se abordan):

1. Obtener ecuaciones de referencia para su uso en la programación de riego en melocotoneros adultos [*Prunus persica* (L.) Batsch cv "Catherine"] a partir de sensores en planta que miden las variaciones continuas de las fluctuaciones del diámetro del tronco, calculando para ello la máxima contracción diaria del tronco (MCD), y relacionándola con las variables climáticas y también con el potencial hídrico de tallo **(Capítulo 5).**

2. Cuantificar las necesidades hídricas de la planta en base a medidas de la MCD, como herramienta de precisión en la programación de riego, manteniendo los valores de intensidad de señal (IS_{MCD}, definido como MCD referencia/MCD Control) cercanos a la unidad durante toda la estación de crecimiento **(Capítulo 6).**

3. Evaluar el uso de la MCD como indicador en planta para la programación del RDC, estableciendo para ello un umbral de la IS de 2 durante los períodos de crecimiento no críticos para el desarrollo del cultivo, evaluando para ello la producción y calidad de cosecha en melocotoneros adultos [*Prunus persica* (L.) Batsch cv "Catherine"] **(Capítulo 6).**

4. Utilización del potencial hídrico de tallo a mediodía como indicador en planta para la programación del riego deficitario controlado (RDC), estableciendo para ello diferentes umbrales del mismo en los períodos fenológicos no críticos para el desarrollo de melocotoneros adultos [*Prunus persica* (L.) Batsch cv "Catherine"], evaluando su respuesta productiva y calidad de cosecha **(Capítulo 7).**

5. Evaluar la aplicación de un protocolo de RDC en las relaciones hídricas de la planta, producción y calidad del fruto en albaricoqueros adultos [*Prunus armeniaca* (L.) cv. "Búlida"] durante tres años consecutivos, cuantificando los ahorros hídricos alcanzables **(Capítulo 8).**

3. Objectives

The main objectives of this doctoral thesis were the following (the chapter where they are addressed is indicated between parentheses):

1. To obtain reference equations from continuous measurements of trunk diameter fluctuations using plant sensors for irrigation scheduling in adult peach trees [*Prunus persica* (L.) Batsch cv "Catherine"], calculating the maximum daily shrinkage (MDS) and relating it to climatic variables and also with the stem water potential **(Chapter 5).**

2. To quantify the plant water needs based on the MDS measurements as a precision tool for irrigation scheduling, by maintaining signal intensity values (IS_{MDS}, defined as $MDS_{reference}$ / $MDS_{Control}$) close to unity for the whole growing season **(Chapter 6).**

3. To assess the use of MDS as a plant-based indicator for regulated deficit irrigation (RDI) scheduling, establishing a signal intensity threshold value of 2 for this irrigation strategy during non critical periods of crop development, and evaluating production and fruit quality in adult peach trees [*Prunus persica* (L.) Batsch cv "Catherine"] **(Chapter 6).**

4. To use the midday stem water potential as a plant-based indicator for RDI scheduling, by establishing different threshold values for this parameter in adult peach trees [*Prunus persica* (L.) Batsch cv "Catherine"] and evaluating production and fruit quality **(Chapter 7).**

5. To assess the RDI effects on plant water relations, yield and fruit quality in adult apricot trees [*Prunus armeniaca* (L.) cv. "Búlida"] during three consecutive years, also quantifying the water savings obtained by the use of this RDI strategy **(Chapter 8).**

ANTECEDENTES

4. Antecedentes

4.1. Situación actual de los frutales en el mundo, España y la Región de Murcia

A nivel mundial, en el año 2012, existían más de 324 millones de hectáreas equipadas para el riego, de las cuales, aproximadamente 275 millones (85%), se encuentran regadas activamente. Esto supone un 20% de la superficie total cultivada, constituyendo aproximadamente un 40% de la producción agrícola total, lo que da fe de su gran importancia (FAO, 2015). En nuestro país las diferencias son aún mayores, contando el regadío poco más del 21% de la superficie total cultivada (aproximadamente 3,6 millones de hectáreas), y aportando más del 55% de la producción agraria total. En la Región de Murcia la importancia del sector agrícola está basada casi en su totalidad en el regadío, ya que con algo menos del 39% de la superficie cultivada, genera un 94% de la producción final (MAGRAMA, 2015a).

En nuestro país, la superficie total de frutales no cítricos (frutales de pepita y hueso) en regadío representa aproximadamente 273.000 ha (32% de la superficie total cultivada) de las que, en términos de producción, representa más del 75% de la fruta producida. (MAGRAMA, 2015a). El melocotonero y el nectarino en nuestro país ocupan una superficie de 84.378 ha, prácticamente en su totalidad bajo regadío (95%), y producen algo más de 1,3 millones de toneladas anuales, aproximadamente el 34% de la producción total de frutales (MAGRAMA, 2015b). El segundo frutal en superficie de cultivo es el manzano (30.794 ha) seguido por el peral (24.243 ha) con una producción de 545.992 y 425.560 toneladas respectivamente, (14% y 11% respecto del total producido). Por último, el albaricoquero y el ciruelo, con una superficie de plantación de 20.334 y 16.614 ha respectivamente, alcanzan un porcentaje de plantación en torno al 3,5 y 4,5 % respectivamente (131.776 y 172.352 toneladas cada uno).

En el contexto mundial, el melocotonero es uno de los cultivos más extendidos, siendo la segunda especie frutal en importancia según su producción después del manzano. Su gran aceptación por el consumidor es debida a su diversidad de usos y a su consumo en fresco.

El melocotonero se encuadra botánicamente dentro de la Familia *Rosaceae*, género *Prunus* y especie *Prunus persica* (L.) Batsch. Es originario de China, donde las referencias de su cultivo se remontan a 3.000 años a.C., extendiéndose probablemente a

Persia a través de las rutas comerciales por las montañas, llegando a ser conocidos allí como fruta pérsica, de ahí su nombre científico. Hacia el año 330 a.C., su cultivo llegó a Grecia, y durante la Edad Media se extendió por toda Europa. Fue introducido en España por los romanos, siendo al principio un cultivo marginal, pero en el siglo XIX comienza su expansión.

El principal país productor es China, seguido de lejos por Italia, Egipto, España, EE.UU y Turquía. En la Región de Murcia el melocotonero es el primer frutal de hueso en producción y el segundo en superficie de cultivo tras el almendro.

La oferta de melocotón fresco que presenta nuestro país supera los 6 meses de duración, desde finales de abril hasta octubre o primeros de noviembre. Con una superficie cultivada de 10.713 ha y una producción de 171.526 t, la Región de Murcia ocupa el tercer lugar en producción de melocotón dentro del territorio nacional, tras Aragón y Cataluña (Figura 4.1, MAGRAMA, 2015b).
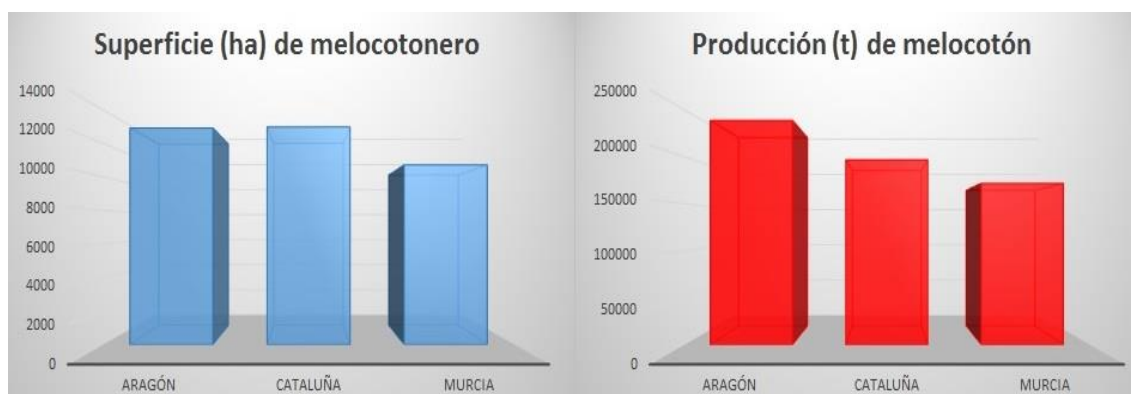
Figura 4.1. Principales Comunidades Autónomas españolas en superficie y producción de melocotones (Datos extraidos de MAGRAMA 2015b).

Las distintas variedades de melocotonero van desde extratempranas, como "Flordastar", árbol de porte semi-erecto, vigoroso con una elevada intensidad de floración cuya recolección tiene lugar la segunda semana de mayo; hasta variedades tardías que se recolectan a partir del 10 de septiembre llegando, incluso, a finales de Noviembre y entre las que destaca la variedad "Melocotón de Calanda".

Una variedad de media estación es "Catherine" que presenta una doble aptitud, siendo su destino principal el mercado en fresco, pero en años de desequilibrio entre la oferta y la demanda, normalmente coincidente con años de fuerte producción, es aceptada por la industria para su procesado. Ha tenido un gran prestigio en el pasado porque está bien adaptada a las condiciones climáticas de la Región de Murcia. Se trata

de un árbol muy vigoroso y productivo, de fruto medio y redondeado, color amarillo-anaranjado, textura bastante firme, buena calidad gustativa, cuya recolección se realiza en la primera quincena de julio (Fotografía 4.1).

Fotografía 4.1. Melocotonero "Catherine" en producción (Fuente propia).

En el caso del albaricoquero su producción mundial supera las 2,500.000 t, siendo Turquía el principal país productor seguido de Irán. En España, la Región de Murcia, con aproximadamente un 60% de la producción nacional, ocupa el primer lugar, tanto en producción como en superficie cultivada, con una gran diferencia respecto al resto de Comunidades Autónomas (Figura 4.2, MAGRAMA, 2015b).

El albaricoque es originario del noreste de China hacia 3000 años a.C, cerca de la frontera con Rusia, y no de Armenia como indica su nombre científico, aunque Armenia tiene una gran tradición en su cultivo. Los romanos lo introdujeron en Europa por Anatolia alrededor del año 70 a. C. llamándole *Praecox* pues florecía temprano, en la primavera. Este cultivo se encuadra botánicamente dentro de la Familia *Rosaceae*, subfamilia *Prunoideae*, genero *Prunus* y especie *Prunus armeniaca* L.
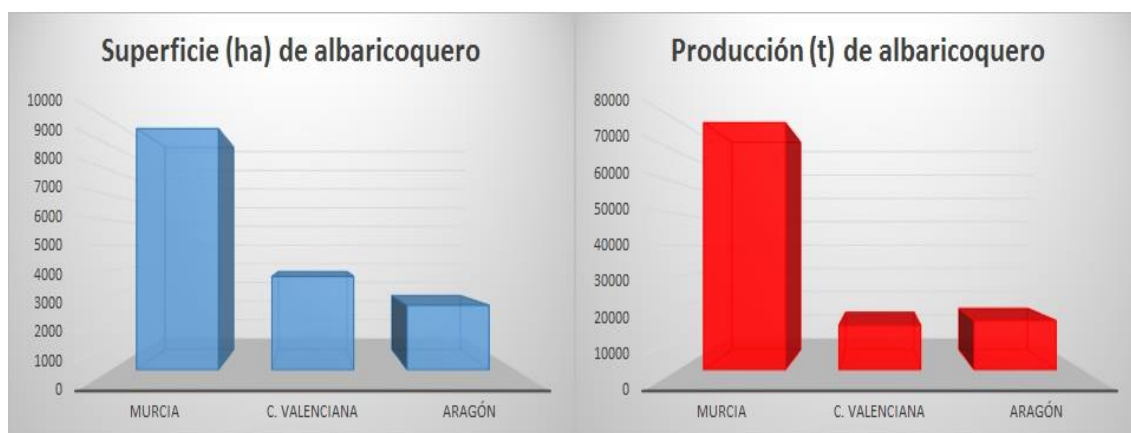
Figura 4.2. Principales Comunidades Autónomas españolas en superficie y producción de albaricoque (Datos extraidos de MAGRAMA 2015b).

El 66% de la superficie de albaricoquero en la Región de Murcia es de la variedad "Búlida" (CARM, 2009). Se trata de una variedad rústica española que se adapta a todo tipo de suelos. Los árboles son muy vigorosos, de producción abundante y regular, sensibles a oidio y monilia, resistentes al viento y a la caída del fruto (Fotografía 4.2.). Los frutos son grandes y poseen un surco poco profundo, siendo su piel amarilla y de pulpa dulce, bastante jugosa y perfumada. El hueso es grande y tiene quilla. La recolección se lleva a cabo a primeros de junio y presenta una buena conservación.

Fotografía 4.2. Albaricoquero "Búlida" en producción (Fuente propia).

Dada la actual expansión en la Región de Murcia de la variedad de melocotón "Catherine" y la variedad "Búlida" en albaricoque, se ha considerado interesante dedicar la presente tesis doctoral a estas dos variedades de frutales de hueso.

4.2. Riego de frutales: metodologías

En el área mediterránea el agua es, sin lugar a dudas, el factor más limitante de la producción de frutas y hortalizas. Esta escasez de recursos hídricos impulsa la necesidad de adoptar estrategias de riego capaces de reducir los aportes de agua aumentando la eficiencia de su uso. Este hecho es de gran importancia en el sector agrario ya que éste utiliza el 75% de estos recursos hídricos (Libro Blanco del Agua en España, 2008). Aunque en la última década la sociedad se ha concienciado de la necesidad de mejorar la gestión y la protección del agua, los criterios económicos y los factores políticos todavía tienden a dirigir todos los ámbitos de la política del agua, no recibiendo la ciencia y las buenas prácticas la atención adecuada.

El término programación del riego describe el procedimiento mediante el cual se determinan la frecuencia y dosis de agua a aplicar en cada riego (Hillel, 1990). Con el fin de poder planificar esta programación, es necesario conocer las necesidades hídricas de los cultivos, es decir, la cantidad de agua que requieren para un desarrollo productivo máximo. Por tanto, es necesario introducir el término de evapotranspiración (ET).

La ET engloba dos procesos que ocurren simultáneamente:

La *evaporación* es la cantidad de agua que, por un proceso de vaporización, pasa del suelo a la atmósfera. Al inicio de la estación del crecimiento, el valor de la evaporación es significativamente más alto que en etapas subsiguientes. La *transpiración* es la cantidad de agua que pasa de la planta a la atmósfera por un proceso de evaporación. A efectos prácticos estos dos componentes se determinan conjuntamente. El conocimiento de la evapotranspiración de los cultivos es esencial para un uso eficiente del agua de riego. Su determinación en plantaciones de frutales es complicada debido a las interacciones existentes entre los diferentes procesos fisiológicos y a la influencia de un gran número de parámetros como las condiciones del medio, técnicas culturales, edad de la plantación, sistema de riego e incluso combinación variedad/patrón (Cohen, 1994).

Evapotranspiración del cultivo de referencia (ET_0)

La FAO (Food and Agriculture Organization) definió la evapotranspiración del cultivo de referencia (ET_0) como el consumo de agua de una superficie extensa de gramíneas, uniforme, de 8 a 15 cm de altura, en crecimiento activo, que sombrea la

totalidad del suelo y bien provista de agua (Doorenbos y Pruitt, 1977). Posteriormente y debido a la gran variedad de gramíneas y prácticas de cultivo, este organismo propuso cambiar el concepto de cultivo de referencia y revisar los métodos de cálculo. De este modo, la ET_0 en casos en que la vegetación no cubra totalmente el suelo, el factor de resistencia debe incluir los efectos de la evaporación de la superficie del suelo. Si el cultivo no está transpirando de manera potencial, la resistencia depende también del estado del agua dentro de la planta. Para estos casos ET_0 se define como la tasa de evapotranspiración de un cultivo hipotético de altura fija de 12 cm, y una resistencia aerodinámica de $208/U_2$ (s m^{-1}), donde U_2 es la media de la velocidad del viento medida a 2 m de altura sobre el dosel vegetal.

Dicha estima puede realizarse bajo condiciones estándar o no estándar. El primer caso hace referencia a la lámina de agua necesaria para cubrir las pérdidas por evapotranspiración en un cultivo sano bajo condiciones óptimas de nutrición y creciendo en lugar amplio. Así, la evapotranspiración del cultivo se estimaría mediante el uso de un coeficiente específico (K_c), que depende fundamentalmente del tipo de cultivo, edad del mismo, humedad de la superficie del suelo y fracción de cubierta vegetal (Dorenbos y Pruitt, 1977).

$$\textbf{ET}_c \ (\textbf{mm d}^{-1}) = \textbf{ET}_0 \ (\textbf{mm d}^{-1}) \cdot \textbf{K}_c$$

Bajo condiciones no estándar, la ET_c se calcularía usando un coeficiente de estrés hídrico (K_s) o ajustando el K_c a las condiciones de estrés y limitaciones ambientales en la evapotranspiración del cultivo.

A continuación se describen brevemente las principales metodologías que se emplean para calcular las necesidades hídricas de los cultivos:

4.2.1. Métodos climatológicos

A pesar de la existencia de varias ecuaciones empíricas o semiempíricas para determinar la ET_0 usando datos meteorológicos, algunas son sólo válidas para determinadas condiciones climáticas y agronómicas, no extrapolables a condiciones diferentes de las que fueron obtenidas. Se pueden diferenciar los métodos basados en la temperatura del aire, radiación solar o los combinados, que son los más empleados a nivel mundial.

Métodos basados en la temperatura del aire

En muchas regiones del planeta, los datos meteorológicos y climatológicos son muy escasos o limitados. En estos casos los modelos de cálculo de la ET basados simplemente en la temperatura del aire constituyen una estimación aceptable. Entre estos métodos, los más comunes son el *método de Thornthwaite, método de Blaney-Criddle, método de Hargreaves, método de Linacre y el método de Turc.*

Métodos basados en la radiación solar

La mayor parte de la energía para producir la evapotranspiración proviene de la radiación, y sólo en regiones áridas y semiáridas, donde la advección juega un papel importante, la radiación no tiene una relación lineal con la evapotranspiración. La dependencia de la evapotranspiración con la radiación cambia con las condiciones climáticas y de la superficie, así como con la estación del año. Algunos métodos basados en la radiación incluyen también la temperatura.

Dentro de este grupo se encuentran el *método de regresión, método Makkink, método de la Unidad Térmica Solar y el método de la radiación Solar y Térmica.*

Métodos combinados

Howard Penman (1948) fue pionero en desarrollar un método de cálculo de la ET que considera tanto las fuentes de energía como el transporte turbulento del vapor de agua a partir de una superficie.

Método de Penman-Monteith

El método de Penman ha sido ampliamente utilizado para cálculos de ET_0. Este método descrito en 1948 estaba pensado para el cálculo de la evaporación de superficies libres de agua, por tanto, desprecia los términos de transpiración, que no se consideran.

El método de Penman no sirve para estimar la ET en presencia de procesos de advección, por lo que frecuentemente falla para estas condiciones (Slatyer, 1970). En condiciones de fuerte advección, Rosenberg (1969) comprobó que el método de Penman subestimaba la evapotranspiración de forma considerable para un suelo desnudo. Por ello, Monteith (1963) introdujo los términos de resistencia al método de Penman. Este método ha sido el que mayor aplicación ha tenido, sobre todo en trabajos de investigación, para estimar la ET en cultivos y bosques. Posteriormente, en la década de

los 90, Allen y colaboradores definieron un nuevo concepto de evapotranspiración de referencia. Al igual que otros modelos, está basado en el modelo de Penman, y es una modificación del método propuesto por la FAO (Doorembos y Pruitt, 1977). Este modelo calcula de forma teórica las resistencias estomática y aerodinámica de un cultivo hipotético de césped, de modo que su valor es comparable para cualquier situación geográfica.

En la actualidad para la estima de la ET_0 con parámetros climáticos, el método más utilizado es el de FAO Penman-Monteith (Allen et al., 1998).

Método del tanque de evaporación

Otro método de estimación de la ET_0 es el que emplea medidas directas de la evaporación de una superficie de agua, que genera un índice que integra los efectos de radiación, temperatura y humedad del aire y viento. El tanque clase A estima la evapotranspiración utilizando un coeficiente corrector K_P que depende de la ubicación del tanque y de las características climáticas existentes.

Métodos micrometeorológicos

Estos métodos se basan en una combinación del balance de energía y del transporte aerodinámico del vapor de agua, utilizando diversas variables climáticas (temperatura, humedad, velocidad del viento y radiación).

Método Balance de Energía y Relación de Bowen

La evaporación precisa energía por lo que el proceso de evapotranspiración resulta limitado por la disponibilidad de energía en la superficie de vegetación. Por tanto, aplicando su principio de conservación podemos predecir la evapotranspiración.

La ecuación del balance de energía es la siguiente:

$$\mathbf{Rn} - \mathbf{G} - \lambda\mathbf{ET} - \mathbf{H} = 0$$

Donde:

Rn es la radiación neta (W m^{-2})

G es el flujo de calor del suelo (W m^{-2})

λ**ET** es el flujo de calor latente (W m^{-2})

H es el calor sensible (W m^{-2})

Se ignora la tasa neta de energía que se trasfiere horizontalmente por advección, por tanto la ecuación anterior solo es aplicable a vegetaciones homogéneas en grandes superficies.

Los términos Rn y G pueden ser estimados en función de parámetros climáticos. Sin embargo, H precisa de medidas de gradiente de temperatura por encima de la superficie. La estima de evapotranspiración mediante el método de transferencia de masa considera los movimientos verticales de pequeñas cantidades de aire por encima de una amplia superficie homogénea. Estos torbellinos transportan la materia (vapor de agua) y la energía (calor) desde y hacia la superficie de la evapotranspiración.

De este modo, la tasa de evapotranspiración puede ser determinada a partir de los gradientes verticales de temperatura del aire y vapor de agua mediante la relación de Bowen (Hatfield, 1989).

Eddy covariance

Este método se basa en la medida de los flujos turbulentos de agua transportados verticalmente por porciones de aire, y permite conocer el flujo de calor sensible y de calor latente. La velocidad vertical de viento (u_v, ms^{-1}) se obtiene con un anemómetro sónico tridimensional y la densidad de vapor de agua (ρv) se mide con un higrómetro de respuesta rápida. La altura de ubicación de los sensores y la distancia entre ellos influye en la estimación de los flujos de calor sensible y calor latente (Villalobos et al., 2000).

4.2.2. Balance hídrico

El uso de este balance se realiza a cualquier escala. Normalmente, se miden todas las variables y se despeja la evapotranspiración según la fórmula:

$$L + R - ET_c - \Delta H - D \pm E = 0$$

Donde:

L es la lluvia (mm d^{-1})

R es el riego aplicado (mm d^{-1})

ET$_c$ es la evapotranspiración del cultivo (mm d^{-1})

ΔH es la variación de la humedad del suelo (mm d^{-1})

D es el drenaje neto (mm d^{-1})

E es el aporte o pérdida de agua por escorrentía superficial (mm d^{-1})

La fiabilidad de este método depende de la precisión y veracidad de los parámetros medidos, pudiendo llegar a ser los errores de medida muy significativos. A pesar de ello, el balance de agua en el suelo ha sido muy utilizado para determinar las necesidades hídricas de cultivos arbóreos. Básicamente, se cuantifican las cantidades de agua que entran, salen o permanecen en un volumen de suelo durante un tiempo determinado (Domingo, 1994).

Con este fin, los lisímetros de pesada constituyen el método más preciso y directo de medida del consumo de agua de las plantas (Jones, 1998) pero presenta un elevado coste, laboriosidad de montaje y mantenimiento.

4.2.3. Indicadores del estado hídrico

La monitorización del riego constituye la técnica más efectiva para optimizar el rendimiento de los cultivos, tanto en cantidad como en calidad. Las técnicas utilizadas para la monitorización del riego pueden basarse en la estimación de la evapotranspiración, el control de la humedad del suelo o en el seguimiento del estado hídrico de la planta, como se explica a continuación.

Indicadores del estado hídrico de la planta: medidas discontinuas y continuas

La planta integra el efecto tanto de la disponibilidad de agua en el suelo como de la demanda evaporativa y, por ello, proporciona una información más adecuada para determinar el efecto de las restricciones del riego sobre su estado hídrico y para la programación del riego (Jones, 2004). Estos indicadores deben detectar lo antes posible una situación de déficit hídrico y ser representativos y robustos. Cabe diferenciar los indicadores del estado hídrico en la planta en dos grupos, según permitan la obtención de datos de forma continua o no, a fin de poder automatizar el riego.

Medidas discontinuas

Estos indicadores no permiten la automatización del riego y deben ser medidos periódicamente para obtener una evolución del estado hídrico de la planta a lo largo de un ciclo de cultivo. Entre ellos, los más usuales son los siguientes:

-Contenido relativo de agua (CRA)

Relaciona la cantidad de agua en un tejido con respecto al contenido máximo a plena turgencia. Su determinación (Barrs y Weatherley, 1962) viene dada por la fórmula:

$$CRA = \frac{P_F - P_S}{P_T - P_S}$$

Donde:

(P_F) Peso fresco de la muestra recién obtenida (g).

(P_T) Peso turgente alcanzado tras sumergir la muestra en agua pura (g).

(P_S) Peso de la materia seca (g).

Según Hsiao (1990), la dificultad en su medida radica en la correcta determinación de P_T.

Esta técnica se considera menos rigurosa que el potencial hídrico, pero presenta la ventaja de correlacionarse mejor con el potencial de presión (principal responsable del proceso de expansión celular), que el potencial hídrico foliar (Jones, 1990).

-Potencial hídrico foliar (Ψ)

Desde la aparición de la cámara de presión (Scholander et al, 1965), se ha hecho posible una lectura rápida en campo del potencial hídrico foliar.

Es conocido que el valor de potencial hídrico foliar (Ψ_h) muestra una tendencia circadiana a lo largo del día, con valores más elevados a primera y a última hora del día y menores a mediodía (Alarcón et al., 2006) ya que estos valores dependen de factores externos e internos a la propia planta. Las interacciones entre el potencial de hoja y la

conductancia estomática, especialmente en especies isohídricas, hacen muy difícil su utilización con el fin de programar el riego.

Fotografía 4.3. Hoja tapada y medición con cámara de presión. Soil Moisture Equip. Corp, model 3000, Santa Barbara, CA, USA (Fuente propia).

Por este motivo, y como alternativa, se comenzaron a utilizar indicadores menos sensibles a las condiciones ambientales como el potencial hídrico de tallo (Ψ_t). Para medirlo, se tapa una hoja cercana al tronco con una bolsa de plástico y se cubre con papel de aluminio durante al menos 2 horas antes de la medida, para impedir la transpiración (Fotografía 4.3). Al provocarse un cierre estomático, el Ψ medido alcanza el equilibrio con el del xilema y, por tanto, puede ser utilizado para estimar Ψ_t. Entre sus ventajas destacan su menor variabilidad, mejor correlación con el déficit de presión de vapor (DPV) y que refleja mejor la disminución de agua en el suelo que Ψ_h. Diversos trabajos han puesto de manifiesto la utilidad de este indicador en diversos frutales como albaricoquero (Pérez-Sarmiento et al., 2010); granado (Intrigliolo et al., 2011); olivo (Moriana et al., 2012); uva de mesa (Gálvez et al., 2014) y melocotonero (Abrisqueta et al., 2015).

La respuesta agronómica de la planta al déficit hídrico puede representarse a través de la integral de estrés (S_Ψ), que es un índice que expresa conjuntamente la intensidad y duración del estrés (Myers, 1988), mediante la siguiente ecuación:

$$S_\Psi = \left| \sum_{i=0}^{i=t} \left(\overline{\Psi}_{i,i+1} - c \right) n \right|$$

Donde:

$\Psi_{i,i+1}$ (MPa) es el promedio de Ψ_t para cada intervalo de tiempo.

c (MPa) es el valor máximo de Ψ_t medido durante el estudio.

n es el número de días del intervalo.

El gran inconveniente que presentan las medidas de Ψ para su uso como indicador para la programación del riego es la imposibilidad de su automatización en campo.

-Intercambio Gaseoso (conductancia estomática y fotosíntesis neta)

La conductancia estomática (g_s) mide el grado de apertura de los estomas, estructuras foliares que regulan el intercambio gaseoso. La transpiración se produce mayoritariamente por difusión de agua en estado de vapor a través de estos estomas aunque también existe una pérdida a través de estructuras como las lenticelas de las ramas, estomas en tallos de herbáceos o cutícula de las hojas (Kramer, 1983). La g_s sigue un ritmo circadiano y está influenciada por diversos factores como la intensidad lumínica, la temperatura, el incremento de la humedad absoluta entre hoja y aire, edad de la hoja, concentración de CO_2 y el potencial hídrico (Jones, 1983). Una respuesta generalizada al aumento en el DPV de la atmósfera que circunda la hoja es la disminución de la g_s, tal y como se ha encontrado en gran número de especies, impidiendo así tasas de transpiración excesivamente elevadas que pudiesen inducir la deshidratación del tejido (Cohen y Cohen, 1983).

Se estima que el 95% del agua absorbida se pierde por transpiración (Sánchez-Díaz y Aguirreolea, 2008), de ahí la importancia de un adecuado control de estos niveles bajo una situación de déficit hídrico. Este control se produce generalmente vía estoma, esto hace que muchos autores consideren la g_s como un indicador del estado hídrico de la planta. (Hsiao, 1990). El estrés hídrico tiene efecto residual sobre los estomas, de tal forma que tras la reanudación del riego se precisa un periodo de tiempo para conseguir la plena recuperación de la g_s (Ruiz-Sánchez et al., 2000).

La fotosíntesis es uno de los procesos más importantes en la respuesta de las plantas ante condiciones de déficit hídrico (Azcón-Bieto et al., 1983). Implica la coordinación de distintos subprocesos tales como la absorción de CO_2, la captación de luz por los complejos clorofila-proteínas, la síntesis de NADPH y la síntesis de ATP, entre otros.

Fotografía 4.4. Sistema portátil para medida de fotosíntesis LI-6400, Li-Cor, Lincoln, NE, USA (Fuente propia).

Cuando el déficit hídrico es leve se provoca un cierre parcial de los estomas, aumentando la fotorespiración y disminuyendo la relación CO_2/O_2, lo que posibilita la rápida recuperación de la fotosíntesis tras la desaparición del estrés. (Ruiz-Sánchez et al., 2000; Medrano y Flexas, 2004). La tasa de asimilación neta de CO_2 o tasa de fotosíntesis (P_n) se mide con analizadores de gases por infrarrojos, algunos de ellos portátiles, que permiten su medición directa en condiciones de campo (Fotografía 4.4).

-Temperatura foliar

La temperatura en las hojas ha sido acreditada ampliamente como indicador de la respuesta de las plantas a factores ambientales adversos. La escasez de agua en el suelo hace que las plantas transpiren a una menor tasa que la demanda evaporativa de la atmósfera, lo que supone un calentamiento de la hoja ya que disminuye el efecto refrigerante de la transpiración (Kramer, 1974). Se usa desde los años 60 como indicador del estrés en la planta, siendo muy difícil su interpretación dada la gran cantidad de factores involucrados, tanto ambientales como de la planta (Gardner et al., 1992).

En 1973, Ehrler estableció un intervalo de temperaturas foliares en función de la humedad del suelo, observando una diferencia de temperatura entre la hoja y el aire que descendía 1.3 ºC por cada kPa de aumento en el DPV. Sobre esto, Idso (1982) propusieron un índice de estrés hídrico (Crop Water Stress Index CWSI) partiendo de las relaciones entre la diferencia de temperatura entre la hoja y el aire frente al DPV,

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obteniendo líneas de base específicas para cada cultivo, que fueron mejoradas aplicando la teoría del balance de energía (Alves y Pereira, 2000). Actualmente, con la expansión de las técnicas de teledetección, el uso de la termografía infrarroja y las imágenes térmicas poseen un futuro prometedor en la monitorización del estrés hídrico de los cultivos (Jones, 2004; Sepulcre-Cantó et al., 2006).

Medidas contínuas

-Cavitación xilemática

Este método se basa en la teoría por la cual el déficit hídrico puede ocasionar la rotura de la continuidad de la columna de agua dentro de los vasos xilemáticos, produciéndose así la cavitación. Cuanto mayor es el déficit hídrico mayor es el número de vasos cavitados (Tyree y Sperry, 1989). Esta interrupción en las columnas de agua libera energía en forma de emisiones acústicas que pueden ser registradas (Cruiziat et al., 2002). La frecuencia de estas pequeñas emisiones, para una especie concreta, puede ser un índice de su estado hídrico (Jones, 1989).

Hace unas décadas, para la detección de estos suaves sonidos, se recurría a su amplificación, sin embargo, los ruidos ambientales interferían seriamente. Este problema ha sido minimizado con el uso de detectores de cavitación ultrasónicos (Tyree y Dixon, 1983). El estrés hídrico no es el único factor que puede causar la cavitación en los vasos del xilema; otros factores como las heladas y los patógenos pueden influir en la aparición de la cavitación.

-Variaciones del diámetro del tronco

Las medidas de las microvariaciones de tronco y ramas proporcionan una valiosa información acerca del crecimiento y estado hídrico de la planta encontrándose directamente relacionadas con variables climáticas y con la disponibilidad de agua, resultado del desequilibrio entre transpiración y absorción de agua durante el día.

A lo largo del día, tienen lugar ciclos de contracción y expansión del diámetro del tronco alcanzando su evolución típica un valor máximo al final de la noche (MXDT), ya que la hidratación de los órganos es máxima y un valor mínimo (MNDT) que generalmente se da una vez transcurrida la transpiración máxima (Figura 4.3).
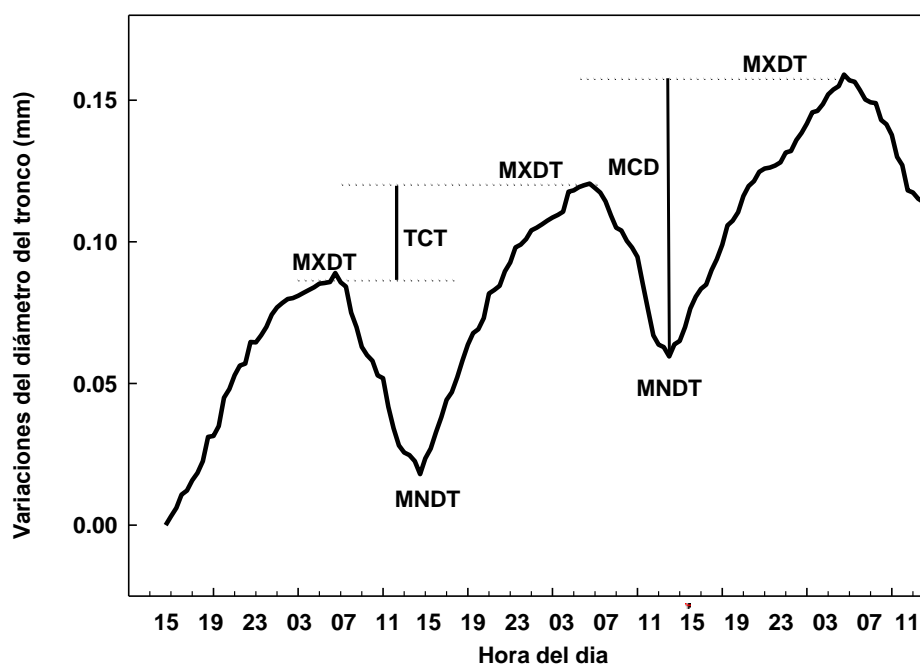
Figura 4.3. Parámetros derivados de las fluctuaciones diarias del diámetro del tronco: máximo diámetro diario de tronco (MXDT) y mínimo (MNDT), máxima contracción diaria (MCD) y la tasa de crecimiento del tronco (TCT) durante 3 días consecutivos.

La diferencia entre ambos valores es denominada máxima contracción diaria del diámetro de tronco (MCD). Dado que el xilema es prácticamente inelástico (Génard et al., 2001), los cambios en el diámetro de los troncos parecen deberse a cambios en el estado hídrico del floema (Irvine y Grace, 1997).

Por ello la magnitud de MCD va a depender de varios factores como el módulo de elasticidad y las propiedades de difusión del agua de los tejidos del floema (Génard et al., 2001), espesor del floema (Naor y Cohen, 2003; Intrigliolo y Castel, 2005) pero también del tamaño del árbol y su carga productiva (Intrigliolo y Castel, 2007). Tanto la magnitud de MCD, como la tasa de crecimiento diario del tronco (TCT), que es la diferencia de los valores de MXDT entre dos días consecutivos, representan una información valiosa sobre la intensidad del estrés hídrico alcanzado (Egea, 2008). El interés de utilizar uno u otro va a estar determinado, en gran medida, por las tasas de crecimiento del árbol. Así, en plantaciones adultas con bajas tasas de crecimiento se desaconseja el uso de TCD; en cambio, en plantaciones jóvenes ocurre lo contrario (Domingo *et al.*, 2005; Nortes *et al.,* 2005).

En los últimos años ha surgido un gran interés por la utilización de este indicador para gestionar el agua de riego de una forma más precisa (Fernández et al.,

2011; Moriana et al., 2013; Ballester et al., 2014). Estas medidas, usando transductores de tipo TDVL (transformador diferencial de variación lineal), pueden ser fácilmente automatizadas y utilizadas para la programación del riego (González-Altozano, 1998).

-Flujo de savia

Este método se basa en la aplicación y transporte de calor como indicador del movimiento de la savia en el tejido xilemático. Huber y Schmidt (1937) fueron los primeros en proponer el uso del pulso de calor como indicador del movimiento de la savia en el xilema, siendo demostrada su utilidad como indicador del estrés hídrico y su gran sensibilidad a los factores climáticos (Alarcón et al., 2000).

Posteriormente, se han desarrollado distintos métodos basados en la interacción entre el flujo de savia y el transporte de calor suministrado por estas técnicas. Las posibilidades de aplicación de estos métodos han aumentado paralelamente con la mejora de los sistemas informáticos ligados a la agricultura y la mejor detección de la temperatura. Las principales técnicas de medida del flujo de savia pueden agruparse en tres tipos: fuente de calor radial constante (Granier, 1985), balance de calor (Valancogne y Nasr, 1989) y pulso de calor (Nicolás et al., 2005). La elección de la técnica dependerá principalmente de la especie considerada y del tamaño del tallo o tronco.

Indicadores del estado hídrico del suelo

En la actualidad existen un buen número de instrumentos de medida del estado hídrico del suelo (Leib et al., 2003). El uso de sensores para conocer el contenido hídrico del suelo implica que el nivel de agua de éste se mantenga dentro de unos límites. El límite superior se correspondería con la capacidad de campo en el perfil y el inferior, con el umbral por debajo del cual el cultivo sufriría déficit hídrico (Campbell y Campbell, 1982). En el mercado existen distintos tipos de sensores, unos de medida del potencial mátrico del suelo y otros que miden el contenido volumétrico del agua en el suelo.

Potencial Mátrico

Este potencial representa el grado de retención del agua, debido a las interacciones con matrices sólidas o coloidales del suelo. Su valor siempre es negativo ya que la presión que lo origina se opone a la expulsión de agua del suelo; por lo tanto, cuanto más seco está un terreno, más bajo es el potencial mátrico y mayor será la presión necesaria para extraer su agua.

Los sensores que miden el potencial mátrico se basan en la medida directa de la tensión de agua en el suelo (tensiómetros) o de forma indirecta de la resistencia eléctrica del suelo (sensores de matriz granular). Estos sensores tienen restricciones técnicas que limitan su rango de trabajo y precisión en suelos en fase de desecación rápida (Thompson et al., 2006), a pesar de ello continúan usándose con éxito (Pedrero et al., 2013).

La disponibilidad de agua para los cultivos depende más del potencial mátrico del suelo que de su contenido en agua por lo que, en principio, el potencial mátrico debe ser mejor indicador del estado hídrico del suelo con relación al desarrollo de las plantas (Hillel, 1973). A pesar de ello, el hecho de que el estado hídrico de la planta sea controlado por diferentes procesos biológicos hace que su validez como indicador único quede en entredicho ya que este solo podrá reflejar el estado hídrico parcialmente.

Contenido volumétrico de agua en el suelo

Los sensores de medida del contenido volumétrico de agua en el suelo incluyen la sonda de neutrones y la sonda de reflectometría en el dominio del tiempo (TDR) (Phene et al., 1990).

Los límites para el inicio del riego con estos sensores barajan la combinación de dos conceptos: por un lado el agua disponible o útil, cantidad de agua entre la capacidad de campo y punto de marchitez y, por otro lado, el nivel de agotamiento permisible, el cual se refiere al contenido de humedad de un suelo por debajo del cual la absorción radicular consume energía. Por ello es conveniente mantener los niveles de humedad del suelo entre valores de capacidad de campo y de agotamiento permisible, es decir en valores de agua fácilmente disponible (Allen et al., 1998; Fares y Polyakov, 2006).

Fotografía 4.5. Equipo Time Domain Reflectometry (TDR). Model
1502C, Tektronix Inc., OR. (Fuente propia).

La metodología de TDR se basa en la medida del tiempo de propagación de un pulso electromagnético a lo largo de una línea de transmisión (sonda) insertada en el suelo, (Cole, 1977). Su rango de medida oscila de 0,065 a 0,5 cm^3cm^{-3}. Estas sondas tienen como principal ventaja que no necesitan calibración y permiten medir con precisión el contenido volumétrico de agua en el suelo (Fotografía 4.5).

Pueden tomarse lecturas en continuo y puntuales y, dentro de unos límites, no se ven afectadas por la salinidad. Se trata de una medida integradora de la humedad de toda la longitud de la sonda y, para las principales clases de suelo no se requiere una calibración, aunque en el caso de ciertos sustratos, de suelos arcillosos o con elevado contenido de materia orgánica, puede ser necesaria.

Otro equipo que se puede utilizar para la medida del contenido volumétrico de agua en el suelo es la sonda de neutrones (Fotografía 4.6). Se trata de un aparato radioactivo que permite estimar la humedad o densidad de los suelos. Para ello se dispone un tubo de acceso de aluminio introducido en el suelo para que, deslizando la fuente radioactiva en él, estima la humedad del suelo a la cota requerida.

Esta sonda consta de un cilindro metálico sellado de 3 a 5 cm de diámetro y de 20 a 30 cm de longitud el cual contiene una fuente de ^{241}Am - ^{9}Be. El americio bombardea con partículas α los núcleos de Berilio que emiten un haz de neutrones con alta energía cinética (neutrones rápidos) que, al chocar con partículas con un similar

peso molecular, como los átomos de hidrógeno del agua, pierden su energía ralentizándose y pasando a denominarse neutrones lentos rebotando hacia su lugar de partida donde, con la ayuda de un contador Geiger Müller, podemos estimar la cantidad de agua contenida en el suelo. El uso de estos aparatos se ha limitado a los centros de investigación debido a su riesgo radioactivo y la complejidad de su mantenimiento (Gear et al., 1977).

Fotografía 4.6. Sonda de neutrones. Model 4300, Troxler Electronic Laboratories Inc., NC (Fuente propia).

4.3. Concepto de Riego Deficitario Controlado (RDC)

Actualmente están aumentando los desequilibrios entre la oferta y la demanda de recursos hídricos, más acentuados debido al aumento exponencial de la población y a una cada vez mayor industrialización, lo que provoca cierta competencia por este bien. Los desequilibrios climáticos están trayendo como consecuencia una distribución de las precipitaciones menos uniforme, hecho que se agrava en regiones áridas y semiáridas del planeta. Ante estas limitaciones actuales se deben emprender acciones dirigidas al incremento de los recursos, adquiriendo prioridad las acciones orientadas al aumento de la eficiencia y el ahorro hídrico. A este respecto no existen dudas de la conveniencia de emprender acciones que tiendan a mejorar la gestión del agua, tales como la necesaria mejora de las infraestructuras hidráulicas, y la flexibilización de la distribución del recurso en función de la demanda de los cultivos.

Dentro de esta línea de aumento de la eficiencia y ahorro hídrico se encuentra el denominado riego deficitario controlado (RDC), basado en reducir los aportes hídricos

en aquellos períodos fenológicos considerados no críticos para la producción y calidad de la cosecha, cubriendo plenamente la demanda de la planta durante el resto del ciclo del cultivo. Esta técnica surge a partir de los primeros trabajos de Chalmers et al. (1981), en los que se pretendía controlar el exceso de vigor en plantaciones frutales de melocotonero, sin que la producción se viera afectada y que sirvió para poner de manifiesto la posibilidad de inducir estrés hídrico en el período de máximo crecimiento vegetativo sin comprometer la productividad (Chalmers et al., 1981; Mitchell y Chalmers, 1982), consiguiendo ahorros de agua importantes con reducciones de riego en las fases I y II de crecimiento del fruto. El RDC tiene un enfoque más fisiológico que el riego deficitario (RD) ya que contempla tanto la fenología del cultivo, como su capacidad para resistir situaciones de déficit hídrico. Con esta estrategia de riego se puede maximizar la producción por unidad de agua aplicada (Domingo et al., 2005).

Hasta la fecha se han realizado numerosos ensayos en distintas especies de frutales, entre ellos destacan: melocotonero (Conejero et al., 2011; Vera et al., 2013), albaricoquero (Pérez-Pastor et al., 2009; Pérez-Sarmiento et al., 2010), cítricos (Ballester et al., 2013; Mounzer et al., 2013), granado (Intrigliolo et al., 2013; Laribi et al., 2013), almendro (Egea et al., 2013) entre otras. En la mayoria de los estudios, las estrategias de RDC en frutales suponen un importante ahorro de agua, aumentando la eficiencia en el uso de la misma (Egea et al., 2010; Hueso y Cuevas, 2010), una disminución del crecimiento vegetativo (Pérez-Pastor et al., 2009), lo cual se traduce en un ahorro de costes de producción (poda), y una producción final que no se ve afectada por la reducción de aportes los hídricos, ni en cantidad, ni en calidad, llegando incluso esta última a mejorar bajo estrategias de RDC (Pérez-Sarmiento et al., 2010; Alcobendas et al., 2013; Laribi et al., 2013).

4.4. Establecimiento de una estrategia de RDC

Para establecer una estrategia de RDC deben tenerse en cuenta aquellos factores que puedan condicionar su viabilidad. Entre otros, adquiere una especial importancia el conocimiento de los períodos críticos del cultivo, la coincidencia entre el crecimiento vegetativo y reproductivo, el sistema de riego, el clima, las características del suelo, la resistencia a la sequía, etc. (Torrecillas et al., 1996). Además, resulta imprescindible determinar aquellos períodos fenológicos en los que el desarrollo de un estrés puede afectar, de forma considerable, la producción y/o la calidad de la cosecha, así como la

intensidad y duración de los mismos para un correcto manejo del RDC (Torrecillas et al., 1996). Asimismo, es necesario conocer la separación natural de los períodos durante los cuales los tejidos y los órganos de los frutales crecen activamente, ya que posibilita el inhibir el crecimiento de un órgano, un tejido o proceso, sin afectar seriamente a otros. Además, algunos frutos como el melocotón y los cítricos, al recuperarse de un déficit hídrico temporal experimentan un crecimiento compensatorio que les permite alcanzar un tamaño similar al de los frutos que no han experimentado déficit (Pérez-Sarmiento et al., 2010).

4.4.1. Periodos críticos del cultivo

Son aquellos periodos en los que el estrés hídrico puede condicionar de forma considerable la producción y/o calidad de la cosecha. Por ello, la programación del riego en los periodos no críticos es esencial en la aplicación de estrategias de RDC, debiéndose determinar la dosis de agua a aplicar para seleccionar las condiciones más adecuadas en las que realizar el riego.

Sin embargo, resulta difícil indicar los periodos críticos concretos ya que son distintos para cada cultivo. Por ejemplo, en melocotonero el déficit hídrico durante la tercera fase del crecimiento del fruto o fase de rápido crecimiento resulta más trascendente que en otras fases fenológicas (Mitchell y Chalmers, 1982; Goldhamer et al., 2002), por lo que debe evitarse la aplicación de esta estrategia de RDC en este periodo. Sin embargo, Intrigliolo y Castel (2005) señalaron que en otros cultivos como el ciruelo los efectos de la supresión del riego son más dependientes de la duración y del nivel de coincidencia con períodos de alta demanda evaporativa, que del momento en el que tiene lugar su supresión, encontrando una alta sensibilidad del cultivo durante el período de endurecimiento del hueso, contrariamente a lo observado en melocotonero.

En albaricoquero, según Pérez-Pastor et al. (2009), el período más crítico al déficit hídrico es la segunda fase de rápido crecimiento del fruto (fase III), junto al de postcosecha inicial (Ruiz-Sánchez et al., 1999), período en el que se registran altos consumos de agua. La supresión del riego durante este período de postcosecha inicial afecta a la diferenciación floral, lo que provoca un desarrollo tardío de las yemas florales (Brown, 1953), disminución de su número y alteración de las mismas.

No sólo deben tenerse en cuenta los momentos de alta incidencia del déficit hídrico, sino también la magnitud y la duración de éste, ya que a largo plazo podría tener una serie de efectos no deseables, siendo conveniente realizar, para cada cultivo y situación, los pertinentes ensayos que nos permitan conocer las respuestas que experimentan los diferentes cultivos de cara a la adopción de este tipo de métodos, por las repercusiones económicas que ello conlleva y el importante ahorro de recursos hídricos que puede suponer (Sánchez-Blanco y Torrecillas, 1995).

4.4.2. Crecimiento vegetativo y de fruto

Resulta esencial, ante la aplicación de estrategias de RDC, conocer en cada cultivo cuándo tiene lugar tanto el crecimiento vegetativo como el productivo, y además qué nivel de coincidencia existe entre uno y otro. Una clara separación entre ambos puede definir la idoneidad de este tipo de estrategias de RDC para un determinado cultivo. Durante el periodo de brotación y desarrollo de ramos, si reducimos los aportes hídricos podemos limitar este proceso para atender plenamente las demandas hídricas de la planta durante el desarrollo del fruto, sin limitar el tamaño final del mismo (Pérez-Sarmiento et al., 2010; López et al., 2010; Alcobendas et al., 2013).

4.4.3. Sistema de riego

El sistema de riego ideal para llevar a cabo estrategias de RDC es el riego localizado, ya que nos permite aplicar volúmenes reducidos de agua en el suelo y controlar más fácilmente la cantidad de agua aplicada. Entre las ventajas del riego localizado se encuentran su mejor aprovechamiento del agua, reducción de la mano de obra, sobre todo porque disminuyen las malas hierbas al no humedecer la totalidad del suelo, y la posibilidad de automatización. Sin embargo, no todo son ventajas, el alto coste de instalación y mantenimiento son desventajas a tener en cuenta.

4.4.4. Clima

El clima es otro factor que influye en la aplicación de estrategias de RDC en el sentido de que éstas suelen ir encaminadas, entre otras razones, a programar situaciones de estrés hídrico en determinados momentos del ciclo de un cultivo, por lo que la presencia de lluvias puede ser un aspecto negativo en la consecución de este fin. En climas donde sean frecuentes las lluvias resulta conveniente suprimir los aportes hídricos en aquellos períodos donde sea necesario limitar el desarrollo vegetativo, de tal

manera que se permita asegurar un tiempo suficiente de déficit hídrico e inducir el efecto deseado.

4.4.5. Características del suelo

Algunos frutos, como el melocotonero y los cítricos, son susceptibles de experimentar crecimientos al reanudar el riego tras un déficit hídrico. Además los cítricos, durante el estrés hídrico, acumulan materia seca que va a facilitar el crecimiento del fruto tras la reanudación del riego. Esto indica la necesidad de facilitar la aparición del déficit hídrico como recuperación. De ahí que Chalmers (1990) indicara que suelos poco profundos con baja capacidad de retención de agua resultan convenientes para su aplicación, al conseguirse un rápido agotamiento y recarga de los niveles de humedad del suelo, además de volúmenes reducidos de suelo humectado, que permitirían una alta concentración de raíces. Otro aspecto a considerar bajo estas circunstancias es controlar el crecimiento radicular durante los períodos de déficit hídrico, ya que se ha observado que al ralentizar el desarrollo radicular, se ve limitado el crecimiento vegetativo y se favorece el del fruto, ya que las sustancias elaboradas en la fotosíntesis se canalizan hacia los frutos.

4.4.6. Resistencia a la sequía

Otro factor importante a tener en cuenta es la capacidad de los cultivos para adaptarse a las condiciones de déficit hídrico. La resistencia a la sequía de un cultivo hace referencia a su capacidad para crecer satisfactoriamente en zonas con déficit hídrico. Según Lange et al (1971), la escasez de agua juega un importante papel al determinar la distribución y abundancia de muchas especies vegetales, de ahí que el conocimiento de los mecanismos de resistencia a la sequía tenga una gran importancia tanto desde un punto de vista tanto ecológico como agrícola.

Las modificaciones que tienen lugar en la estructura y función de las plantas para aumentar la probabilidad de sobrevivir y reproducirse en un ambiente determinado se llama adaptación. La influencia de los mecanismos adaptativos sobre la productividad del cultivo fue estudiada por Turner en 1986, comprobando que sólo aquellos mecanismos que favorecen el escape a la sequía, el mantenimiento de la entrada de agua y el mantenimiento de la presión de turgencia, no reducen la fotosíntesis, el crecimiento ni el rendimiento del cultivo.

Se distinguen tres mecanismos de adaptación de las plantas a la sequía (Blum, 1988; Ceccarelli, 1989):

1. Mecanismos de escape de la sequía: capacidad de las plantas para completar su ciclo antes de que el déficit hídrico en el suelo y en la planta se desarrollen. Para este fin, la planta cumple una determinada fase fenológica de forma rápida o, en todo caso, adapta su desarrollo a las condiciones dominantes en ese momento.

2. Mecanismos de aplazamiento o evitación de la deshidratación: capacidad de las plantas para mantener un potencial hídrico relativamente alto en condiciones de estrés hídrico, atmosférico o del suelo, mediante el cierre estomático y el ajuste osmótico.

3. Mecanismos de tolerancia a la deshidratación: *(i)* capacidad de las plantas para reducir la actividad química del agua; *(ii)* concentrar solutos y macromoléculas y *(iii)* producir modificaciones en las membranas celulares.

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REFERENCE VALUES OF MAXIMUM DAILY TRUNK SHRINKAGE FOR IRRIGATION SCHEDULING IN MID-LATE MATURING PEACH TREES

5. REFERENCE VALUES OF MAXIMUM DAILY TRUNK SHRINKAGE FOR IRRIGATION SCHEDULING IN MID-LATE MATURING PEACH TREES

Abstract

Precise irrigation is essential in arid and semi-arid areas where water is scarce, such as the South-East of Spain. Therefore, finding a precise and reliable water stress indicator which could be automatically controlled is of paramount importance. Maximum daily trunk shrinkage (MDS) showed a great potential for commercial irrigation scheduling. However, MDS records may be difficult to interpret and reference baselines could be useful for this interpretation. In the current study, measurements of midday stem water potential (Ψ_s) and MDS were taken over a 3-year period in peach trees [*Prunus persica* (L.) Batsch cv. 'Catherine'] in order to obtain reference baselines for irrigation scheduling. Plants were daily irrigated above their water requirements (~120%) in order to obtain non-limiting soil water conditions. Climate parameters and MDS were recorded automatically, whereas midday stem water potential was assessed in the field every 3 days. The relationships between MDS and climate parameters such as ET_0, daily maximum and midday air temperatures (T_{max} and T_{mid}, respectively), maximum and midday air vapour pressure deficit (VPD_{max} and VPD_{mid}, respectively) were determined. The results indicate that MDS records were better related to T_{mid} and T_{max} than to other meteorological variables. The relationship between MDS and Ψ_s differed from year to year, although similar equations were found among seasons for the post-harvest period. However, these relationships varied greatly with the conditions of each year, tree phenological stage and crop load. Therefore, the growers must be aware of these factors when using MDS values for irrigation scheduling.

Keywords: Maximum daily trunk shrinkage; Baselines; Stem water potential; *Prunus persica*; Irrigation scheduling.

5.1. Introduction

In the world context, peach tree [*Prunus persica* (L.) Bastch] is one of the most extended fruit crops, the second most important fruit species by production after apple. Its great acceptance by consumers is due to its diverse uses and fresh consumption. Spain is the second largest peach producer in the world. Peach tree plantations are located in the Mediterranean area, being Murcia (SE Spain) the third main peach

production area in the country after Aragon and Catalonia, with a cultivated area of 10,713 ha and a production of 171 526 t per year, which represents 21% of the Spanish total production (MAGRAMA, 2015).

Currently, the pressure on water resources is increased by the competition for water between agriculture, industry and population, leading to an urgent need to develop new techniques of irrigation scheduling that allow increasing crop water productivity in irrigated agriculture, which accounts for up to 70-80% of the total water consumption in arid and semi-arid zones (Fereres and Soriano, 2007).

The evaluation of the crop water status, by means of direct measurements in the plants constitutes a valuable tool for irrigation management given its dynamic nature, which is closely related to the climatic and soil conditions, as well as with crop productivity (Goldhamer et al., 2003; Remorini and Massai, 2003). Among these, several indicators have been studied such as stem water potential (Ψ_s) (discontinuous measurement) and trunk diameter fluctuations (TDF) (continuous measurement) (Conejero et al., 2011). In this sense, Ψ_s is traditionally the most commonly used parameter to estimate the plant water status due to its reliability, low variability and a moderately good prediction of yield response to water stress (Naor, 2006; Shackel et al., 1997). However, since its measurement cannot be easily automated, finding water stress indicators that can be continuously recorded has been of great interest for researchers in the last years.

Within these, the maximum daily trunk shrinkage (MDS) has been proposed as a suitable tool for precise irrigation scheduling (Goldhamer and Fereres, 2001) because its relatively uncomplicated monitoring procedure providing continuous and automatic information of plant water status in contrast to discontinuous measures such as the Ψ_s, where regular visits to the field make it an impractical and costly method. The MDS measurements have demonstrated their sensitiveness to changes in tree water status in many stone-fruit species as apricot trees (Nicolás et al., 2005), extra-early maturing peach trees (Conejero et al., 2007) and in nut-fruit species as almond (Egea et al., 2009). However, the fact that MDS is the result not only of the soil water available to the plant but also of the evaporative demand of the atmosphere means that using absolute MDS values for irrigation scheduling is unsuitable.

Consequently, it is better to use the concept of MDS signal intensity, normalizing the MDS values with respect to values under non-limiting soil water conditions (MDS actual value/MDS reference value) in order to avoid the effect of climatic conditions (Fernández and Cuevas, 2010).

Usually, the reference values are obtained by irrigating trees above their water needs or by means of the elaboration of reference equations (baseline relationships) in which the values of the plant-based indicator are correlated with a climatic variable closely related to the evaporative demand (Fernández and Cuevas, 2010). Moreno et al. (2006) showed that MDS in olive trees reflected changes in the evaporative demand variables, even though the MDS behaviour was best correlated with both midday vapour pressure deficit (VPD_{mid}) and air temperature at midday (T_{mid}). In addition, Pagán et al. (2012) reported the suitability of MDS to establish reference baselines for irrigation scheduling in mandarin trees due to its linear response and good correlation with temperature.

They found that MDS was best correlated with T_{mid}; however, they recommended the use of average (T_m) or maximum air temperature (T_{max}) due to easiness in their measurement. De la Rosa et al. (2013) showed the suitability of MDS for establishing reference lines to be used in early nectarine trees for irrigation scheduling, due to its linear response and good correlation with VPD_{mid}. The reference lines that they established were stable over three years, and were not crop-load dependent, at least in the range studied. Respect to peach trees, Conejero et al. (2011) measured Ψ_s and MDS over a 4-year period in early maturing peach trees [*Prunus persica* (L.) Batsch cv. 'Flordastar'] and found that the effects of environmental conditions on daily MDS values were dependent on crop load, indicating that specific MDS reference equations should be developed as a function of crop load for irrigation scheduling. These findings mean that MDS measurements may need adjustments before they can be used for irrigation scheduling.

Therefore, it is necessary to test the baselines stability, both in the short (through the season) and the long-term (over a few years), in order to prove that it is a good and reproducible method for irrigation scheduling.

In this context, the objective of this study was to obtain MDS reference equations in mid-late maturing peach trees, based on appropriate climate variables and Ψ_s, for their use in irrigation scheduling.

5.2. Materials and Methods

Site description and plant material

The experiment was conducted over three consecutive years (2008–2010) in a 0.5 ha plot of a commercial orchard located in Mula valley, Murcia, SE Spain (37°55'N, 1°25'W, 360 m above sea level). The soil at the site is calcareous, stony, with a sandy-loam texture, low organic matter content and its available water capacity is 0.25 m^3 m^{-3}, approximately. The climate of the region is semiarid Mediterranean with hot and dry summers and low rainfall; annual evaporation calculated from reference crop evapotranspiration (ET_0) and rainfall during the growing season were, respectively, 792 and 254 mm in the first year of experiments (2008), 613 and 304 mm in 2009 and 784 and 188 mm in 2010.

Picture 5.1. View of the experimental site (Own source).

Plant material consisted of peach trees [*Prunus persica* (L.) Batsch cv. 'Catherine'] planted in 1999 and grafted on GF-677 rootstock. Spacings were 4 m x 6 m. Hand thinning was used to space fruitlets 20 cm along the fruit bearing shoots in order to achieve a commercial crop load. Pest control was that commonly used by the growers and all treatments received the same fertilization (N–P_2O_5–K_2O), applied through the drip irrigation system (275–125–200 kg ha^{-1} $year^{-1}$) over the study period.

Irrigation treatment and experimental design

Irrigation water was supplied through a drip irrigation system, one pipeline for each row, with three emitters per tree (delivering 4 L h^{-1} each). The irrigation water was considered of good quality with a very low electrical conductivity (0.6 dS m^{-1}).

Crop irrigation requirements were scheduled weekly according to daily ET_0, calculated using the Penman-Monteith equation (Allen et al., 1998), and a local crop factor based on the time of the year and used in this region at commercial level. Monthly average values of K_c employed from April to October were 0.73, 0.83, 0.94, 0.96, 0.39, 0.39 and 0.39 respectively. A total of 64 trees were used in this study. The experiment was laid out in completely randomized blocks with 4 replications (16 trees each). The four central trees of each replicate were used for measurements, and the other 12 trees acted as guard.

Trees were irrigated above their water requirements (~120% ET_c) throughout the experimental period in order to obtain non limiting soil water conditions.

Irrigation was automatically controlled by a head unit programmer and the amounts of water applied for each irrigation treatment were measured with in-line flowmeters placed in each experimental plot.

Field and laboratory determinations

Climate data

Climate data were recorded at an automatic weather station placed within the experimental orchard. Data on air temperature (maximum, minimum and average), solar radiation, air relative humidity, rainfall and wind speed 2.5 m above the soil surface, were collected every 15 min. These data were used for calculating ET_0 and crop water

requirements. In addition, data of midday air temperature and air vapour pressure deficit (VPD) were extracted from these records.

Picture 5.2. Automatic weather station placed within the experimental orchard (Own source).

Stem water potential

Midday stem water potential (Ψ_s) was measured every 3 days using a pressure chamber (Soil Moisture Equip. Corp, model 3000, Santa Barbara, CA, USA) following the procedures described by Turner (1981). Measurements were performed on mature leaves (one per tree) from the north face of the trunk, in the four central trees of each experimental plot. Leaves were enclosed in plastic bags covered with aluminum foil at least two hours prior to the measurements, which were carried out between 12:00 and 13:00 h solar time.

Trunk diameter fluctuations

The micrometric trunk diameter fluctuations (TDF) were measured throughout the experimental period in four trees (one tree per experimental plot), using linear variable displacement transducers (LVDT) (Solartron Metrology, Bognor Regis, UK, model DF ± 2.5 mm, accuracy ± 10 μm,) 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 30 s and one datalogger and a multiplexor (model CR1000, Campbell Scientific, Inc., Logan, USA) were programmed to report 15 minute-means. Maximum daily trunk shrinkage (MDS) was calculated daily as the difference between maximum and minimum daily trunk diameter (Goldhamer and Fereres, 2001).

Yield and crop load

Fruits were individually harvested on July in two or three commercial picks, depending on market demands in the four central trees of each experimental plot. The number of fruits per tree was obtained by counting the fruits in the four inner trees of each plot.

Picture 5.3. Harvested "Catherine" peaches (Own source).

Trunk cross-sectional area (TCSA) and canopy volume

Trunk diameter was measured annually in all trees, during the dormancy stage with a sliding caliper, 0.20 m above the soil surface, and used to estimate trunk cross-sectional area (TCSA). Linear and transverse lengths and heights of the canopy were measured annually in all trees of treatment to estimate the canopy volume (Westwood, 1988).

Picture 5.4. Measurement of the tree canopy (Own source).

Statistical analysis

Statistical analysis of tree characteristics among years was performed as a weighted analysis of variance (ANOVA; statistical software IBM SPSS Statistics v. 21 for Windows). The Shapiro–Wilk test was used to evaluate the normality of the data. Relationships between MDS measurements and the other variables (Ψ_s and climate variables) were assessed through Pearson's r correlation coefficient and linear regression techniques.

The differences in slopes and intercepts of the fitted lines among seasons were assessed through an analysis of covariance (ANCOVA). Unless otherwise stated, the significance level was $p \leq 0.05$.

5.3. Results

Climatic variables showed a similar dynamics for the different years studied (Figure 5.1). However, rainfall was different in 2008 than on the other two growing seasons studied; higher rainfall amounts were registered in springtime in 2008, whereas rainfall peaks at the end of the summer were observed in 2009 and 2010. Potential evapotranspiration over the growing season was very similar in 2008 and 2009, while greater ET_0 values were recorded in 2010, mainly until the end of August.

Daily mean VPD values were very similar among years, whereas the midday values of this variable differed greatly, being higher in 2009 (Figure 5.1). Mean air temperatures were slightly higher in 2009 and 2010 than in 2008; however, midday air temperature showed a similar trend between years, with slightly greater values in 2009 (Figure 5.1).
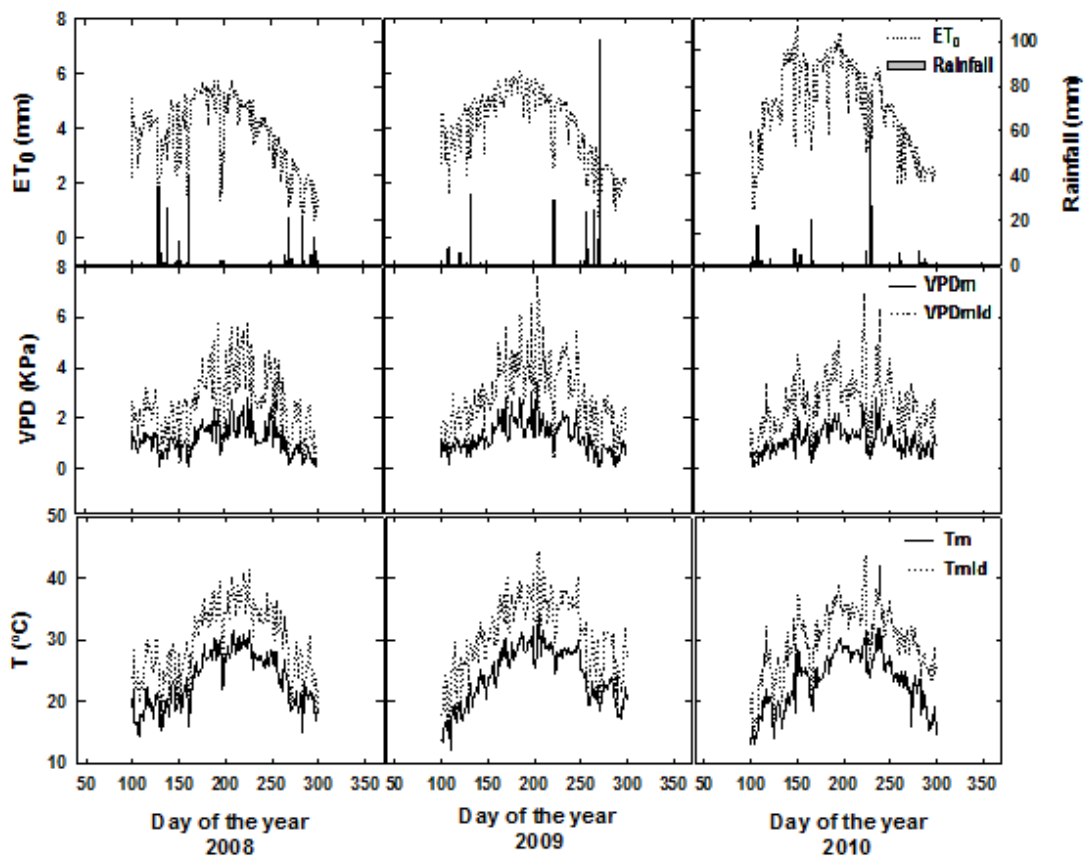
Figure 5.1. Evolution of different climate parameters over the three years studied (2008-2010). Potential evapotranspiration (ET_0), mean daily temperature (T_m), midday temperature (T_{mid}), mean air vapour pressure deficit (VPD_m) and midday air vapour pressure deficit (VPD_{mid}).

Tree characteristics differed from year to year (Table 5.1). As the trees grew, trunk diameter and TCSA increased from the first to the last year of experiments.

However, canopy volume was similar on the last two years of studies, being greater than that measured at the beginning of the experiment. In contrast, crop load and yield were, respectively, 4 and 2.5 times greater in 2009 than in 2008 and 2010 (Table 5.1).

The dynamics of Ψ_s over the growing season was different from year to year (Figure 2). The most negative values of Ψ_s were measured in 2008 (with a minimum of -1.3 MPa at post-harvest) and the least negative ones in 2010. The greatest differences among years for this water stress indicator were observed at post-harvest. In 2008, Ψ_s values ranged from -0.35 to -1.3 MPa, whereas in 2009 and 2010 they varied between -0.4 and -1 MPa for the fruit growth and post-harvest periods.

Similarly, MDS values over the growing season were slightly different from one year to the next (Figure 5.2). In 2008, MDS showed the lowest values, ranging from 30 to 260 µm, for the three growing seasons studied. In 2009, MDS varied between 40 and 290 µm; whereas in 2010, it oscillated between 20 and 300 µm (Figure 5.2). The highest MDS values were observed at the end of fruit growth in the two first years and at early post-harvest in the last year of the experiment.

Table 5.1. Characteristics of the studied trees over the three growing seasons studied (2008-2010). TCSA indicates trunk cross-sectional area.

Year	Trunk diameter (cm)	Canopy volume (m³)	TCSA (cm²)	Crop load (Fruits tree⁻¹)	Yield (kg tree⁻¹)
2008	13.93 c	7.93 b	155.2 c	150.31 b	24.73 b
2009	15.00 b	8.48 a	179.4 b	630.17 a	61.47 a
2010	15.80 a	8.39 ab	199.2 a	152.67 b	26.01 b
2008-2010	14.91	8.27	177.9	311.05	37.40

Different letters in the column indicate significant differences among years at $p < 0.05$.

According to these observations, the relationships between Ψ_s and MDS differed among years and between fruit growth and post-harvest stages (Figure 5.2). In 2008, Ψ_s and MDS were linearly related during fruit growth, but this relationship was not maintained at post-harvest. In contrast, the relationships between these two plant-based indicators in 2010 were very similar for fruit growth and post-harvest. The intermediate case was observed in 2009 (Figure 5.2).

The relationships between MDS and climate parameters such as daily maximum air temperature (T_{max}), midday air temperature (T_{mid}), maximum air vapour pressure

deficit (VPD$_{max}$) and midday VPD (VPD$_{mid}$) and ET$_0$ during the three years of the experiment showed the best fit in a lineal form (Figures 5.3 and 5.4).
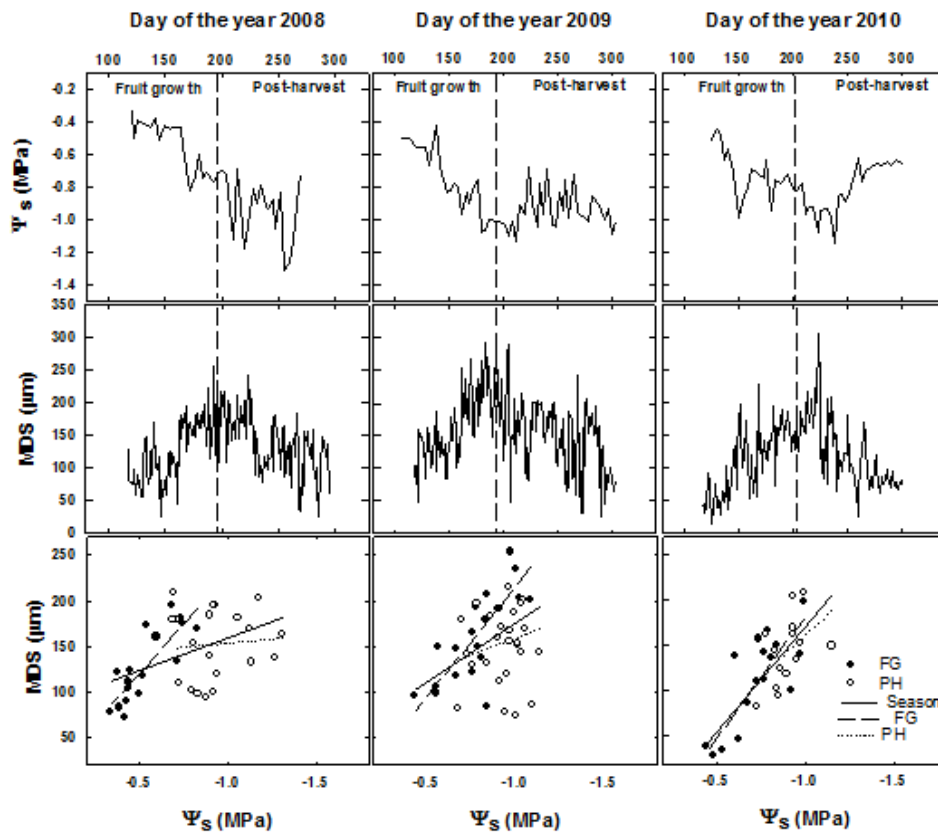
Figure 5.2. Midday stem water potential (Ψ$_s$) and maximum daily trunk diameter shrinkage (MDS) dynamics over the three growing seasons studied (2008-2010). The relationships between both parameters are depicted for each season. FG and PH indicate fruit-growth and post-harvest stages, respectively.

All the relationships were significant, although the degree of correlation varied between parameters and years (Table 5.2). The coefficients of determination were rather low, especially for ET$_0$ (r^2 between 0.21 and 0.54, depending on the year). The highest r^2 was observed for T$_{mid}$ in 2010 (r^2 = 0.69). When data for the three seasons were pooled together, the rank order for the determination coefficients was as follows: T$_{max}$ = T$_{mid}$ > VPD$_{max}$ = VPD$_{min}$ > ET$_0$ (Table 5.2).

ANCOVA results proved that the slopes of the relationships between MDS and ET$_0$ were only significantly different for the fruit growth stage, whereas the intercepts were significantly different among seasons in all cases. In the case of the relationships between MDS and T$_{max}$, significant differences were observed for both slopes and intercepts over the whole season and for the fruit growth and post-harvest periods. Similar results were found for the relationships between MDS and T$_{mid}$. The

relationships between MDS and VPD (either VPD_{max} or VPD_{mid}) presented slopes that were not significantly different among years, whereas intercepts showed significantly different values among years (Table 5.2).
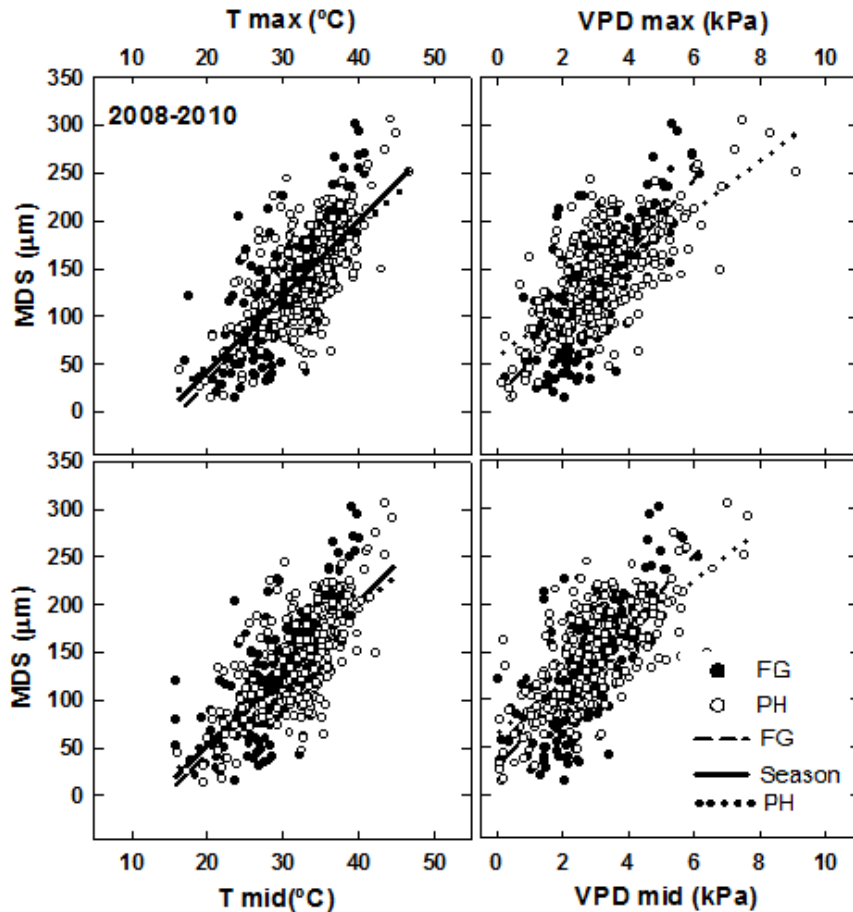
Figure 5.3. Relationships of MDS with the maximum daily temperature (T_{max}), midday temperature (T_{mid}), maximum and midday air vapour pressure deficit (VPD_{max} and VPD_{mid}, respectively), pooling data for the three seasons studied (2008-2010). The regression equations for these relationships are presented in Tables 5.2 and 5.3. FG and PH indicate fruit-growth and post-harvest stages, respectively.

Under our conditions, the relationships between MDS and the midday and daily maximum temperatures were very similar (Table 5.2 and Figure 5.3). However, maximum temperature is easier to obtain than midday temperature. Moreover, only slight differences in the aspect of the regressions were observed when considering separately the fruit-growth and post-harvest stages (Figure 5.3).

In contrast, VPD showed a greater data dispersion when compared with temperature. This fact caused that the fitted lines between VPD and MDS differed when fruit-growth and post-harvest stages were considered separately (Figure 5.3).
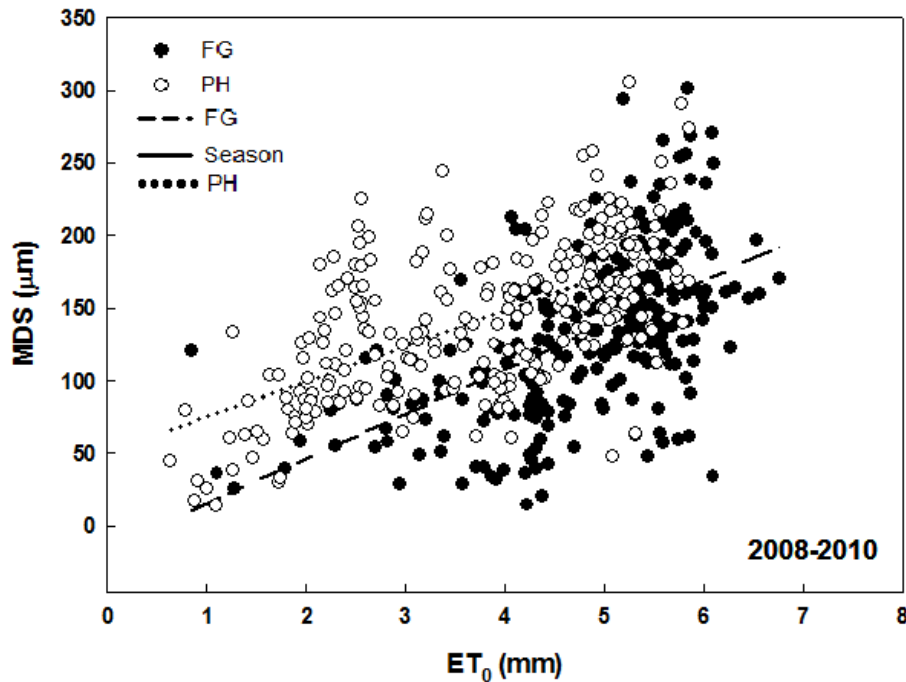
Figure 5.4. Relationship of MDS with potential evapotranspiration (ET_0) pooling data from the three consecutive seasons studied (2008-2010). The regression equations obtained for each season and the total pool of data are presented in Tables 5.2 and 5.3. FG and PH indicate fruit-growth and post-harvest stages, respectively.

Regarding the parameters of the fitted curves for each developmental stage separately (Table 5.3), the highest determination coefficients were observed in 2009 for all the variables, being the maximum one ($r^2 = 0.76$) observed for T_{mid} at fruit-growth. In addition, consistently higher determination coefficients were found for fruit-growth than for post-harvest period (Table 5.3).

When data for all years were pooled together, the rank order of the determination coefficients varied for each developmental stage, being $T_{max} = T_{mid} >$ $VPD_{max} > VPD_{min} > ET_0$ for fruit-growth, and $VPD_{mid} > VPD_{max} > T_{mid} > T_{max} > ET_0$ for post-harvest (Table 5.3).

Table 5.2. Parameters of the reference equations for maximum daily trunk shrinkage (MDS) as a function of selected environmental variables during the three seasons studied (2008-2010). ANCOVA results for the comparison of the slopes and intercepts of the fitted curves among the seasons studied.

MDS vs.	ET_0				T_{max}				T_{mid}				VPD_{max}				VPD_{mid}			
	a	b	r^2		a	b	r^2		a	b	r^2		a	b	r^2		a	b	r^2	
2008	23.42	38.74	0.33	***	6.78	-82.36	0.46	***	6.39	-64.58	0.47	***	28.47	44.44	0.48	***	28.17	53.60	0.47	***
2009	25.66	49.06	0.54	***	8.22	-111.99	0.59	***	7.96	-98.10	0.60	***	29.16	59.08	0.59	***	30.25	64.60	0.59	***
2010	25.10	0.71	0.21	**	9.12	-172.13	0.63	***	8.69	-151.03	0.69	***	34.06	13.54	0.58	***	34.66	21.34	0.50	***
2008-2010	20.91	48.33	0.25	***	7.91	-116.08	0.53	***	7.55	-98.60	0.53	***	30.19	41.64	0.50	***	30.73	48.87	0.50	***
ANCOVA	a	b			a	b			a	b			a	b			a	b		
RESULTS	**Season**				**Season**				**Season**				**Season**				**Season**			
2008-2009	ns	**			*	*			*	**			ns	**			ns	**		
2009-2010	ns	**			ns	*			ns	**			ns	**			ns	**		
2008-2010	ns	**			**	**			**	**			ns	**			*	**		
2008-2009-2010	ns	**			*	*			**	**			ns	**			ns	**		
	Fruit growth				**Fruit growth**				**Fruit growth**				**Fruit growth**				**Fruit growth**			
2008-2009	**	**			**	**			**	**			*	**			*	**		
2009-2010	*	**			*	**			**	**			ns	**			ns	**		
2008-2010	ns	**			ns	**			**	**			ns	**			ns	**		
2008-2009-2010	**	**			*	**			**	**			ns	**			*	**		
	Post-harvest				**Post-harvest**				**Post-harvest**				**Post-harvest**				**Post-harvest**			
2008-2009	ns	*			ns	**			ns	**			ns	**			ns	**		
2009-2010	ns	**			*	**			*	**			ns	ns			ns	ns		
2008-2010	ns	ns			*	ns			*	ns			ns	ns			ns	ns		
2008-2009-2010	ns	**			ns	*			*	**			ns	*			ns	*		

ET_0: daily potential evapotranspiration; T_{max}: daily maximum air temperature; T_{mid}: air temperature at midday; VPD_{max}: daily maximum air vapour pressure deficit; VPD_{mid}: midday air vapour pressure deficit. a: slope of the fitted curve; b: intercept of the fitted curve; r^2: determination coefficient. *** Significant at $p < 0.01$; ** Significant at $p < 0.05$.

Table 5.3. Parameters of the reference equations for maximum daily trunk shrinkage (MDS) as a function of selected environmental variables during the fruit-growth and post-harvest stages of the three seasons studied (2008-2010).

	Fruit growth			**Post-harvest**		
ET_0	a	b	r^2	a	b	r^2
2008	28.19	4.04	0.41***	25.37	43.32	0.38***
2009	51.14	-85.96	0.54***	25.04	58.11	0.43***
2010	35.07	-72.08	0.46***	32.11	3.53	0.34***
2008-2010	30.71	-15.09	0.32***	24.31	51.03	0.37***
T_{max}						
2008	7.46	-96.56	0.51***	6.79	-87.40	0.42***
2009	10.43	-173.02	0.75***	7.17	-85.74	0.54***
2010	8.39	-151.62	0.66***	10.65	-222.32	0.45***
2008-2010	9.02	-147.83	0.59***	7.14	-93.09	0.46***
T_{mid}						
2008	6.88	-72.19	0.52***	6.58	-76.21	0.44***
2009	10.33	-162.52	0.76***	6.92	-72.49	0.56***
2010	7.84	-127.85	0.64***	10.79	-219.45	0.50***
2008-2010	8.48	-123.47	0.59***	6.49	-81.78	0.48***
VPD_{max}						
2008	31.59	38.74	0.45***	27.46	45.35	0.50***
2009	39.88	29.55	0.71***	24.86	67.60	0.56***
2010	37.77	-7.36	0.58***	23.65	65.70	0.32***
2008-2010	38.09	15.31	0.55***	25.6	58.63	0.49***
VPD_{mid}						
2008	28.34	55.43	0.42***	28.51	50.79	0.51***
2009	37.07	40.84	0.70***	25.81	73.17	0.55***
2010	37.86	2.90	0.56***	25.46	66.60	0.38***
2008-2010	36.92	28.95	0.53***	26.72	63.30	0.50***

ET_0: daily potential evapotranspiration; T_{max}: daily maximum air temperature; T_{mid}: air temperature at midday; VPD_{max}: daily maximum air vapour pressure deficit; VPD_{mid}: midday air vapour pressure deficit. a: slope of the fitted curve; b: intercept of the fitted curve; r^2: determination coefficient. *** Significant at $p < 0.01$.

It is noticeable the low determination coefficient value of the relationship between MDS and ET_0, either when considering data for the whole season (Table 5.2) or when considering fruit-growth and post-harvest stages separately (Table 5.3). The values of ET_0 presented a great variability, which does not correspond with the fluctuations of MDS (Figure 5.4).

Table 5.4. Parameters of the reference equations for maximum daily trunk shrinkage (MDS) as a function of midday stem water potential (Ψ_s) for the whole season and during the fruit-growth and post-harvest stages of the three years studied (2008-2010). ANCOVA results for the comparison of the slopes and intercepts of the fitted curves among the seasons studied.

MDS vs Ψ_s	Season				Fruit growth				Post-harvest			
	a	b	r^2		a	b	r^2		a	b	r^2	
2008	-71.97	87.18	0.22	ns	-220.05	10.22	0.68	***	-18.14	135.25	0.01	ns
2009	-130.8	45.55	0.18	ns	-242.65	-26.13	0.62	***	-76.17	83.46	0.04	ns
2010	-231.8	62.80	0.58	***	-266.37	-85.08	0.65	***	-177.90	-17.08	0.24	ns
2008-2010	-122.2	44.23	0.26	***	-203.87	-4.98	0.51	***	-58.59	96.91	0.04	ns

ANCOVA RESULTS

MDS vs Ψ_s	Season		Fruit growth		Post-harvest	
	a	b	a	b	a	b
2008-2009	ns	ns	ns	**	ns	ns
2009-2010	*	*	ns	*	ns	ns
2008-2010	**	**	ns	**	ns	ns
2008-2009-2010	**	**	ns	**	ns	ns

a: slope of the fitted curve; b: intercept of the fitted curve; r^2: determination coefficient. * Significant at $p < 0.05$; ** Significant at $p < 0.01$; *** Significant at $p < 0.001$; ns not significant at $p < 0.05$.

When pooling together data from the three seasons studied, a clear relationship between Ψ_s and MDS was observed during fruit growth (Figure 5.5), higher MDS values corresponding to more negative values of Ψ_s. However, this relationship did not hold for the post-harvest period and the slope of the fitted line decreased. In fact, these relationships were not significant for the entire seasons of 2008 and 2009; in contrast, during the fruit-growth stage, the correlation between MDS and Ψ_s was highly significant with r^2 up to 0.68 in 2008, the first year of the experiment (Table 5.4).

At post-harvest, the relationship between both variables was not significant for all the studied years. ANCOVA results proved that slopes and intercepts of the fitted relationships differed from year to year (Table 5.4) when all the data were pooled together, except for the seasons 2008 and 2009. However, the relationship between MDS and Ψ_s did not differ for the post-harvest stage and the slopes of the curves were not significantly different among years at the fruit growth stage (Table 5.4).
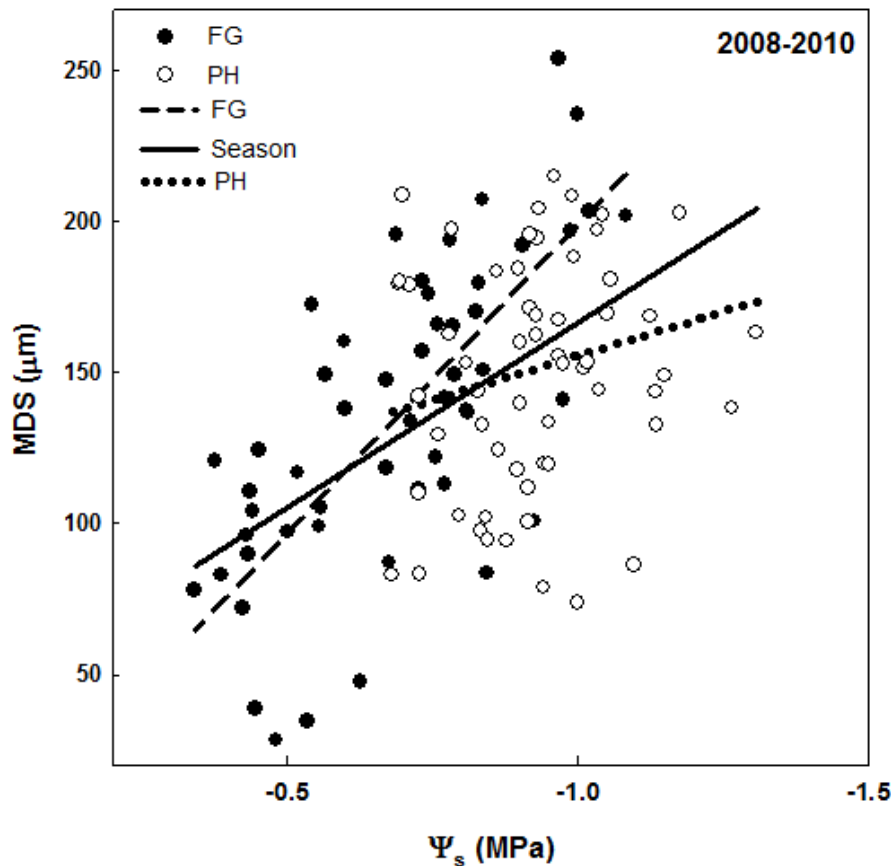
Figure 5.5. Relationship of MDS and midday stem water potential (Ψ_s) pooling data from the three consecutive seasons studied (2008-2010). The regression equations obtained for each season and the total pool of data are presented in Table 5.4. FG and PH indicate fruit-growth and post-harvest stages, respectively.

5.4. Discussion

In the current experiment, trees were well watered and thus grew under non-limiting soil water conditions (at field capacity), which was proven by increases in trunk diameter and TCSA from year to year (Table 5.1), as well as tree water status (Ψ_s values). This fact allowed us to obtain baseline relationships between MDS records and meteorological variables closely related to plant water stress and easy to measure, as pointed out by Fernández and Cuevas (2010).

From the five meteorological variables employed in this study, temperature (measured either at midday or the daily maximum) showed the best fit to MDS records for the three growing seasons considered. However, the relationships between both variables differed from year to year (Table 5.2). This result is in agreement with previous reports by Conejero et al. (2007) for an early-maturing peach cultivar, Moriana et al. (2011) for olive, Fereres and Goldhamer (2003) for almond and Ortuño et al.

(2009) for lemon trees, who found that temperature was the best predictor of MDS for the whole growing season. However, other studies (Intrigliolo and Castel, 2007; Egea et al., 2009) pointed out better adjustments for other climate variables such as VPD.

In addition, when the season was splitted into fruit growth and post-harvest stages, we observed that the parameters (slope and intercept) of the equations relating MDS to temperature varied, being best fitted during the fruit growth stage. This is in accordance with the observations made by Intrigliolo and Castel (2007) in fully-irrigated plum trees and implies that a reference equation obtained under certain conditions should not be applied in subsequent years if tree conditions change. In contrast, Ortuño et al. (2009) concluded for citrus that reference equations between MDS and temperature can be obtained by pooling data across several seasons.

Even though MDS is considered a good indicator of the transpiration stream (Herzog et al., 1995), the relationship of this measurement with VPD was slightly lower than the results obtained with temperature (Tables 5.2 and 5.3). This has been observed by several authors for different fruit trees such as almond (Fereres and Goldhamer, 2003), olive (Corell et al., 2013) and lemon (Ortuño et al., 2009). The midday measurements of temperature presented a better fit than the maximum value, likely due to the fact that midday temperatures are more related to the higher rate of shrinkage occurred around this time of the day.

The presence and amount of fruits may affect MDS records. In our study, the best fits between MDS and climate variables were observed in 2009, the season with the highest fruit load out of the three seasons considered, due to grower's decision associated to market criteria. Moreover, correlations between MDS and the meteorological variables decreased after harvest (Table 5.3), except in 2008 for VPD measurements, as did the slope of the relation between MDS and Ψ_s (Figure 5.5 and Table 5.4). Similar results were obtained by Intrigliolo and Castel (2004) for plum and Moriana et al. (2003) for olive. These results indicate some of the difficulties in obtaining reference values useful for irrigation scheduling based exclusively on plant water status parameters.

Furthermore, year-to-year effects of fruit growth on these reference equations were significant (Table 5.3), and this made intercepts and slopes of the equations to be

rather different among years. However, post-harvest equations were more similar across years. These results suggest that crop load is a very important factor to take into account when using MDS records for irrigation scheduling in this mid-late maturing peach cultivar. This response has already been found in olive and plum trees (Moriana and Fereres, 2004; Intrigliolo and Castel, 2007) but not in citrus (Ortuño et al., 2009).

As pointed out by Ortuño et al. (2010), this behaviour might 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 reason, it is of paramount importance to consider crop load when using MDS as a water stress indicator. Consequently, 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, 2007).

Surprisingly, daily ET_0 was the climate variable showing the poorest correlation with MDS records (Tables 5.2 and 5.3, Figure 5.4). This has been previously observed by a number of authors who found better correlations between MDS and climate variables other than ET_0, such as VPD (Goldhamer and Fereres, 2004; Egea et al., 2009) or midday temperature (Ortuño et al., 2009; Moriana et al., 2011), coinciding with our results and suggesting that for woody species ET_0 would not be the best criterium for determining crop water requirements using reference equations. However, ET_0 is the most widely used criterium for assessing crop water requirements, calculated through the Penman-Monteith equation (Allen et al., 1998), and some authors found it significantly correlated with MDS records (Ortuño et al., 2006; Fereres and Goldhamer, 2003).

Finally, it is important to point out that data obtained during the course of the entire experiment and shown in Table 5.4 and Figure 5.5 suggest that there was not a single unique relationship between MDS and Ψ_s that was valid for the whole period. This behaviour is similar to that previously observed in peach (Marsal et al., 2002), plum (Intrigliolo and Castel, 2006) or pomegranate (Intrigliolo et al., 2011). In these experiments and the one reported in the current work, the relationship between MDS and Ψ_s changed in concordance with changes in the fruit growth pattern or fruit

removal. In the case reported here, better fits were obtained for data recorded during fruit growth than at post-harvest. Intrigliolo et al. (2011) explained this behaviour because of changes in tissue elasticity since it is generally accepted that tissue age affects its elasticity, older tissues being less elastic (higher resistance to shrinkage; Tyree and Jarvis, 1982). Therefore, the lower MDS for a given Ψ_s value obtained late in the season may be due to less elastic, older tissues.

In summary, results presented here indicate that MDS records of a mid-maturing peach cultivar are better related to midday and maximum temperature than to other meteorological variables during fruit growth; and to VPD during the postharvest period. However, these relationships were greatly affected by the conditions of each year, tree phenological stage and crop load. Therefore, the growers must be aware of these factors when using MDS values for irrigation scheduling.

Acknowledgements

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USEFULNESS OF MAXIMUM DAILY TRUNK SHRINKAGE FOR ESTIMATING WATER NEEDS AND REGULATED DEFICIT IRRIGATION SCHEDULING IN PEACH TREES

6. USEFULNESS OF MAXIMUM DAILY TRUNK SHRINKAGE FOR ESTIMATING WATER NEEDS AND REGULATED DEFICIT IRRIGATION SCHEDULING IN PEACH TREES

Abstract

Water scarcity and the increase of water use in many socio-economical sectors leads to an urgent need to improve irrigation management. In this sense, the scientific community is immersed in the search to develop new and precise technologies for scheduling irrigation, especially in arid and semi-arid areas, such as the South East of Spain. For this reason, we studied the possibility of scheduling regulated deficit irrigation (RDI) using maximum daily shrinkage (MDS) measurements on peach trees [*Prunus persica* (L.) Batsch cv. "Catherine"] in Murcia (Spain) during three years. Three irrigation treatments were established: a control treatment (C_{ETc}), irrigated above the estimated crop water requirements, and two treatments based on measurements of maximum daily shrinkage signal intensity (MDS SI). Precision treatment (C_{MDS}), using a threshold value of MDS SI=1 during all the period and a deficitary treatment (RDI) using MDS SI=1 all the period except for stage II and postharvest where MDS SI=2. The low coefficients of variation of MDS SI indicated that the information generated by these measurements under C_{MDS} and RDI was sufficient to adjust the irrigation schedule to maintain MDS SI close to the selected threshold values. Hence, peach tree irrigation scheduling can be exclusively based on MDS measurements. Maintaining the MDS SI close to unity throughout the growing season can be a useful tool to estimate K_c values when these are not available. The RDI treatment significantly reduced pruning weight, but not significant differences were found in terms of reproductive growth and yield. Moreover, RDI increased water productivity, fruit quality, since soluble solids content and maturity index were higher in the RDI treatment compared to C_{ETc} and C_{MDS}.

Keywords: *Prunus persica*, trunk diameter fluctuations, yield, signal intensity, water productivity.

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6.1. Introduction

Spain is the second largest peach [*Prunus persica* (L.) Bastch] producer in the world, and this is the first stone fruit crop in Spain. The area devoted to peach tree varieties with low cold requirements has increased in recent years, especially in southern regions. Peach tree plantations are located in the Mediterranean area, being Murcia (SE Spain) the third main peach production area in the country, yielding 249,500 t per year, 19% of the Spanish production, approximately (MAGRAMA, 2015). More than 70% of the surface devoted to peach cultivation in the region is managed under irrigation conditions.

Irrigated agriculture is the primary water user worldwide, reaching a proportion that exceeds 70-80% of the total in arid and semi-arid regions. This, added to an increasing pressure on water resources due to the competition for water between agriculture, industry and population, creates an urgent need to increase irrigation water productivity and to develop and provide new tools and water conservation methods in agriculture. There is a growing awareness of the need for sustainable irrigation planning in commercial orchards. This implies a continuous reduction in water inputs throughout the growing season that can only be beneficial as long as fruit quality and yield can be maintained (Fereres and Soriano, 2007). For this reason, it is of paramount importance to determine the tree water status throughout the year in order to rapidly detect any water stress and correctly manage irrigation over the growing season.

The use of plant-based water status indicators has become very popular for planning precise irrigation, because plant water status controls many physiological processes and crop productivity, this information can be highly useful in irrigation scheduling (Fernández and Cuevas, 2010; Ortuño et al., 2010).

In this sense, several plant water stress indicators such as the plant leaf and stem water potentials have been tested for schedule irrigation. However, these measurements cannot be easily automated and there is a need to look for other tools that continuously monitor plant water status. In this respect, the continuous measurements made by lineal variable diameter transducers (LVDT) of trunk diameter fluctuations are easily recordable with a datalogger, and could provide real-time knowledge of the plant water stress levels reached in the implementation of regulated deficit irrigation strategies. From these records, two indexes are normally obtained, the maximum diurnal trunk

shrinkage (MDS) and the trunk growth rate (TGR). Particularly, MDS has been shown to have the potential to serve as plant water stress indicator (Fernández and Cuevas, 2010).

Because plants are in the middle of the soil-plant-atmosphere, plant water status is the result of soil water availability and evaporative demand. Therefore, absolute water stress indicator values recorded without considering the evaporative demand might be meaningless. For this reason, it is better to use the concept of signal intensity (SI) for irrigation scheduling, normalizing an indicator's absolute values with respect to values under non-limiting soil water conditions (Naor and Cohen, 2003; Ortuño et al., 2006). The SI for water stress indicators 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).

Previous research confirmed that MDS SI is a suitable parameter for irrigation scheduling (Vélez et al., 2007 in orange trees; Ortuño et al., 2009 in lemon trees; Conejero et al., 2011 in peach trees; Puerto et al., 2013 in almond trees and De la Rosa et al., 2014 in nectarines trees).

In the current work, MDS SI was used as a potential indicator for irrigation scheduling in peach trees and the impact of irrigation strategies based on MDS SI on yield and fruit quality were evaluated:

1) To quantify peach tree water requirements maintaining MDS SI values close to unity during crop development, in order to determine crop factors (K_c) in this species.

2) To evaluate a methodology for scheduling peach orchard irrigation based on MDS SI thresholds as a water stress indicator for triggering irrigation, and assess the effects of this RDI on peach tree physiology, yield and fruit quality, as well as water savings, when compared to a fully irrigated control.

6.2. Materials and methods

Site description and plant material

The experiment was conducted over three consecutive years (2008–2010) in a 0.5 ha plot of a commercial orchard located in Mula valley, Murcia, SE Spain (37°55'N, 1°25'W, 360 m above sea level). The soil at the site is calcareous, stony, with a sandy-

loam texture, low organic matter content and its available water capacity is 0.25 m^3 m^{-3}, approximately. The climate of the area is typically Mediterranean, with mild winters, hot dry summers and low rainfall amounts.

Plant material consisted of peach trees [*Prunus persica* (L.) Batsch cv."Catherine"] planted in 1999 and grafted on GF-677 rootstock. Spacings were 4 m x 6 m. Hand thinning was used to space fruitlets 20 cm along the fruit bearing shoots in order to achieve a commercial crop load. Pest control was that commonly used by the growers and all treatments received the same fertilization (N–P$_2$O$_5$–K$_2$O), applied through the drip irrigation system (275–125–200 kg ha^{-1} year^{-1}) over the study period.

Picture 6.1. Plot location. (Source Google Maps).

Irrigation treatments and experimental design

Irrigation water was supplied through a drip irrigation system, one pipeline for each row, with three emitters per tree (delivering 4 L h^{-1} each). The irrigation water was considered of good quality with a very low electrical conductivity (0.6 dS m^{-1}).

Crop irrigation requirements for control treatment were scheduled weekly according to daily ET_0, calculated using the Penman-Monteith equation (Allen et al., 1998), and a local crop factor based on the time of the year and used in this region at commercial level. Monthly average values of K_c employed for the control treatment from April to October were 0.73, 0.83, 0.94, 0.96, 0.39, 0.39 and 0.39, respectively. A total of 192 trees were used in this study. The experiment was laid out in completely randomized blocks with 4 replications (16 trees each). The four central trees were used for measurements, and the other 12 trees acted as guard.
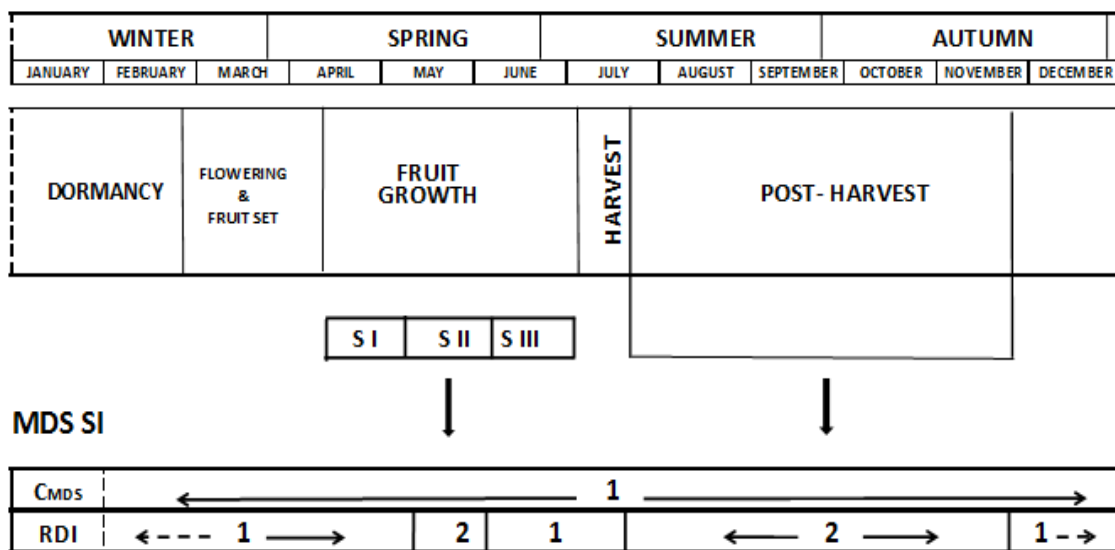
Figure 6.1. Precision (C_{MDS}) and Regulated Deficit Irrigation (RDI) strategies based on threshold values for maximum daily shrinkage signal intensity (MDS SI) applied in stage II (S II) of fruit growth and post-harvest during the three years of the experiment.

Three irrigation treatments were applied based on peach tree phenological stage: Control plants (C_{ETc}) were daily irrigated above the estimated crop evapotranspiration in order to obtain non-limiting soil water conditions (average 120% ET_c in three years of experiments), and two RDI strategies that consisted of a full irrigation during critical periods, and water restrictions during the non-critical periods of crop development

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(stage II of fruit growth and post-harvest periods) (Figure 6.1). These RDI treatments were:

a) Precision treatment (C_{MDS}) in which the MDS SI values were maintained close to unity during crop growth.

b) Deficit treatment (RDI) consisting of full irrigation during critical periods (values of MDS SI close the unity), which corresponded to the flowering and fruit set, stages I and III of fruit growth, and dormancy period, and subjected to water shortage during the non-critical periods of crop development corresponded to stage II of fruit growth and post-harvest periods (MDS SI values close to 2 for these two stages).

The irrigation rate was decreased by 10% when the MDS SI did not exceed the threshold value on at least two out of three consecutive days, and increased by 10% when the MDS SI exceeded the threshold value on at least two out of three consecutive days.

This irrigation protocol was based on that proposed by Goldhamer and Fereres (2001) for mature trees under high frequency irrigation. Irrigation was controlled automatically by a head unit programmer and the amounts of water applied for each irrigation treatment were measured with in-line flowmeters placed in each experimental plot.

Field and laboratory determinations

Climate data

Climate data were recorded at an automatic weather station placed within the experimental orchard. Data on air temperature (maximum, minimum and average), solar radiation, air relative humidity, rainfall and wind speed 2.5 m above the soil surface, were collected every 15 min. These data were used for calculating ET_0 and crop water requirements. The evolution of these parameters over the study period is shown in figure 6.2.

Figure 6.2. Reference evapotranspiration (ET_0, mm), rainfall (mm) and vapour pressure deficit (VPD, KPa) in Fuente Librilla. Monthly values from data collected during 2008, 2009 and 2010.

Soil water content

The volumetric soil water content (θ_v, $m^3 m^{-3}$) of the top 0.2 m of the soil profile was measured by time domain reflectometry (TDR) using a Tektronix device (Model 1502C, Tektronix Inc., OR), as described by Moreno et al. (1996). The θ_v from 0.2 m down to a maximum depth of 1.0 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 from the trees and beside the emitters. The probes were placed at 0.2 m from the perperdicular emitter and next to the TDR rods. Measurements using one neutron probe and TDR per experimental plot (3 replications per treatment) were taken in the morning, every 7 to 15 days, during the experimental period.

Stem water potential

Midday stem water potential (Ψ_s) was measured using a pressure chamber (Soil Moisture Equip. Corp, model 3000, Santa Barbara, CA, USA) following the procedures described by Turner (1981). Measurements were performed on mature leaves (one per tree) from the north face of the trunk, in the four central trees of each experimental plot. Leaves were enclosed in plastic bags covered with aluminum foil at least two hours prior to the measurements, which were carried out between 12:00 and 13:00 h solar time.

Trunk diameter fluctuations

The micrometric trunk diameter fluctuations (TDF) were measured throughout the experimental period in four trees per treatment (one tree from each experimental plot), using a set of linear variable displacement transducers (LVDT) (Solartron Metrology, Bognor Regis, UK, model DF ± 2.5 mm, accuracy ± 10 μm,) 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 30 s and the 2 dataloggers (model CR1000, Campbell Scientific, Inc., Logan, USA) were programmed to report 15 min means. Maximum daily trunk shrinkage (MDS) was calculated daily as the difference between maximum and minimum daily trunk diameter (Goldhamer and Fereres, 2001).

Picture 6.2. LVDT sensor installed in peach "Catherine" (Own source).

Gas exchange parameters

Net photosynthesis (P_n) and stomatal conductance (g_s) were measured at solar midday, in one fully expanded sun-facing leaf in the four central trees of each experimental plot per treatment, in the same days that stem water potential was

recorded, using a field-portable photosynthesis system (LI-6400, Li-Cor, Lincoln, NE, USA).

Fruit growth and yield

Fruit diameter was measured perpendicularly to the fruit suture on 160 fruits per treatment (40 fruits per replication) every 7-10 days. Each date, 10 fruits per tree were randomly selected in the four inner trees per experimental plot and their diameters measured using a digital caliper (Powerfix model Nr Z22855F, Milomex Ltd, Bedfordshire, UK).

Picture 6.3. Peach harvesting (Own source).

Fruits from each tree were individually harvested on July in two or three commercial picks, depending on market demands. The number of fruits per tree was obtained by counting the fruits in the four inner trees (16 trees per treatment). 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) nº 1861/2004, 56 mm is the minimum diameter for a fruit to be considered in the "extra" category, which can be subdivided into different categories: AAAA (diameter > 90 mm), AAA (90 mm > diameter ≥ 80 mm), AA (80 mm > diameter ≥ 73 mm), A (73 mm > diameter ≥ 67 mm),

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B (67 mm > diameter ≥ 61 mm), C (61 mm > diameter ≥ 56 mm) and out of "extra" category D (56 mm > diameter ≥ 51 mm).

Vegetative growth

Pruning weight was recorded for 16 trees per treatment (4 per replication) at winter pruning.

Fruit quality

At harvest, 100 fruits per treatment (25 fruits per experimental plot) were randomly selected for quality assessment. Firmness, pH, soluble solids content (SSC) and titratable acidity (TA) were evaluated as quality indices. Chemical analyses were conducted according to Artés et al. (1993). Fruit firmness was evaluated using a Durofel penetrometer DFT100 (Agro-Technologie S.A., Paris, France). Juice was extracted from combined samples of longitudinal unpeeled slices. Total soluble solids concentration (SSC) was determined with a hand refractometer (Atago, Co., Japan); values were expressed as ºBrix. Titratable acidity (TA) was measured by titration of 5 mL of juice with 0.1 mol L^{-1} NaOH to pH 8.1 using an automatic titration system and expressed as g malic acid L^{-1} (AOAC, 1984). The maturity index (MI), which affects the perception of taste (sweetness and acidity), was calculated as the ratio of SSC to TA. pH was measured using a pH-meter (Crison, Barcelona, Spain).

Water stress integral

The water stress integral (MPa-days) was calculated from the Ψ_s data in order to evaluate the intensity of water stress, according to the following equation (Myers, 1988):

$$S_\Psi = \left| \sum_{i=0}^{i=t} \left(\overline{\Psi}_{i,i+1} - c \right) n \right|$$

where:

$\Psi_{i,i+1}$ is the average Ψ_s for each time interval

c is the value of the maximum Ψ_s in all seasons

n is the number of days in the interval.

Statistical analysis

Statistical analysis was performed as a weighted analysis of variance (ANOVA; statistical software IBM SPSS Statistics v. 21 for Windows). The Shapiro–Wilk test was used to evaluate the normality of the data. Tukey's HSD test was used for mean separation. Percentage values of fruit categories were arcsine-transformed before statistical analysis. Unless otherwise stated, the significance level was $p \leq 0.05$.

6.3. Results

The average values of ET_0 and rainfall recorded during the experimental period were, respectively, 792 and 254 mm in 2008; 613 and 304 mm in 2009, and 784 and 188 mm in 2010.

Table 6.1. Average volumetric soil water content (m^3 m^{-3}) for the three irrigation treatments considered at different phenological periods for the three studied growing seasons. Each data is the mean of all values in the corresponding stage. Different letters in each column indicate significant differences among treatments according to Tukey's multiple range test ($p < 0.05$).

Treatment	Dormancy	Flowering and fruit set	Stage I	Stage II	Stage III	Post-Harvest
2008-2010						
C_{ETc}	0.25a	0.26a	0.26a	0.25a	0.25a	0.26a
C_{MDS}	0.25a	0.25a	0.24a	0.24a	0.24a	0.24a
RDI	0.25a	0.25a	0.24a	0.16b	0.24a	0.19b

Table 6.1 shows the average values of the volumetric soil water content (θ_v) recorded during the experimental period within the soil profile, from 0 to 1 m depth. This content was nearly constant in the C_{ETc} and C_{MDS} treatments, with values close to field capacity (0.25 m^3 m^{-3}). In the RDI treatment, θ_v decreased significantly in all phenological periods when water stress was imposed. The soil moisture profile in all treatments was characterized by the fact that, during the water deficit periods, the θ_v values at depths greater than 0.6 m were clearly below field capacity, indicating the non existence of drainage (data not shown).

The amounts of water applied during the 2008 growing season were 962, 727 and 413 mm in C_{ETc}, C_{MDS} and RDI treatments, respectively. In 2009, these amounts were 849, 737 and 280 mm, whereas in 2010 they were 710, 636 and 224 mm (Figure 3A).
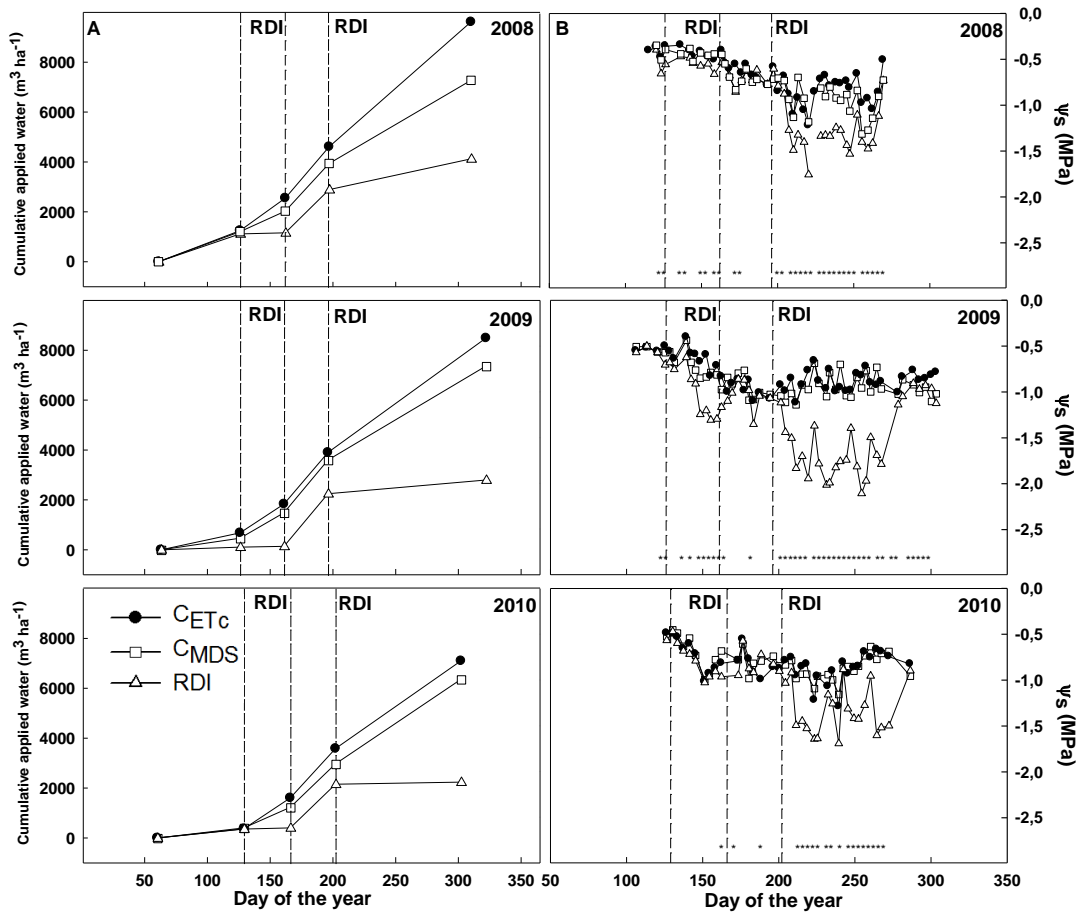
Figure 6.3. Seasonal patterns of (A) cumulative applied water and (B) midday stem water potential values for each irrigation treatment for the 3 years of the experiment: C_{ETc} (closed circles), C_{MDS} (open squares) and RDI (open triangles) plants. Each data point is the mean of sixteen values. Asterisks indicate significant differences among treatments ($p < 0.05$). The interval between vertical lines, from left to right, represents the beginning of stages II and III of fruit growth and postharvest.

The Ψ_s values for control trees, in average for the three growing seasons studied, decreased from an initial value of -0.5 MPa (stage I) to -1.0 MPa (post-harvest). During 2008, significant differences among treatments were observed for Ψ_s in stage II, and these were more clearly observed in 2009, whereas not significant differences were detected for this stage in 2010 (Figure 6.3B). After harvest, more negative Ψ_s values were evident for the RDI treatment about 10-15 days after water restriction started.

These differences increased, reaching average Ψ_s values of -1.24 MPa for RDI in 2008, -1.52 MPa in 2009 and -1.36 MPa in 2010. Under the C_{MDS} treatment, similar Ψ_s values to those of the C_{ETc} were observed until the end of the growing season. When full irrigation was restored, all treatments showed similar Ψ_s values.
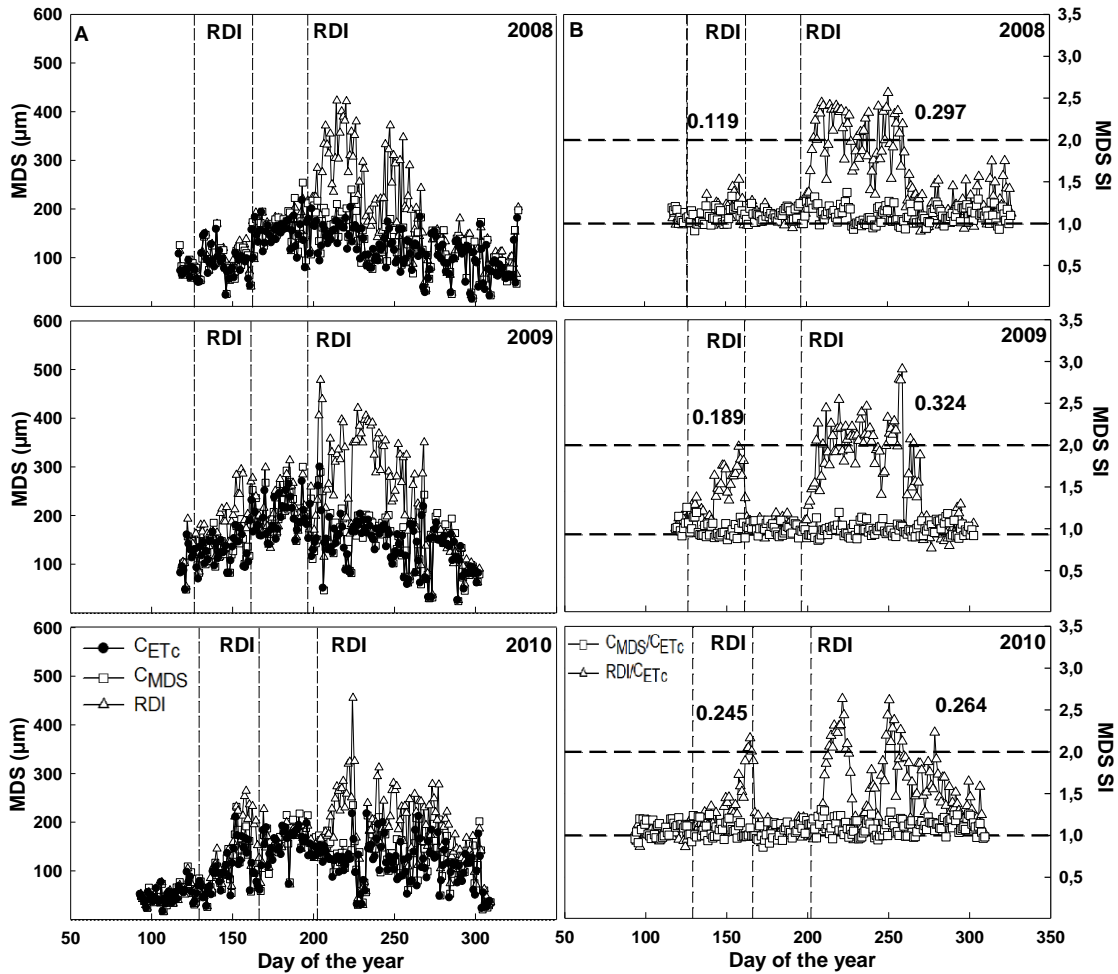
Figure 6.4. Maximum daily shrinkage (A, µm) evolution in the C_{ETc} (closed circles), C_{MDS} (open squares) and RDI (open triangles) treatments, and maximum daily shrinkage signal intensity (MDS SI) (B) as C_{MDS}/C_{ETc} ratio (open squares) and RDI/C_{ETc} ratio (open triangles) for the irrigation treatments during the fruit growth period 2008-2010. The interval between vertical short dash lines from left to right represent the beginning of stages II and III of fruit growth and post-harvest. Horizontal short dash lines represent the threshold values for MDS SI. Each data point is the mean of four values.

The MDS evolution over the growing season (Figure 6.4A) was similar for the C_{ETc} and C_{MDS} treatments, with increasing values in the summer months. In RDI plants, MDS values showed a tendency to increase because of the imposed reduced irrigation volumes. Just a few days after the onset of the irrigation deficit period, the daily values of MDS of the plants under RDI treatment showed a significant increase, reaching values of 400 µm. These values of MDS resulted in MDS SI levels close to the threshold values established for both treatments. For the C_{MDS} treatment, MDS SI values were close to unity all over the three-year period. For the RDI treatment, MDS SI only reached threshold values in the last part of stage II in 2009 and 2010 and in post-harvest for the three years.

The coefficient of variation (CV) of MDS SI throughout the growing season in the C_{MDS} treatment was around 0.080, very close to the values obtained in the RDI treatment during stage III of fruit growth (0.078), indicating that imposed irrigation was similar. The CV values increased during stage II of fruit growth, with the lowest value (0.119) in 2008 when water stress conditions were not reached, and increasing during 2009 and 2010 in proportion to the water stress level reached. During the postharvest period, the CV was similar in the three years, with values ranging from 0.264 to 0.324.

Overall for the whole season, S_{Ψ} values reflected significant differences among treatments, RDI showed the highest values of water stress integral (Figure 6.5), which were significantly higher than those from C_{ETc} and C_{MDS} in the three years of the experiment. No significant differences were observed between C_{ETc} and C_{MDS} treatments.

Table 6.2. Average maximum daily shrinkage signal intensity (MDS SI) in different stages of fruit growth for the three studied growing seasons. Each data is the mean of all values in the corresponding stage. Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

	Stage I	Stage II	Stage III	Post-Harvest
2008				
C_{MDS}/C_{ETc}	1.10a	1.09a	1.11a	1.10a
RDI/C_{ETc}	1.04a	1.15a	1.09a	1.95b
2009				
C_{MDS}/C_{ETc}	1.13a	1.06a	1.08a	1.06a
RDI/C_{ETc}	1.14a	1.48b	1.11a	2.03b
2010				
C_{MDS}/C_{ETc}	1.09a	1.07a	1.06a	1.11a
RDI/C_{ETc}	1.03a	1.37b	1.05a	1.61b

Table 6.2 shows the average values of MDS SI for the different growth stages during each year studied. The MDS SI values were higher for the RDI treatment in all stages during which the water deficit was imposed, except for stage II in 2008 when rainfall events and mild temperatures occurred. The C_{MDS} treatment showed average MDS SI values close to unity throughout the growing season in the three years studied.

Significant differences between RDI and C_{ETc} treatments were detected for pruning weight (Figure 6.6). In 2009, these differences were also significant with

respect to C_{MDS}. However, no significant effects have been observed on the evolution of fruit equatorial diameter for the irrigation treatments studied (C_{ETc}, C_{MDS} and RDI) (data not shown).

Crop load and yield were similar among treatments, although highly variable between years (Table 6.3). Furthermore, no differences among treatments were observed for fruit distribution into commercial categories (Figure 6.7).
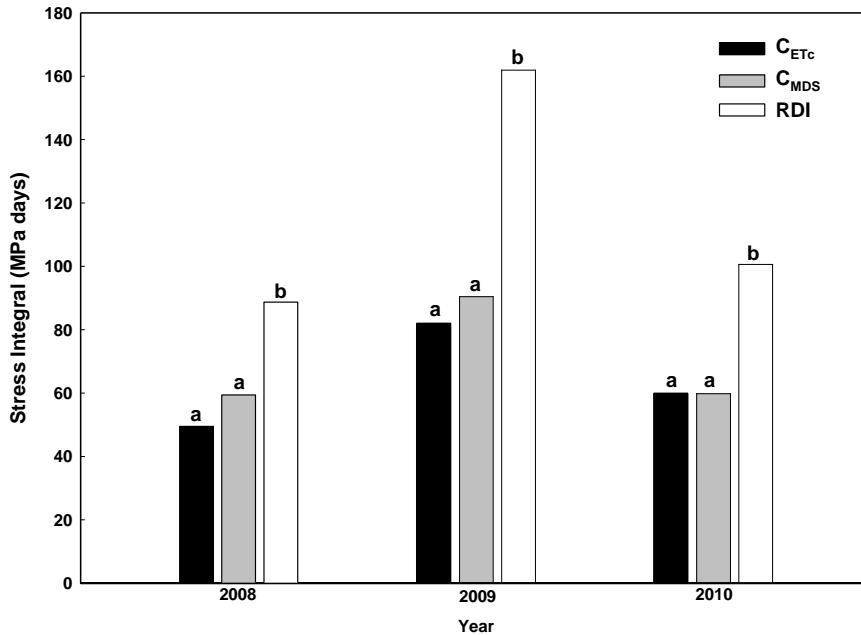
Figure 6.5. Water stress integral for each irrigation treatment, C_{ETc} (black bars), C_{MDS} (gray bars) and RDI (white bars) in the 2008, 2009 and 2010 growing seasons. Different letters on top of bars indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

The fact that similar yields were obtained for the three treatments studied made that water productivity (WP) values were higher under the RDI treatment when compared to C_{ETc} and C_{MDS} (Table 6.3), although they were similar between C_{ETc} and C_{MDS}. Consequently, important water savings were registered for the RDI treatment. Depending of the year, RDI supposed between 43 and 65% water savings for the whole season (Table 6.3).
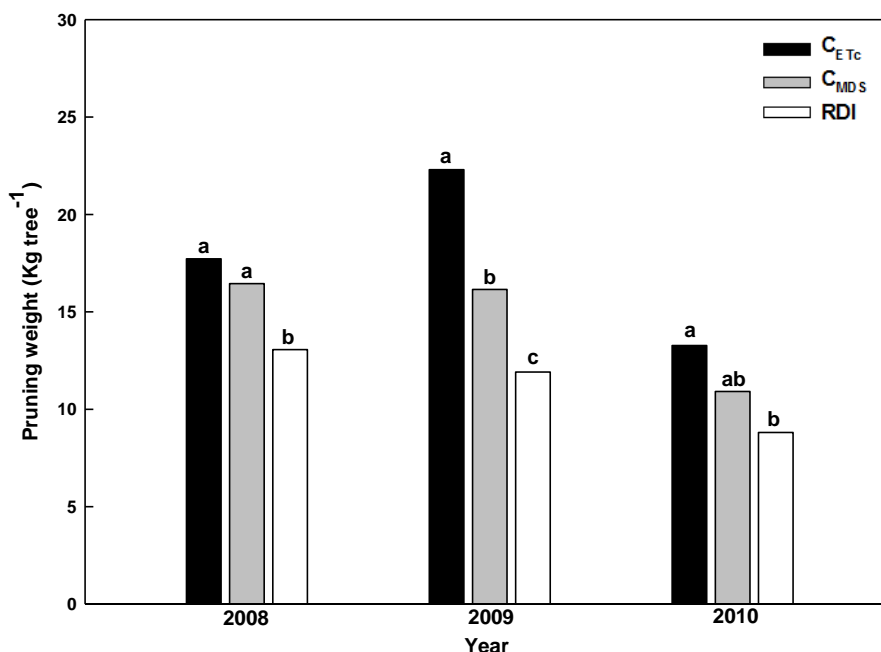
Figure 6.6. Pruning weight as a function of the irrigation treatment, C_{ETc} (black bars), C_{MDS} (gray bars) and RDI (white bars) in the 2008, 2009 and 2010 growing seasons. Each bar corresponds to the mean of sixteen trees. Different letters on top of bars indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

Table 6.3. Crop load, yield, water productivity (WP) and water spends/savings in each non-critical period and total in response to the different irrigation treatments for the experimental period 2008-2010. Different letters in the column within each year indicate significant differences among treatments according to Tukey's multiple range test ($p < 0.05$).

	Crop load	Yield	WP	Water spends/savings (%)		
	(Fruits tree^{-1})	(Kg tree^{-1})	(Kg m^{-3})	SII	Postharvest	Total
2008						
C_{ETc}	170a	29.87a	1.29a			
C_{MDS}	150a	24.74a	1.42a			
RDI	127a	21.18a	2.07b	95	37	43
2009						
C_{ETc}	489a	67.23a	3.30a			
C_{MDS}	487a	60.75a	3.43a			
RDI	467a	63.13a	9.39b	97	85	62
2010						
C_{ETc}	173a	30.16a	1.77a			
C_{MDS}	153a	26.02a	1.70a			
RDI	181a	32.13a	5.97b	95	97	65

In relation to fruit quality (Table 6.4), no significant differences were detected for firmness. Significant differences in pH were detected in 2008 and 2009. Soluble solids content (SSC) was higher in the fruits from the RDI treatment in 2009 and 2010. Titratable acidity (TA) was lower in the RDI treatment in 2009 and 2010. Consequently,

the maturity index or ratio SSC/TA presented higher values in the RDI treatment in both years (2009 and 2010).
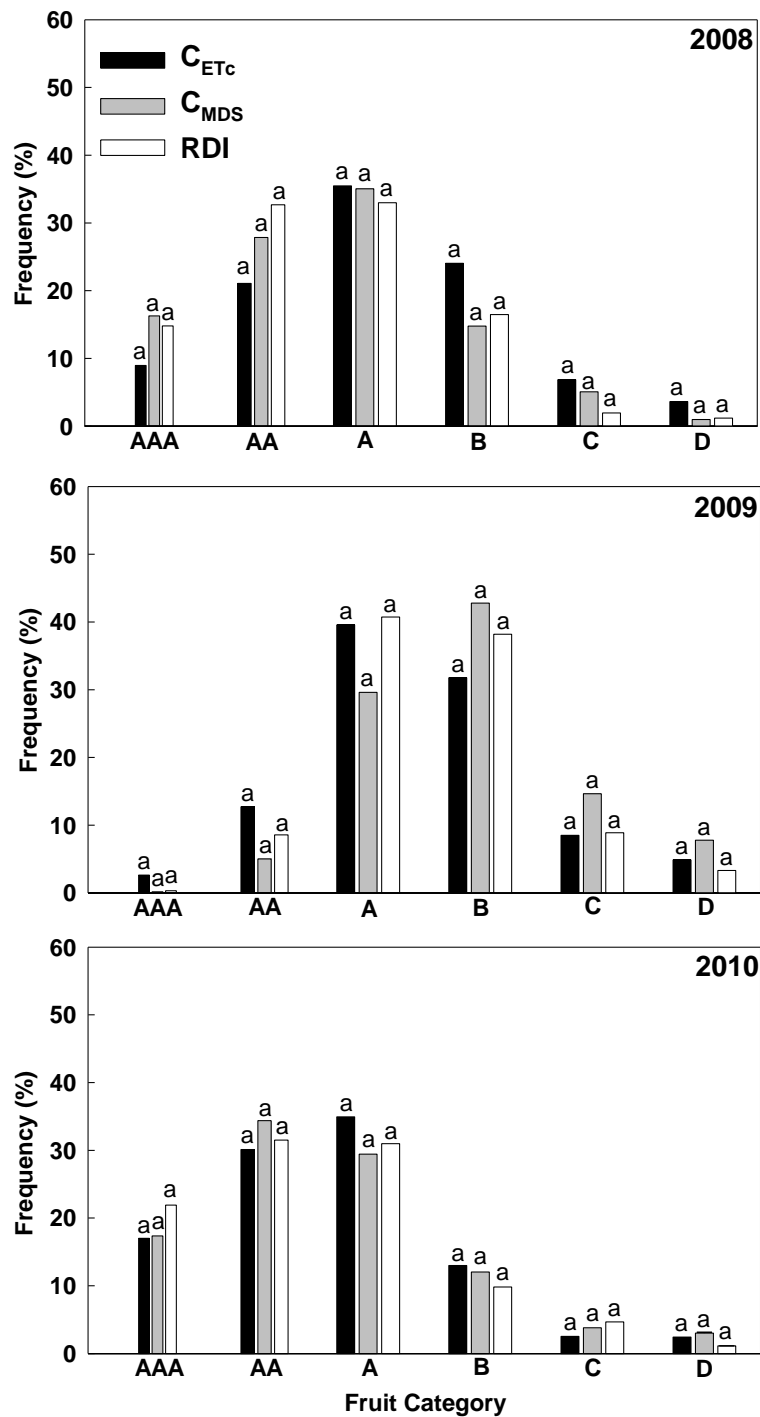
Figure 6.7. Percentage of fruit categories for each irrigation treatment, C_{ETc} (black bars), C_{MDS} (gray bars) and RDI (white bars) in the 2008, 2009 and 2010 growing seasons. Each bar corresponds to the mean of sixteen trees. Different letters on top of bars indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

Table 6.4. Fruit firmness, pH, soluble solids content (SSC), tritratable acidity (TA) and SSC/TA ratio at harvest for all treatments. Values are the mean of 100 measurements. Different letters in each column within each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

	Firmness (N)	pH -	SSC (ºBrix)	TA (g 100 mL^{-1})	Maturity Index (SSC/TA)
2008					
C_{ETc}	50.47a	4.13a	10.64a	0.59a	18.82a
C_{MDS}	54.10a	3.99b	10.62a	0.60a	19.49a
RDI	53.90a	4.00b	10.06a	0.51a	20.35a
2009					
C_{ETc}	49.29a	3.86a	10.61a	0.61a	17.91a
C_{MDS}	49.39a	3.83a	10.83a	0.66a	17.43a
RDI	53.61a	4.00b	11.21b	0.52b	21.86b
2010					
C_{ETc}	52.23a	3.88a	11.51a	0.75a	15.60a
C_{MDS}	52.82a	3.86a	11.66a	0.75a	15.86a
RDI	52.14a	3.83a	12.25b	0.67b	18.73b

6.4. Discussion

The results from the current study confirmed the hypothesis that it is possible to schedule irrigation in mid-late maturing peach trees by keeping MDS SI values close to unity and also to develop a moderate water deficit maintaining the values of MDS SI close to 2 in the RDI treatment during non-critical periods (stage II of fruit development and postharvest), saving a considerable amount of water without affecting yield and fruit quality. This observation is in accordance with other studies that have shown how maintaining MDS signal intensity around the unity could be successfully employed for scheduling irrigation in other fruit species such as lemon, early-maturing peach or pomegranate trees (e.g. Conejero et al., 2007 and 2010; Ortuño et al., 2009; Intrigliolo et al., 2011).

In our experiment, θ_v in C_{ETc} remained close to field capacity during the 3 years of the experimental period indicating that irrigation scheduling in this treatment kept the plants under non-limiting soil water conditions (Table 6.1). Similarly, trees from the C_{MDS} treatment did not suffer from water restrictions. The deficit irrigation (RDI) during stage II and postharvest resulted in a reduction in θ_v values, which induced a decrease in Ψ_s values, reflecting a moderate drought stress especially during the postharvest period (Figure 6.3B). In addition, these conditions induced an increase in

MDS and MDS SI values (Figure 6.4), proving that these signal intensities can be a useful tool for irrigation scheduling.

The fact that MDS SI values in the C_{MDS} treatment showed a low variability and remained close to the selected MDS SI threshold value (unity) and that their Ψ_s values and gas exchange measurements (data not shown) were similar to those of C_{ETc} plants shows that the irrigation water amounts applied were suitably adjusted and able to satisfy plant water requirements. This would allow us to estimate crop coefficient values for this species when these are not available or to adjust the requirements according to the area where trees are located.

In addition, MDS SI in the RDI treatment showed more variability during the stage II and postharvest periods than in the other treatments, values increased between 0.119 (stage II 2008) and 0.324 (postharvest 2009). This indicated that the information generated from these records 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 exclusively based on MDS measurements (Conejero et al., 2007; Ortuño et al., 2009). In the RDI treatment, the MDS SI threshold was only reached during the stage II at the end of this phase in 2009 and 2010, showing these the highest values of CV. However, this threshold was reached during the 3 years in the postharvest period, in a similar way a similar CV was observed between years, about 0.3, being the highest one (0.324) reached in 2009, coinciding with the greatest water stress integral observed over the study period.

Goldhamer and Fereres (2004) considered, in almond trees, that a threshold value of 1.75 would result in mild water stress with little effect on production, and that a threshold value of 2.75 would cause a more severe water stress. The severe treatment (MDS SI 2.75) caused hastening fruit maturation (hull splitting), while the less severe deficit irrigation regime (MDS SI 1.75) did not affect kernel size and other important almond fruit parameters. Conejero et al. (2007), in peach trees, followed an irrigation scheduling based on maintaining MDS SI threshold value close to 1. Their results indicated the consistence and sensibility of this parameter to changes in peach tree water status. García-Orellana et al. (2007) followed the same approach for lemon trees, using two levels of the MDS SI fixed to threshold values of 1.25 and 1.35. The authors concluded that it is feasible to schedule irrigation in lemon trees using only MDS SI

values. Vélez et al. (2007) reached water savings between 12-18% from June to October, maintaining the threshold value of MDS SI close to 1.25 in "Clementina de Nules" trees. These results suggest that deciduous trees accepted higher threshold values of MDS SI respect to perennial tress.

Pruning weight was significantly reduced by irrigation withholding during stage II and postharvest, when compared to full irrigation conditions, as previously reported in similar studies (López et al., 2008; Abrisqueta et al., 2010) (Figure 6.6). This reduction seems to be directly related to the amount of water applied and is desirable for high-density orchards in order to optimize tree-light interception and improve economic revenues (Chalmers et al., 1981) due to lower operational costs.

In contrast, fruit growth was not reduced by water deprivation during stage II and postharvest showing the typical double sigmoidal curve characteristic of stone fruit growth (Baldini, 1992) (data not shown). In fact, similar crop loads and yields were observed for C_{MDS} and RDI treatments when compared to C_{ETc} trees (Table 6.3). This trend was maintained over the three years of the experiment. Therefore, greater water productivity values were observed for the RDI treatments.

Figure 6.7 represents the percentage of fruit categories, a higher percentage of fruits within the largest sizes (AAA and AA) were observed in 2009 compared to the other two years. This was caused by a lesser thinning in this year than in 2008 and 2010, because the fate of fruits was not fresh consumption on that year, as corroborated by the load and yield (Table 6.3).

Fruit quality indices such as SSC and TA warrant particular attention due to their importance in fruit taste (Crisosto et al., 1994). In our case, SSC values were increased in 2009 and 2010 in RDI treatment (Table 6.4). Higher values of the maturity index were observed during 2009 and 2010, being significantly higher under RDI. This ratio affects the perception of taste (sweetness and acidity) by the consumer, thereby influencing buying decisions (Crisosto et al., 1997).

In summary, this study demonstrated that irrigation scheduling in peach trees can be based exclusively on the MDS SI measures was feasible without detrimental effects on yield and fruit quality. In this sense, water savings of 43-65% and water

productivity increments in the RDI treatment were achieved without affecting production and improving fruit quality.

This study also showed the possibility to quantify peach tree water requirements maintaining MDS SI values close to unity during crop growth, in order to determine crop factor (K_c) for this species.

Acknowledgements

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USE OF MIDDAY STEM WATER POTENTIAL FOR DEFICIT IRRIGATION SCHEDULING IN PEACH ORCHARDS IN SOUTH-EAST SPAIN

7. USE OF MIDDAY STEM WATER POTENTIAL FOR DEFICIT IRRIGATION SCHEDULING IN PEACH ORCHARDS IN SOUTH-EAST SPAIN

Abstract

Irrigation techniques that reduce water spends are being increasingly applied in areas with scarce water resources. In this study, the effect of two different regulated deficit irrigation (RDI) strategies on peach [*Prunus persica* (L.) Batsch cv. "Catherine"] performance were studied over three growing seasons. The experimental site was located in Murcia (SE Spain), a Mediterranean region. Two RDI strategies (restricting water applications at stage II of fruit development and postharvest) based on stem water potential (Ψ_s) thresholds were compared to a fully irrigated control. Soil water content (θ_v), Ψ_s, gas exchange parameters, vegetative growth, crop load, yield and fruit quality were determined. RDI treatments showed significantly lower values of θ_v and Ψ_s than control trees when irrigation water was restricted, causing reductions in stomatal conductance and photosynthesis rates. Vegetative growth was reduced by RDI, as lower shoot lengths and pruning weights were observed under those treatments when compared to control. However, fruit size and yield were unaffected. Crop quality was slightly improved by RDI. Water savings up to 65% were achieved depending on the year and the RDI strategy and no negative carry-over effect was detected during the study period. In conclusion, RDI strategies using Ψ_s thresholds for scheduling irrigation in mid-late maturing peach trees under Mediterranean conditions is a viable option to save water without compromising yield.

Keywords: Regulated deficit irrigation; fruit quality; stem water potential; soil water content; *Prunus persica*; yield.

7.1. Introduction

Agriculture is the primary user of water worldwide, reaching a proportion that exceeds 70-80% of the total in arid and semi-arid regions (Fereres and Soriano, 2007). The pressure on water resources is increased by the competition for water between agriculture, industry and population. This situation leads to find new ways of reducing water use in agriculture, especially for fruit tree irrigation.

Spain is the second largest peach [*Prunus persica* (L.) Bastch] producer in the world. Peach tree plantations are located in the Mediterranean area, being Murcia (SE Spain) the third main peach production area in the country, yielding 249,500 t per year, 19% of the Spanish production, approximately (MAGRAMA, 2015).

Due to the increasing limitation of irrigation water for horticultural crops in Mediterranean areas, characterized by water shortage, there is an increasing risk of losing irrigated land. Hence, reducing applied water during certain periods of the year could improve water use efficiency and conservation. Under these circumstances, the focus would not only be to achieve productions above the average or control vegetative growth but to reduce water use even at a possible risk of a slight reduction in production (Girona et al., 2003). Therefore, precise tools for assessing crop water requirements are needed in order to cope with water scarcity and reduce irrigation water use without compromising crop yield and quality.

One of the most promising techniques to achieve this objective is Regulated Deficit Irrigation (RDI), which was developed in Australian peach orchards (Chalmers et al., 1981). This technique consists of applying less irrigation water than crop evapotranspiration (ET_c) during certain periods of the crop cycle when yield and quality would be hardly affected, restoring full irrigation for the rest of the cycle. The concept was to control excessive vegetative growth and enhance fruit growth (Chalmers et al., 1981), other advantages have also been described such as improvements of fruit quality and taste (Crisosto et al., 1994; López et al., 2011).

RDI has normally been applied when reproductive growth is relatively slow and when vegetative growth and other plant processes may be affected, such effects being translated into improved fruit quality (Ruiz-Sánchez et al., 2010). In this respect, RDI has been successfully employed in many fruit crops including citrus (Goldhamer and Salinas, 2000; González-Altozano and Castel, 2000), peach (Girona et al., 2003; Buendía et al., 2008; López et al., 2008), and other species (Ruiz-Sánchez et al., 2010).

In most of the research on peach responses to RDI, water restriction was applied during stages I and II of fruit development (initial growth and pit hardening, respectively), as well as at postharvest, whereas full irrigation was applied at stage III when deficit irrigation should provoke yield reductions (Abrisqueta et al., 2010).

The water balance method (Allen et al., 1998) is the established technique for estimating full irrigation requirements. However, when dealing with RDI, other indicators that account for plant water status must be used. Among these, several approaches have been studied such as trunk diameter fluctuations (TDF) (Fernández and Cuevas, 2010; Conejero et al., 2011), sap flow (Conejero et al., 2007) and stem water potential (Ψ_s) (Shackel et al., 2010). Sap flow and TDF have been reported less reliable than Ψ_s (Moriana et al., 2003; Intrigliolo and Castel, 2006). At commercial level, the use of leaf and stem water potential is considered more practical (Naor and Cohen, 2003; Bonet et al., 2010; Moriana et al., 2010).

Several studies proved the feasibility of using tentative threshold values of plant parameters as irrigation triggers (Besset et al., 2001; Goldhamer and Fereres, 2004). Girona et al. (2006) proved that leaf water potential thresholds could be successfully used for scheduling irrigation in vineyards and a similar approach has been suggested for peach orchards (Ghrab et al., 2013).

In this context, the aims of the current study were to (1) evaluate a methodology for scheduling peach orchard irrigation based on Ψ_s thresholds as a stress indicator for triggering irrigation, and (2) assess the effects of these RDI on peach tree physiology, vegetative growth, yield and fruit quality, as well as water savings, when compared to a fully irrigated control.

7.2. Materials and Methods

Site description and plant material

The experiment was conducted over three consecutive years (2008–2010) in a 0.5 ha plot of a commercial orchard located in Mula valley, Murcia, SE Spain (37°55'N, 1°25'W, 360 m above sea level). The soil at the site is calcareous, stony, with a sandy-loam texture, low organic matter content and its available water capacity is 0.25 $m^3 \, m^{-3}$, approximately. The climate is typically Mediterranean, with mild winters, hot dry summers and low rainfall. During the growing season (April-October), total rainfall was 254, 304 and 188 mm in 2008, 2009 and 2010, respectively; whereas reference crop evapotranspiration (ET_0) was 792, 817 and 784 mm in 2008, 2009 and 2010, respectively.

Plant material consisted of peach trees [*Prunus persica* (L.) Batsch cv. 'Catherine'] planted in 1999 and grafted on GF-677 rootstock. Spacings were 4 m x 6 m. Hand thinning was used to space fruitlets 20 cm along the fruit bearing shoots in order to achieve a commercial crop load. Pest control was that commonly used by the growers and all treatments received the same fertilization ($N-P_2O_5-K_2O$), applied through the drip irrigation system ($275-125-200$ kg ha^{-1} year^{-1}) over the study period.

Irrigation treatments and experimental design

Irrigation water was supplied through a drip irrigation system, one pipeline for each row, with three emitters per tree (delivering 4 L h^{-1} each). The irrigation water was considered of good quality with a very low electrical conductivity (0.6 dS m^{-1}).

Crop irrigation requirements were scheduled weekly according to daily ET_0, calculated using the Penman-Monteith equation (Allen et al., 1998), and a local crop factor based on the time of the year and used in this region at commercial level. Monthly average values of K_c employed for the control treatment from April to October were 0.73, 0.83, 0.94, 0.96, 0.39, 0.39 and 0.39, respectively. A total of 192 trees were used in this study. The experiment was laid out in completely randomized blocks with 4 replications (16 trees each). The four central trees were used for measurements, and the other 12 trees acted as guard.

Three irrigation treatments were applied based on peach tree water status (Figure 7.1): Control plants (treatment C) were daily irrigated above the estimated crop evapotranspiration in order to obtain non-limiting soil water conditions (average 120% ET_c in three years of experiments), and two RDI strategies that consisted of a full irrigation during critical periods, and water restrictions during the non-critical periods of crop development (stage II of fruit growth and postharvest period). These RDI treatments were:

a) RDI I (Moderate deficit) plants were irrigated to maintain Ψ_s values close to -1.5 MPa during stage II of fruit growth and postharvest.

b) RDI II (Severe deficit) plants were irrigated to maintain Ψ_s values close to -1.8 MPa at stage II of fruit growth and -2.0 MPa at postharvest.
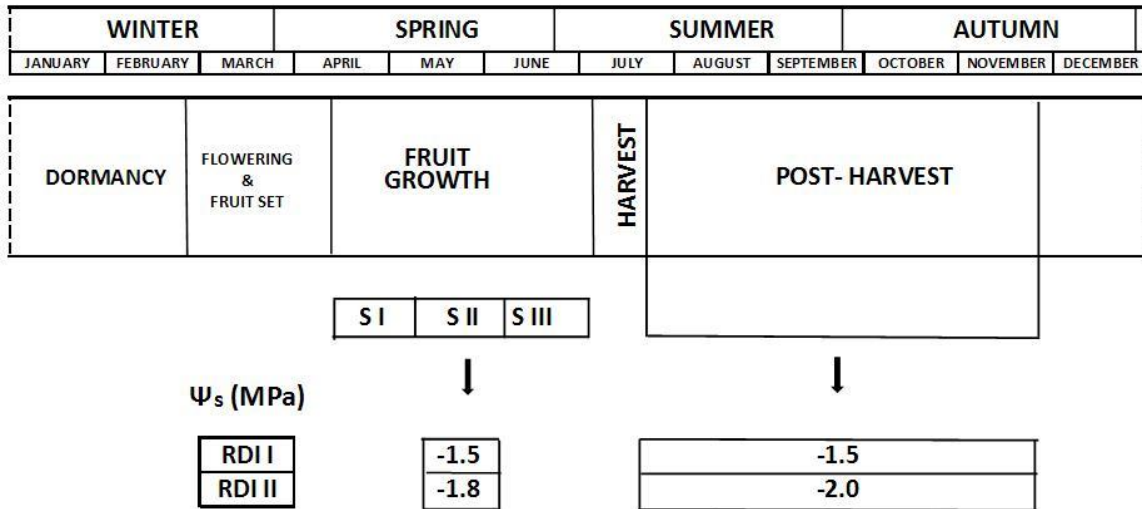
Figure 7.1. Regulated deficit irrigation (RDI I: moderate deficit, RDI II: severe deficit) strategies based on threshold values for midday stem water potential (Ψ_s), applied in stage II (S II) of fruit growth and postharvest during the three years of the experiment.

The irrigation rate was decreased by 10% when stem water potential on at least two out of three consecutive days was at or below the threshold value. The irrigation rate was increased by 10% when the stem water potential on at least two out of three consecutive days exceeded the threshold value. This irrigation protocol was based on that proposed by Goldhamer and Fereres (2001) for mature trees grown with high frequency irrigation.

Irrigation was automatically controlled by a head unit programmer and the amounts of water applied for each irrigation treatment were measured with in-line flowmeters placed in each experimental plot.

Field and laboratory determinations

Climate data

Climate data were recorded at an automatic weather station placed within the experimental orchard. Data on air temperature (maximum, minimum and average), solar radiation, air relative humidity, rainfall and wind speed 2.5 m above the soil surface, were collected every 15 min. These data were used for calculating ET_0 and crop water requirements.

Soil water content

The volumetric soil water content (θ_v, m^3 m^{-3}) of the top 0.2 m of the soil profile was measured by time domain reflectometry (TDR) using a Tektronix device (Model 1502C, Tektronix Inc., OR), as described by Moreno et al. (1996). The θ_v from 0.2 m

down to a maximum depth of 1.0 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 from the trees and beside the emitters. The probes were placed at 0.2 m from the perperdicular emitter and next to the TDR rods. Measurements using one neutron probe and TDR per experimental plot (3 replications per treatment) were taken in the morning, every 7 to 15 days, during the experimental period.

Stem water potential

Midday stem water potential (Ψ_s) was measured using a pressure chamber (Soil Moisture Equip. Corp, model 3000, Santa Barbara, CA, USA) following the procedures described by Turner (1981).

Picture 7.1. Pressure chamber (Own source).

Measurements were performed on mature leaves (one per tree) from the north face of the trunk, in the four central trees of each experimental plot. Leaves were enclosed in plastic bags covered with aluminum foil at least two hours prior to the measurements, which were carried out between 12:00 and 13:00 h solar time.

Gas exchange parameters

Net photosynthesis (P_n) and stomatal conductance (g_s) were measured at solar midday, in one fully expanded sun-facing leaf in the four central trees of each experimental plot per treatment, in the same days that stem water potential was recorded, using a field-portable photosynthesis system (LI-6400, Li-Cor, Lincoln, NE, USA).

Fruit growth and yield

Fruit diameter was measured perpendicularly to the fruit suture on 160 fruits per treatment (40 fruits per replication) every 7-10 days. Each date, 10 fruits per tree were randomly selected in the four inner trees per experimental plot and their diameters measured using a digital caliper (Powerfix model Nr Z22855F, Milomex Ltd, Bedfordshire, UK).

Fruits from each tree were individually harvested on July in two or three commercial picks, depending on market demands. The number of fruits per tree was obtained by counting the fruits in the four inner trees (16 trees per treatment). 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° 1861/2004, 56 mm is the minimum diameter for a fruit to be considered in the "extra" category, which can be subdivided into different categories: AAAA (diameter > 90 mm), AAA (90 mm > diameter ≥ 80 mm), AA (80 mm > diameter ≥ 73 mm), A (73 mm > diameter ≥ 67 mm), B (67 mm > diameter ≥ 61 mm), C (61 mm > diameter ≥ 56 mm) and out of "extra" category D (56 mm > diameter ≥ 51 mm).

Picture 7.2. Fruit Calibrator (Own Source).

Vegetative growth

Trunk diameter was measured annually during the dormancy stage in 64 trees per treatment with a sliding caliper, 0.20 m above the soil surface, and used to estimate trunk cross-sectional area (TCSA). Pruning weight was recorded for 16 trees per treatment (4 per replication) at winter pruning. Shoot length values were collected every 7-10 days by measuring the lengths of 10 randomly selected shoots in the four inner trees of each experimental plot per treatment.

Fruit quality

At harvest, 100 fruits per treatment (25 fruits per experimental plot) were randomly selected for quality assessment. Firmness, pH, soluble solids content (SSC) and titratable acidity (TA) were evaluated as quality indices. Chemical analyses were conducted according to Artés et al. (1993). Fruit firmness was evaluated using a Durofel penetrometer DFT100 (Agro-Technologie S.A., Paris, France).

Picture 7.3. Durofel penetrometer (Own Source).

Juice was extracted from combined samples of longitudinal unpeeled slices. Total soluble solids concentration (SSC) was determined with a hand refractometer (Atago, Co., Japan); values were expressed as ºBrix. Titratable acidity (TA) was

measured by titration of 5 mL of juice with 0.1 mol L^{-1} NaOH to pH 8.1 using an automatic titration system and expressed as g malic acid L^{-1}. The maturity index (MI), which affects the perception of taste (sweetness and acidity) was calculated as the ratio of SSC to TA. pH was measured using a pH-meter (Crison, Barcelona, Spain).

Water stress integral

The water stress integral (MPa-days) was calculated from the Ψ_s data in order to evaluate the intensity of water stress, according to the following equation (Myers, 1988):

$$S_\Psi = \left| \sum_{i=0}^{i=t} \left(\overline{\Psi}_{i,i+1} - c \right) n \right|$$

where:

$\Psi_{i,i+1}$ is the average Ψ_s for each time interval

c is the value of the maximum Ψ_s in all seasons

n is the number of days in the interval.

Statistical analysis

Statistical analysis was performed as a weighted analysis of variance (ANOVA; statistical software IBM SPSS Statistics v. 21 for Windows). The Shapiro–Wilk test was used to evaluate the normality of the data. Tukey's HSD test was used for mean separation. Percentage values of fruit categories were arcsine-transformed before statistical analysis. Unless otherwise stated, the significance level was $p \leq 0.05$.

7.3. Results

Seasonal evaporative demand was quite similar from year to year, ranging between 784 mm in 2010 and 817 mm in 2009. Rainfall was more variable during the experimental period, from 188 mm during the 2010 growing season to 304 mm in 2009. Rainfall was relatively important during the vegetative phase and postharvest, although more than 50 mm were registered during stage II of fruit development in 2008 (Figure 7.2). During the experimental period, rainfall accounted for an average of 31% of total ET$_0$ over the growing season.
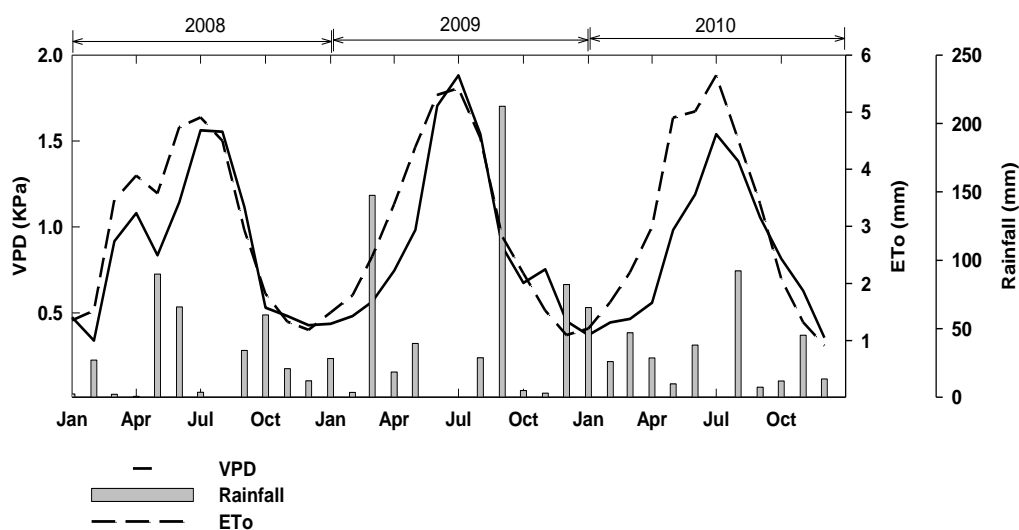
Figure 7.2. Reference evapotranspiration (ET$_0$), rainfall (mm) and VPD (KPa) in Fuente Librilla. Monthly values from data collected during 2008, 2009 and 2010.

Soil water content from 0 to 1 m depth (Figure 7.3), was nearly constant over the experimental period for C treatment, with values close to field capacity. In the RDI treatments, θ$_v$ decreased during the stage II of fruit development when compared to C, and recovered in stage III, when full irrigation was restored. During the postharvest period, the θ$_v$ decreased as a result of the deficit irrigation applied, reaching significantly lower values in RDI I (Ψ$_s$ -1.5 MPa) and RDI II (Ψ$_s$ –2.0 MPa) when compared to the C treatment (Figure 7.3).

Midday stem water potential (Ψ$_s$) used as a threshold for irrigation scheduling revealed clear differences in Ψ$_s$ average values for each irrigation treatment (Figure 7.4B). In the early part of the season, Ψ$_s$ below the thresholds for RDI I and RDI II trees were rarely observed; only by the end of stage II of fruit development in 2009. Consequently, little water was applied to the RDI trees during this stage (Figure 7.4A). However, RDI trees presented significantly lower Ψ$_s$ values than C trees during stage II of fruit development. When irrigation was restored in stage III, Ψ$_s$ was similar for the three treatments.
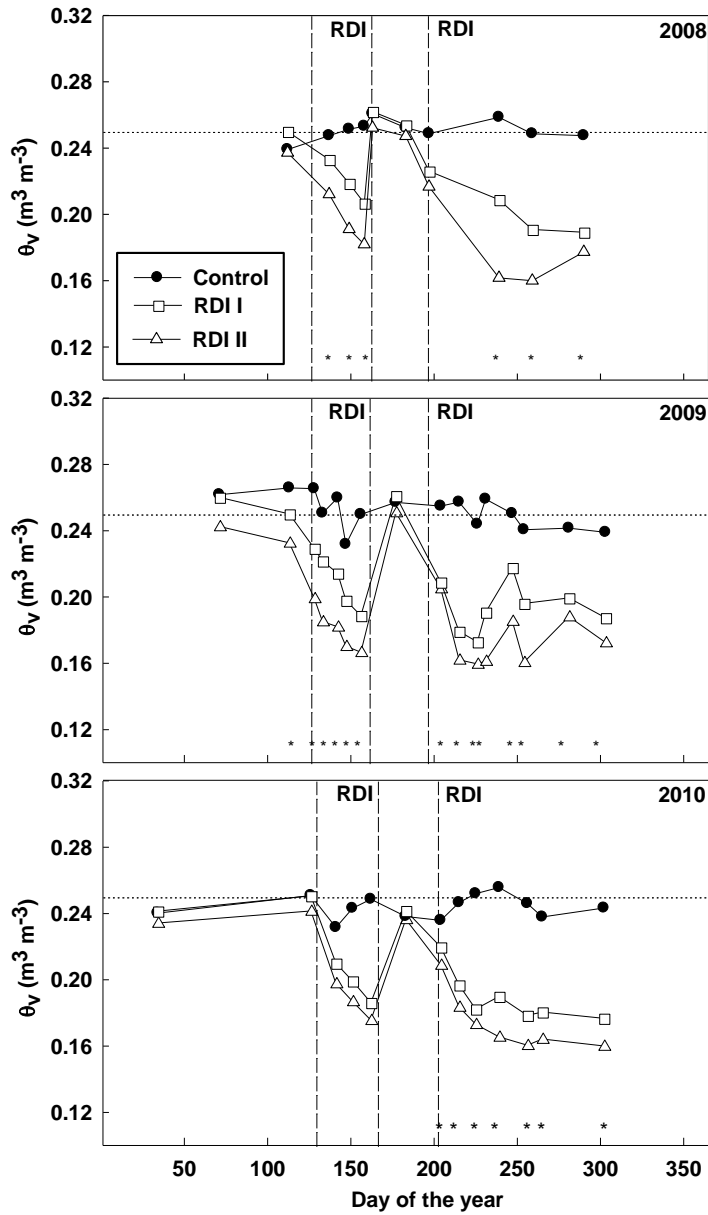
Figure 7.3. Volumetric soil water content down to 1 m depth (θ_v), in C (closed circles), RDI I (open squares) and RDI II (open triangles) treatments for the three growing seasons studied (2008-2010). Each data point is the mean of three values. Asterisks indicate significant differences among treatments ($p < 0.05$). The interval between vertical lines, from left to right, represents the beginning of stages II and III of fruit growth and postharvest. Horizontal lines represent field capacity.
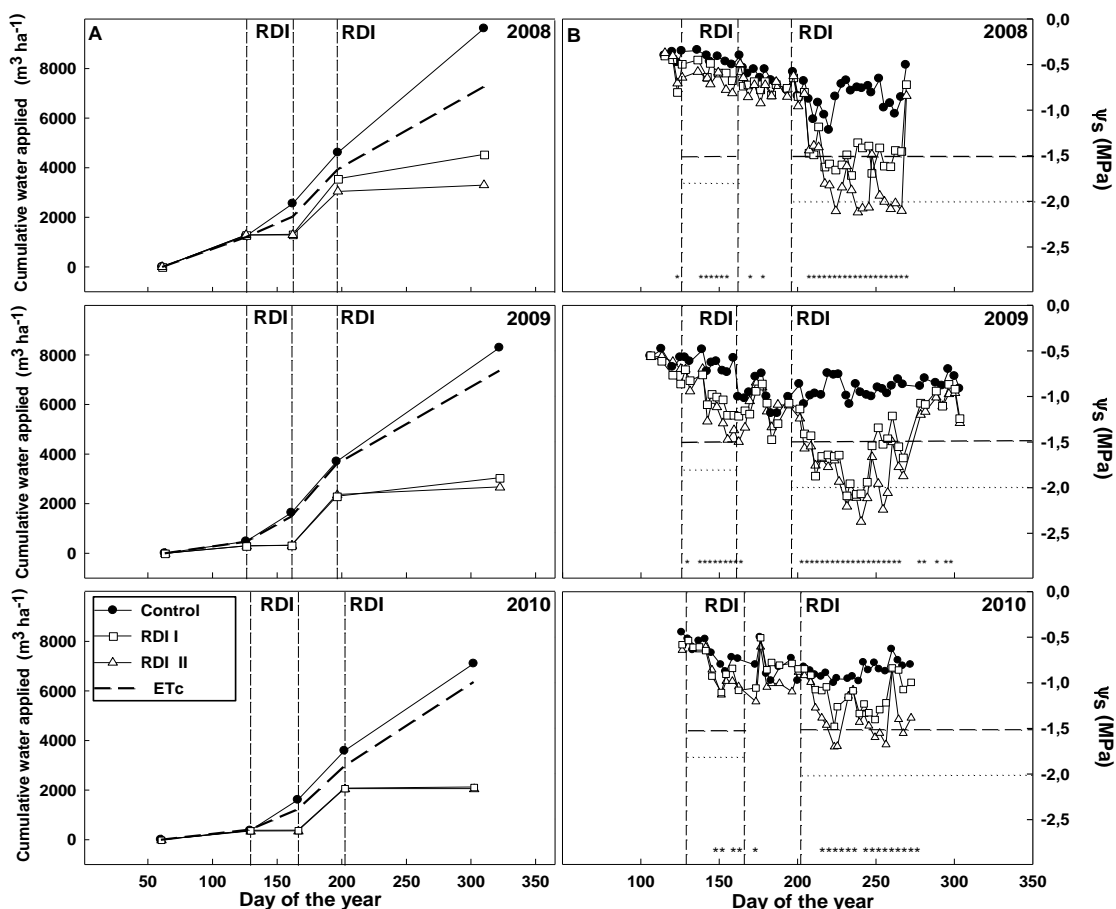
Figure 7.4. Seasonal patterns of (A) cumulative applied water and (B) midday stem water potential values for each irrigation treatment for the 3 years of the experiment: C (closed circles), RDI I (open squares) and RDI II (open triangles) plants. Each data point is the mean of sixteen values. Asterisks indicate significant differences among treatments ($p < 0.05$). The interval between vertical lines, from left to right, represents the beginning of stages II and III of fruit growth and postharvest. Horizontal lines represent threshold values in each phenological stage for both RDI treatments.

During postharvest, Ψ_s was below the thresholds most of the time in 2008 and 2009 (Figure 7.4B), with a resulting increase in irrigation rate during this period (Figure 7.4A). Differences in Ψ_s between both RDI treatments were significant on certain dates; however, the lower threshold for irrigation triggering in RDI II (-2.0 MPa) was rarely observed in 2009 and never reached in 2010 due to the specific climate conditions of those years and, consequently, lower irrigation water amounts were applied to this treatment (Figure 7.4B).

Average midday stem water potential values for each stage in the growing cycle showed clear differences between treatments, mainly at postharvest, and these were repeated with the same trends for the three years of the experiment (Table 7.1). During the stage I and stage III of fruit development, Ψ_s values were very similar among

treatments, except in stage III of fruit development in 2008. The decrease of Ψ_s in RDI treatments compared to control was about 40-51% during 2008, 39-46% during 2009 and 6-26% during 2010 for the RDI I and RDI II treatments, respectively.

Table 7.1. Average midday stem water potential in different stages of fruit growth for the three studied growing seasons. Each data is the mean of all values in the corresponding stage. Different letters next to a value in each year indicate significant differences among treatments according to Tukey's multiple range test ($p < 0.05$).

	Stage I	Stage II	Stage III	Postharvest
2008				
C	**-0.40a**	**-0.43a**	**-0.60a**	**-0.85a**
RDI I	**-0.53a**	**-0.57b**	**-0.71ab**	**-1.40b**
RDI II	**-0.53a**	**-0.68b**	**-0.74b**	**-1.69c**
2009				
C	**-0.57a**	**-0.62a**	**-0.99a**	**-0.90a**
RDI I	**-0.64a**	**-0.96b**	**-1.14a**	**-1.48b**
RDI II	**-0.58a**	**-1.05b**	**-1.14a**	**-1.66b**
2010				
C	**-0.45a**	**-0.67a**	**-0.82a**	**-0.86a**
RDI I	**-0.58a**	**-0.80a**	**-0.80a**	**-1.13b**
RDI II	**-0.64a**	**-0.82a**	**-0.97a**	**-1.36c**

The amounts of water applied during the first year of the experiment (2008) were 962, 454 and 330 mm for C, RDI I and RDI II, respectively (Figure 7.4A). These amounts were reduced in 2009 and 2010, and were similar for the two RDI treatments, namely 849, 289 and 247 mm for C, RDI I and RDI II, respectively, in 2009; and 710, 213 and 206 mm for C, RDI I and RDI II, respectively, in 2010. These differences were due to climate conditions that did not cause Ψ_s values to be lower than the scheduled thresholds in both RDI periods (stage II of fruit development and postharvest), thus irrigation was restricted to the point that hardly was applied in 2010 during porhasvest (Figure 7.4A).

As a consequence, when compared to ET_c, water reductions of 26-45% in 2008, 49-55% in 2009 and 64-65% were achieved for RDI I and RDI II treatments, respectively.
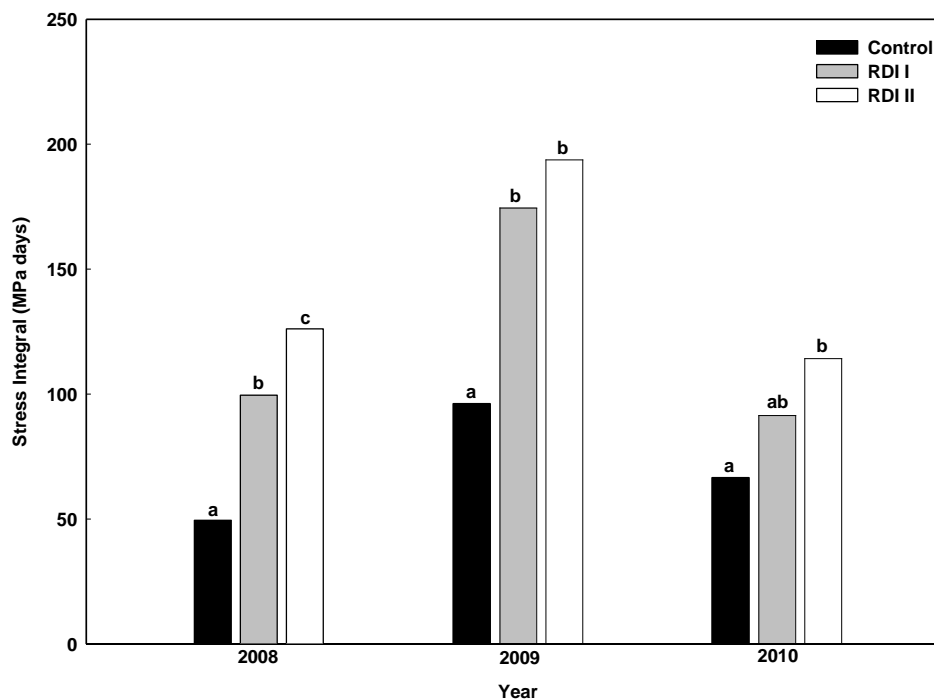
Figure 7.5. Stress integral for each irrigation treatment, control (black bars), RDI I (gray bars) and RDI II (white bars) in the 2008, 2009 and 2010 growing cycles. Different letters on top of bars indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

Overall for the whole season, S_Ψ values reflected those significant differences among treatments, RDI II showed the highest values of water stress integral (Figure 7.5), but only significantly higher than RDI I in 2008. For stages of fruit development, water stress integral values reflected the differences in irrigation treatments, as observed by Ψ_s.

During stage II of fruit development, sigficantly greater S_Ψ values were detected for RDI I and RDI II treatments when compared to C (Table 7.2). However, these differences were not maintained in 2010, when a low evaporative demand made the values of S_Ψ to be similar among treatments. However, at postharvest, RDI II reflected the highest S_Ψ values, showing significant differences from RDI I only in 2008 (Table 7.2).

Table 7.2. Stress integral average values (MPa days) in different stages during the three seasons of the experiment. These values were calculated with data of the midday stem water potential of Figure 7.4B. Each data point is the mean of all values in the corresponding stage. Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

	Stage I	Stage II	Stage III	Postharvest
2008				
C	0.65a	2.74a	10.69a	36.42a
RDI I	2.16a	8.18b	14.96a	76.76b
RDI II	1.83a	12.07c	16.48a	98.46c
2009				
C	4.53a	11.05a	22.58a	58.91a
RDI I	6.84a	23.65b	28.01a	118.19b
RDI II	5.13a	28.12b	27.53a	135.84b
2010				
C	0.42a	12.59a	16.63a	36.86a
RDI I	0.64a	18.28a	19.82a	54.96b
RDI II	0.73a	19.03a	25.92a	70.99b

Gas exchange parameters showed a similar trend over the growing season as those of Ψ_s. Significant reductions in net photosynthesis rate (P_n, Figure 7.6A) and leaf stomatal conductance (g_s, Figure 7.6B) for the RDI treatments compared to C were observed at postharvest and in one date during the stage II of fruit development. The P_n and g_s values for the RDI treatments were, approximately, one third of those measured in C trees.

Pruning weight was significantly higher in the C trees than in those subjected to RDI (Figure 7.7). A linear correlation between pruning weight and the amount of water applied was detected (Figure 7.8), with a significant determination coefficient ($r^2 = 0.81$, $p < 0.01$).

In addition, TCSA was similar for the three treatments considered on the first year of the experiment (Table 7.3); however, this parameter was significantly lower for RDI trees in 2009 and 2010.
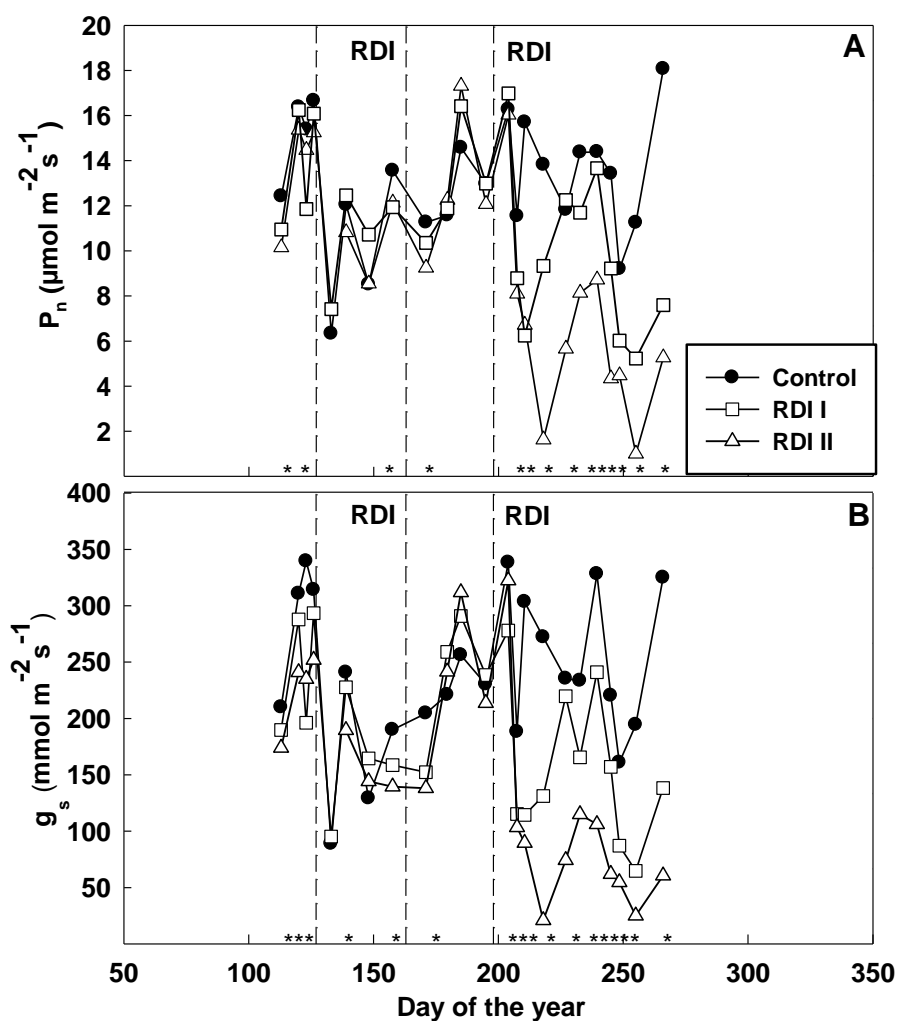
Figure 7.6. Net photosynthesis (P_n, A) and stomatal conductance (g_s, B) values averaged for the three studied growing seasons in C (closed circles), RDI I (open squares) and RDI II (open triangles) plants. Each data point is the mean of sixteen values. Asterisks indicate significant differences among treatments ($p < 0.05$). The interval between vertical lines, from left to right, represents the beginning of stages II and III of fruit growth and postharvest.

Vegetative growth was restricted by RDI when compared to C: Shoot length from RDI trees was significantly lower than that observed for C trees (Figure 7.9A), although no differences were observed between both RDI treatments by the end of the season.
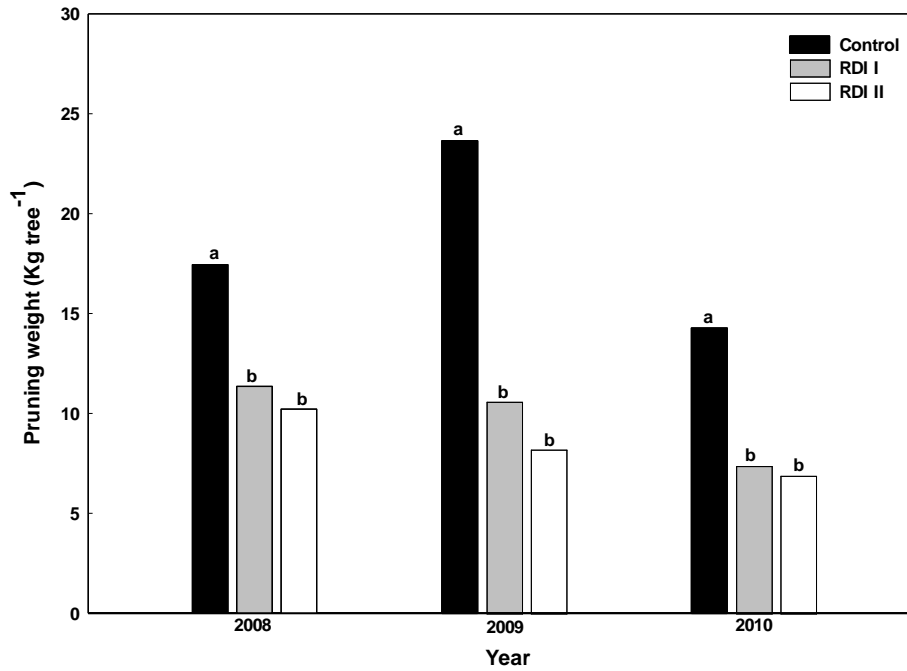
Figure 7.7. Pruning weight as a function of the irrigation treatment, control (black bars), RDI I (gray bars) and RDI II (white bars) in the 2008, 2009 and 2010 growing cycles. Each bar corresponds to the mean of sixteen trees. Different letters on top of bars indicate significant differences according to Tukey's multiple range test ($p < 0.05$).
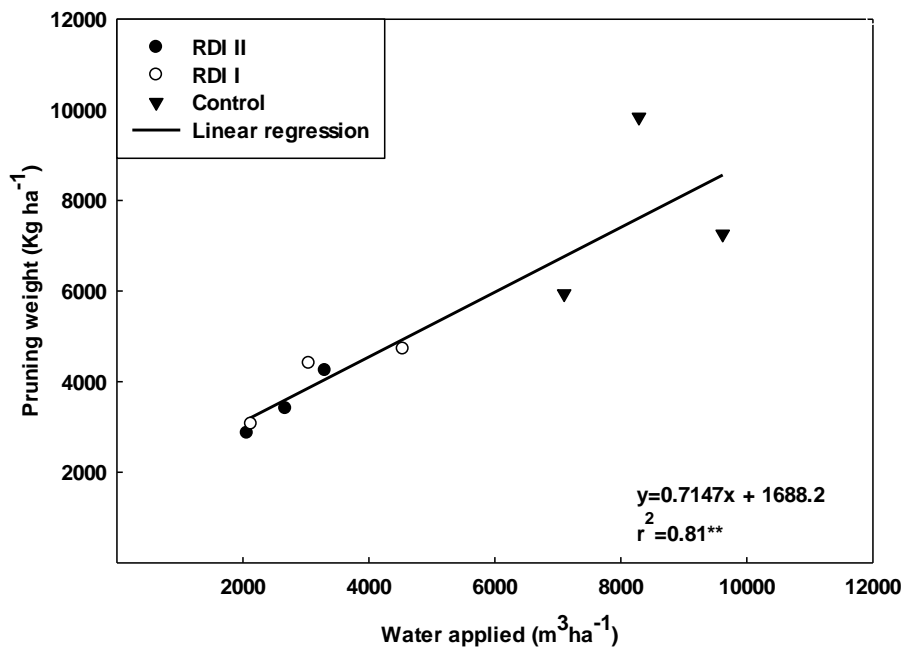
Figure 7.8. Relation between pruning weight and water applied in C (closed triangles), RDI I (open circles) and RDI II (closed circles) plants for the three studied growing seasons. Solid line represents the linear regression between pruning weight and water applied. Asterisks indicate a significant relationship between variables ($p < 0.01$).

Table 7.3. Flower density, fruit set and trunk cross sectional area (TCSA) average values in different treatments during the three seasons of the experiment. Each data point is the mean of 160 values per treatment (Fruit set and flower density) and 64 values per treatment (TCSA). Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

	Flower density (Fl cm^{-1})	Fruit set (%)	TCSA (cm^2)
2008			
C	0.32a	60.34a	151.51a
RDI I	0.32a	58.73a	149.78a
RDI II	0.21a	66.67a	146.99a
2009			
C	0.48b	78.38a	180.66a
RDI I	0.60ab	79.74a	175.06ab
RDI II	0.67a	85.36a	162.65b
2010			
C	0.22b	87.01a	208.44a
RDI I	0.38a	91.30a	188.14b
RDI II	0.34ab	94.82a	186.54b

On the contrary, fruit development was mainly unaffected by water restrictions. Fruit growth, expressed as fruit diameter, was very similar among treatments (Figure 7.9B), as well as fruit set (Table 7.3).
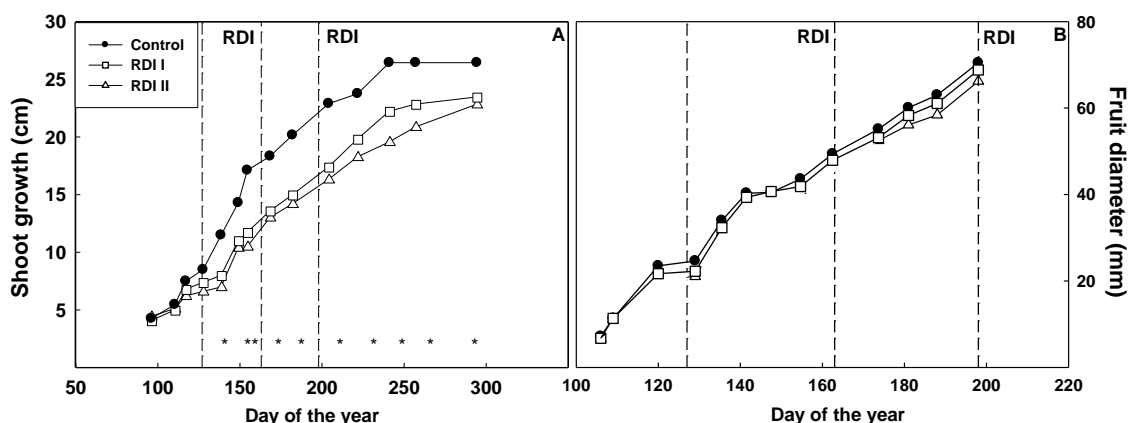
Figure 7.9. Shoot growth (A, cm) and fruit diameter (B, mm) evolution in C (closed circles), RDI I (open squares) and RDI II (open triangles) tress for the three studied growing seasons. The interval between vertical lines, from left to right, represents the beginning of stages II and III of fruit growth and postharvest. Each value is the mean of 160 measurements.

Table 7.4. Crop load (number of fruits tree^{-1}), yield (kg tree^{-1}), water productivity (WP, kg m^{-3}) and water spends/savings in each non-critical period and total in response to the irrigation treatments for the experimental period 2008-2010. Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

	Crop load	Yield	WP		Water savings	
	(Fruits tree^{-1})	(Kg tree^{-1})	(Kg m^{-3})	SII (%)	Postharvest (%)	Total (%)
2008						
C	170a	29.87a	1.29a	-58	-50	-32
RDI I	137a	26.99a	2.47ab	97	74	38
RDI II	160a	29.78a	3.75b	99	92	55
2009						
C	489a	67.23a	3.30a	-13	-22	-12
RDI I	523a	66.54a	9.73b	98	80	59
RDI II	488a	63.18a	10.63b	99	92	64
2010						
C	173a	30.16a	1.77a	-50	-4	-12
RDI I	197a	33.79a	6.61b	99	98	67
RDI II	244a	40.40a	8.15b	99	99	68

Flower density followed an opposite trend as that of TCSA, namely, it was unaffected in 2008 but was higher in RDI trees when compared to C trees in 2009 and 2010 (Table 7.3). Crop load and yield were similar among treatments although highly variable between years (Table 7.4). Furthermore, no differences among treatments were observed for fruit distribution into commercial categories (Figure 7.10).

The fact that similar yields were obtained for the three treatments studied made that water productivity (WP) values were higher under RDI treatments when compared to control (Table 7.4). Therefore, important water savings were registered for RDI treatments, being greater under RDI II than for RDI I (Table 7.4). When compared to control and depending on the year, RDI I supposed between 38 and 67% water savings for the whole season, whereas RDI II saved between 55 and 68% than C.

Fruit quality parameters reflected certain differences among treatments (Table 7.5). Fruit firmness was unaffected by irrigation treaments and titratable acidity was only affected in 2010, although pH showed a tendency to reach lower values under RDI treatments. On the contrary, SSC was significantly higher under RDI when compared to C. This caused that maturity index (MI) was greater in RDI than in C, except for 2009 (Table 7.5).
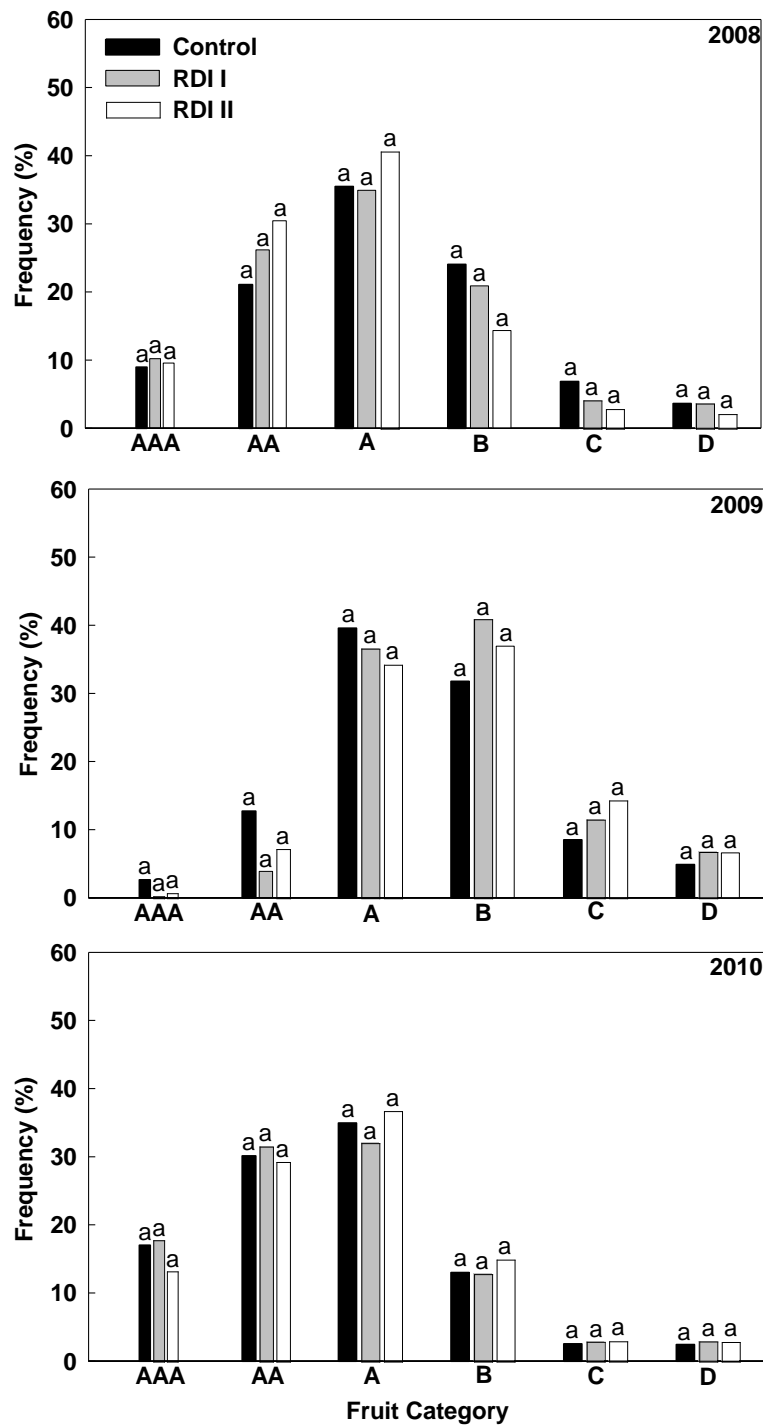
Figure 7.10. Percentage of fruit categories for each irrigation treatment, control (black bars), RDI I (gray bars) and RDI II (white bars) in the 2008, 2009 and 2010 growing cycles. Each bar corresponds to the mean of sixteen trees. Different letters on top of bars indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

**Table 7.5.** Fruit firmness (N), pH, soluble solids content (SSC, ºBrix), tritratable acidity (TA, g 100 mL^{-1}) and SSC/TA ratio at harvest for all treatments. Values are the mean of 100 measurements. Different letters next to a value in each year indicate significant differences according to Tukey's multiple range test ($p < 0.05$).

	Firmness (N)	pH -	SSC (ºBrix)	TA (g 100 mL^{-1})	Maturity Index (SSC/TA)
2008					
C	50.47a	4.13a	10.64a	0.59a	18.82a
RDI I	48.80a	3.98b	11.16a	0.52a	21.93b
RDI II	51.74a	3.92b	11.23a	0.54a	21.78b
2009					
C	49.29a	3.86a	10.61ab	0.61a	17.91a
RDI I	49.10a	3.93b	10.40a	0.57a	18.82a
RDI II	51.45a	3.82a	11.36b	0.61a	19.23a
2010					
C	52.23a	3.88a	11.51a	0.75a	15.60a
RDI I	56.45a	3.97a	12.09ab	0.64b	19.23b
RDI II	56.45a	3.88a	13.07b	0.72ab	18.23b

7.4. Discussion

During pit hardening (Stage II), peach fruit growth is not very sensitive to water stress (Chalmers et al., 1981). In this study, the effects of two different RDI treatments on peach fruit growth were negligible during the three years of the experiment. These RDI strategies were applied at stage II of fruit development and at postharvest based on Ψ_s thresholds, as proposed by Girona et al. (2006), since this indicator of plant water status is very sensitive to water deprivation (Remorini and Massai, 2003).

The use of Ψ_s for irrigation scheduling has progressed in recent years, especially for managing RDI in fruit trees and vines (Girona et al., 2006; Shackel et al., 2010). This indicator provides more site-specific information than the water balance method and, therefore, it can account for spatial variations (Girona et al., 2006).

A wide range of tree water status was observed as a result of the different watering conditions imposed. At the beginning of the season, Ψ_s was very similar for the three treatments considered, around –0.5 MPa. During stage II of fruit development, significant differences were observed between fully irrigated trees and those subjected to RDI due to water withholding. However, values close to the predetermined Ψ_s thresholds were rarely observed during this stage and, consequently, low water amounts were applied to the RDI treatments. When irrigation was restored in stage III, Ψ_s for RDI trees recovered to values close to those found in C trees.

The increasing evaporative demand during postharvest caused that Ψ_s thresholds were attained and, thus, irrigation was applied accordingly. However, in the last year of the experiment (2010), the Ψ_s threshold for triggering irrigation in the RDI II treatment was never achieved and irrigation water was not applied (only the minimum amount of water with the fertilizer needs). The lowest Ψ_s values measured for C, RDI I and RDI II trees were, respectively, -0.9, -2.0 and -2.4 MPa, depending on the year, although they were always reached at postharvest. These reflect conditions of absence of water stress, moderate and severe water stress, respectively (Remorini and Massai, 2003) and followed the same trend as soil water content in the different treatments.

Tree functioning was affected by water deprivation, as lower P_n and g_s values were observed under RDI treatments. This indicates that peach trees regulated their transpiration when subjected to water constraints (Girona et al., 1993; Ruiz-Sánchez et al., 2010), which is a common response of cultivated plants grown in Mediterranean climates (Schulze et al., 1972; Tenhunen et al., 1982; Pereira et al., 1986). A delay in the recovery of these functions was observed when irrigation was restored, as previously reported for other species (Torrecillas et al., 1999; Romero et al., 2004). This progressive recovery after rewatering can be considered a mechanism for maintaining leaf productivity and promoting leaf rehydration (Torrecillas et al., 1999).

Vegetative growth (shoot elongation, TCSA and pruning weight) was significantly reduced by irrigation with holding during stage II and postharvest, when compared to full irrigation conditions, as previously reported in similar studies (Bradford and Hsiao, 1982; Pérez-Pastor, 2001; Girona et al., 2003, 2005; López et al., 2008; Abrisqueta et al., 2010). This reduction seems to be directly related to the amount of water applied and is desirable for high-density orchards in order to optimize tree-light interception and improve economic revenues (Chalmers et al., 1981) due to lower operational costs.

In contrast, fruit growth was not reduced by water deprivation during stage II and postharvest. In fact, similar crop loads and yields were observed for RDI treatments when compared to C trees. This trend was maintained for the three years of the experiment. As a consequence, greater water productivity values were observed for the RDI treatments. Moreover, flower density and fruit set were slightly affected by RDI,

suggesting that withholding water during postharvest did not cause any carry-over effect from year to year in a medium-term. This is in contrast with previous results (Girona et al., 2003) and can be explained by the greater soil depth and rainfall amounts occurred in our study.

Fruit distribution into marketable categories was unaffected by the irrigation treatment in any of the three years studied. These results are in disagreement with those reported by Conejero et al. (2007) for an early-maturing peach cultivar and by Alcobendas et al. (2013) for the same cultivar used in the current study. In the latter case, this contradiction might have been caused by the low crop load of the trees studied by Alcobendas et al. (2013), since high-loaded peach trees are more sensitive to water stress than those with low loads (Marsal et al., 2006; López et al., 2008). In our case, fruit destination caused a lower thinning in 2009 with respect to those of 2008 and 2010; consequently, Ψ_s values in 2009 were lower compared to those from the other years. In spite of this, water deprivation did not limit crop yield and marketable fruit size in the following year.

Improvements in fruit taste and quality are expected for RDI treatments due to increasings in SSC (Crisosto et al., 1994; Mpelasoka et al., 2000; López et al., 2011). Our results showed significant increasings in SSC for RDI treatments. Moreover, the ratio SSC/TA was greater for the fruits from the RDI treatments, hence this may affect taste perception (Crisosto et al., 1997; Scandella et al., 1997) by the consumer, which might have implications in buying decisions.

Finally, when comparing the combination of deficit irrigation during stage II and postharvest with fully irrigated trees, higher water savings were achieved, up to 65% in the case of RDI II for 2010. Hence, water savings depended on the Ψ_s threshold used and on climate conditions of the specific year. As reported by Girona et al. (2003), the level of water savings during postharvest was much greater than that of stage II, making postharvest a more appealing period than stage II for saving applied water. Several studies in other fruit-tree crops support these findings (Romero et al., 2004; Girona et al., 2006; Pérez-Pastor et al., 2009).

In summary, the major effects of RDI in this study were related to reductions in vegetative growth and improvements in fruit quality, whereas crop yield remained

unaffected. From a viewpoint of sustainability of water resources, RDI allowed to reduce water consumption around 55%, in average for the three studied years. However, these water savings were dependent on the Ψ_s threshold used, which must be explored in order to adapt them to the specific conditions of the site where they will be used (Ghrab et al., 2013).

7.5. Conclusions

Our results proved that using Ψ_s thresholds for scheduling irrigation in mid-late maturing peach trees under Mediterranean conditions is a viable option to save water without compromising yield. In this experiment, a Ψ_s threshold of -1.8 MPa at stage II of fruit development and -2.0 MPa at postharvest induced water savings up to 68% over the growing season when compared to full irrigation based on the water balance method.

Tree vegetative growth was restricted by RDI and this trend was maintained over the whole experiment. This feature may be of interest for growers since lower costs for pruning operations (reductions in work-time) are expected, as well as a better distribution of light interception by the tree canopy.

Fruit set, crop load and yield were unaffected by the RDI strategies considered in this study. In addition, chemical attributes indicated a slight improvement in fruit quality under the RDI treatments. However, carry-over effects from year to year need to be assessed for the long-term. Hence, further experiments are required in order to evaluate the sustainability of the strategies considered in this study as well as to adapt the Ψ_s thresholds to other soil and climate conditions.

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EFFECTS OF REGULATED DEFICIT IRRIGATION ON PHYSIOLOGY, YIELD AND FRUIT QUALITY IN APRICOT TREES

8. EFFECTS OF REGULATED DEFICIT IRRIGATION ON PHYSIOLOGY, YIELD AND FRUIT QUALITY IN APRICOT TREES

Abstract

Scarce water resources mainly in arid and semiarid areas caused an increasing interest for applying irrigation techniques aiming to reduce water spends. The effects of regulated deficit irrigation (RDI) were studied on the performance of 9 year old apricot-trees (*Prunus armeniaca* L. cv. "Búlida") in Murcia (SE Spain), during three consecutive growing seasons (2008-2010). Two irrigation treatments were established: a control treatment, irrigated to fully satisfy crop water requirements (100% ET_c) and an RDI treatment, that reduced the amount of applied irrigation water to: a) 40% of ET_c at flowering and first stage of fruit growth; b) 60% of ET_c during the second stage of fruit growth and c) 50% and 25% of ET_c during the late postharvest period. Stem water potential (Ψ_s), gas exchanges, trunk cross-sectional area, fruit diameter, yield and fruit quality parameters were determined for each treatment. The results indicated that the apricot tree is an appropriate species to apply RDI thanks to the clear separation between its vegetative and reproductive growths and its ability to recover the fruit diameter reduction suffered during RDI application. Furthermore, some qualitative characteristics of the fruits, such as the level of soluble solids, sweetness/acidity relation and fruit colour, are enhanced. These reasons, as well as average irrigation water savings of 33%, emphasize the RDI strategies as a possible solution in areas with water shortages, like the south-eastern region of Spain.

Keywords: fruit growth, photosynthesis; *Prunus armeniaca* L.; regulated deficit irrigation; stomatal conductance; water stress.

8.1. Introduction

The apricot tree (*Prunus armeniaca* L.) is one of the most important fruit species worldwide since its fruit is highly appreciated by consumers (Roussos et al., 2011). Apricot world production is about 2.5 million t per year and Turkey is the leading producing country, according to the Food and Agriculture Organization, with approximately 676,000 t (FAO, 2013). Spain produces about 132,000 t from a cultivation area of 20,000 ha. In the Murcia Region (SE Spain) almost all the cultivated area (≈10,000 ha in 2014) is irrigated. This cultivation area yielded 79,000 t in 2014

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(60% of apricot production in Spain) (MAGRAMA, 2015). The most important Spanish apricot cultivar is "Búlida", which represents 66% of the total production in the Murcia Region (CARM, 2009).

Apricot drought tolerance is mainly based on avoidance mechanisms, such as stomatal control, epinasty and limitation transpiration by reducing leaf area (Ruiz-Sánchez et al., 2000a), together with some degree of osmotic adjustment in young apricot trees although this adjustment is not observed in adult trees (Ruiz- Sánchez et al., 2007). However, apricot trees are highly sensitive to drought stress at particular phenological stages, such as stage III of fruit growth and during the 2 months after harvest (early postharvest) (Torrecillas et al., 2000; Pérez- Pastor et al., 2009).

Mediterranean regions are characterised by the shortage on water resources. This situation is aggravated by the strong competition for water between agriculture and other non-agricultural users like industry or increasing population. It is therefore necessary to develop and implement techniques in order to optimize agricultural water use without affecting crop yields. One of the most promising techniques to attain this objective is the use of Regulated Deficit Irrigation (RDI).

RDI was developed in Australia in peach orchards based on the use of water stress to control vigour and competition for photoassimilates between fruits and other plant organs (Chalmers et al., 1981). This technique consists of applying water in quantities below those necessary to fully satisfy crop evapotranspiration (ET_c) requirements during certain periods of the crop cycle when yield and crop quality are hardly affected, applying all the water needed during the rest of the cycle, especially at critical periods when the yield and/or quality would be greatly affected by a lack of water. RDI is normally applied when reproductive growth is relatively slow and when vegetative growth and other plant processes may be affected, such effects frequently being translated into improved fruit quality (Ruiz-Sanchez et al., 2010).

RDI has been successfully used, maintaining yield and fruit quality, in many fruit species (Buendía et al., 2008; López et al., 2008), citrus species (González-Altozano and Castel, 2000) and olives (Moriana et al., 2010). Researches about RDI strategies applied to apricot trees reported benefits such as higher values of total soluble

solids, titratable acidity and hue angle in apricot fruits grown under RDI (Pérez-Pastor et al., 2009, 2014).

The aim of this paper was to evaluate the effects of RDI on plant-water relations, yield and fruit quality in adult apricot trees (*Prunus armeniaca* L. cv. "Búlida") over three consecutive growing seasons (2008-2010) under the climatic conditions of SE Spain.

8.2. Materials and methods

Description of the study site and plant material

The experiment was conducted over three consecutive years (2008–2010) in a 1-ha plot of a commercial orchard located in Mula valley, Murcia, SE Spain (37°55'N, 1°25'W, 360 m above sea level).
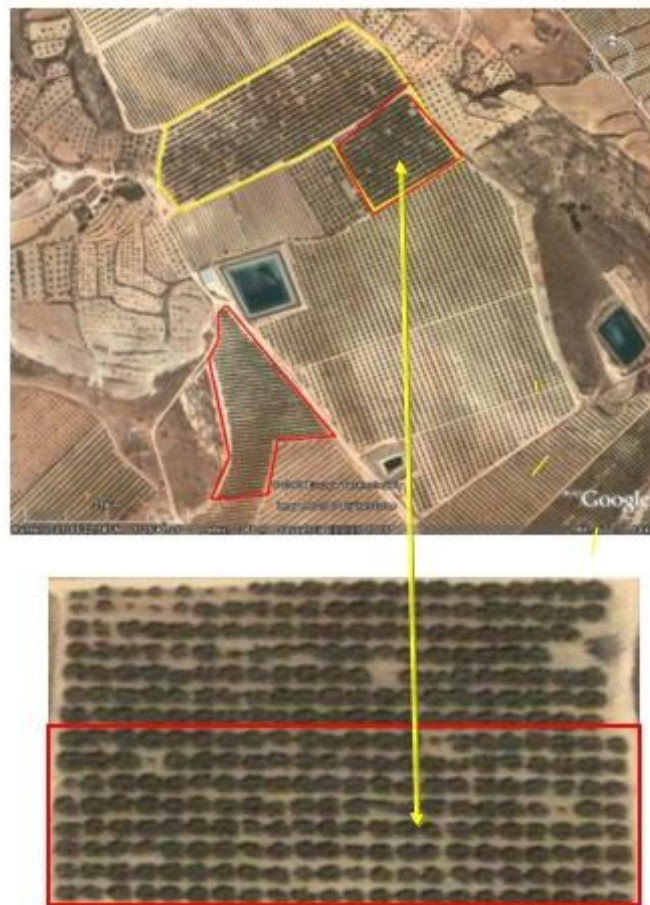
Picture 8.1. Plot location. (Source: Google Maps).

The soil is clay-loam textured and classified as a Xeric Torriorthent (Soil Survey Staff, 1999). It is highly calcareous (pH = 7.8), with low organic matter content and cationic exchange capacity. The available water capacity is about 0.31 m^3 m^{-3}. The climate of the region is semiarid Mediterranean with hot and dry summers; annual evaporation calculated from reference crop evapotranspiration (ET_0) and rainfall during the growing season were, respectively, 1,055 and 318 mm in the first year of experiments (2008), 1,064 and 568 mm in 2009 and 991 and 388 mm in 2010.

The plant material consisted of apricot trees (*Prunus armeniaca* L.cv. "Búlida") grafted on Real fino apricot rootstock, and planted in 1999. Spacings were 8 m x 6 m. Trees were drip irrigated using one drip irrigation line for each row, with five emitters per tree (each delivering 4 L h^{-1}).

Irrigation treatments and experimental design

Crop irrigation requirements were scheduled weekly according to daily ET_0, calculated using the Penman-Monteith equation (Allen et al., 1998), and a local crop factor based on the time of the year (Abrisqueta et al., 2001): 0.5 February, 0.75 March, 0.8 April, 0.9 May, 0.6 June, 0.5 July-November. The correction coefficient for ground cover was obtained according to Fereres and Goldhamer (1990). All trees received the same quantity of nutrients through the irrigation system: 110 kg N, 62 kg P_2O_5 and 117 kg K_2O ha^{-1} $year^{-1}$. Pest control was that commonly used by growers, and no weeds were allowed to develop within the orchard. A total of 192 trees were used in this study. The experiment was laid out in completely randomized blocks with 4 replications (24 trees each). The four central trees from each replication were used for measurements, and the other trees acted as guard.

Two irrigation treatments were applied: i) Control (C), daily irrigated to fully satisfy the estimated crop evapotranspiration (ET_c) and ii) RDI irrigated at 100% ET_c during the critical periods (stage III of fruit growth and 2 months after harvest) and subjected to water shortage during the non-critical periods of crop development by reducing the amount of applied irrigation water to: a) 40% of ET_c from flowering until the end of the first stage of fruit growth; b) 60% of ET_c during the second stage of fruit growth and c) 50% and 25% of ET_c during the late postharvest period (that starts 60 days after harvesting), for the first 30 days and until the end of tree defoliation, respectively (Figure 8.1).

This distribution of applied water during non-critical periods was based on studies by Torrecillas et al. (2000). The irrigation water was considered of good quality with a very low electrical conductivity (0.6 dS m^{-1}).

Irrigation was automatically controlled by a head unit programmer and the amounts of water applied for each irrigation treatment were measured with in-line flowmeters placed in each experimental plot
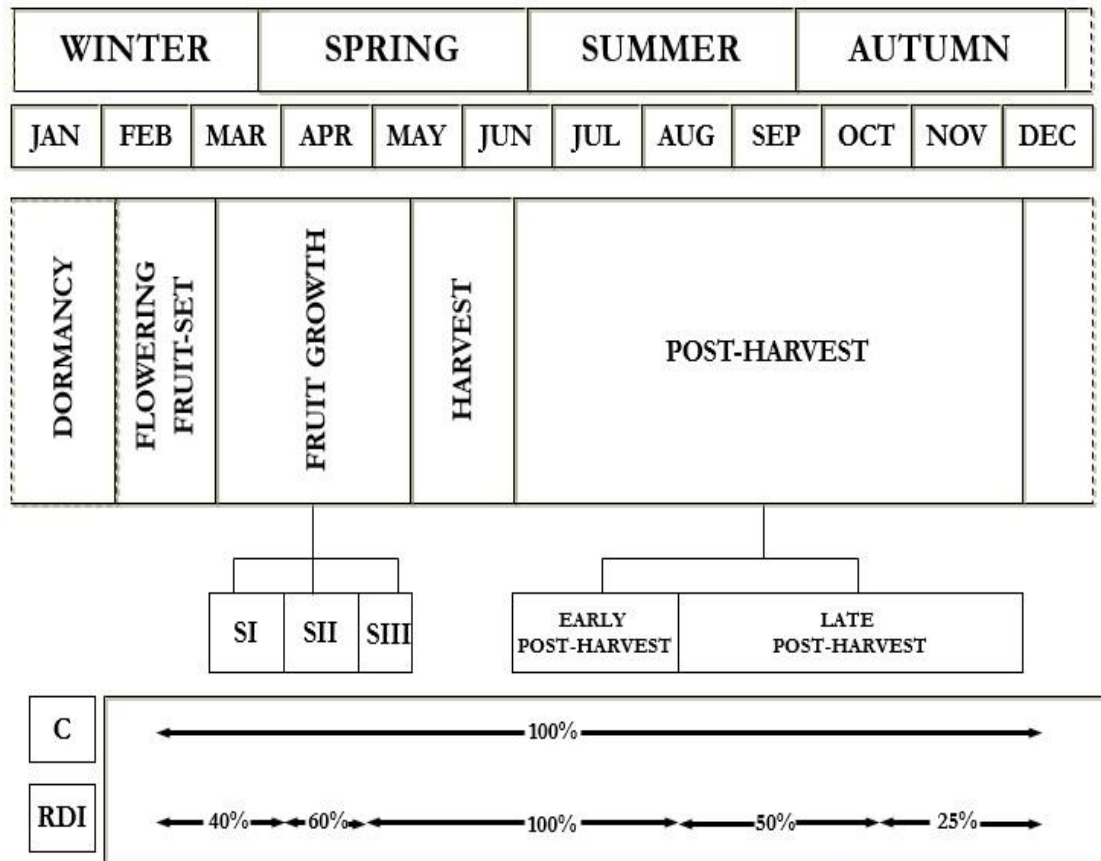
Figure 8.1. Percentages of crop evapotranspiration (ET_c) applied to the regulated deficit irrigation (RDI) treatment for each phenological stage of "Búlida" apricot trees over the experimental period.

Measurements

Climate data

Climate data were recorded at an automatic weather station placed within the experimental orchard. Data on air temperature (maximum, minimum and average), solar radiation, air relative humidity, rainfall and wind speed 2.5 m above the soil surface, were collected every 15 min.

These data were used to calculate ET_0 and to establish crop water requirements. The evolution of these parameters over the study period is shown in figure 8.2.

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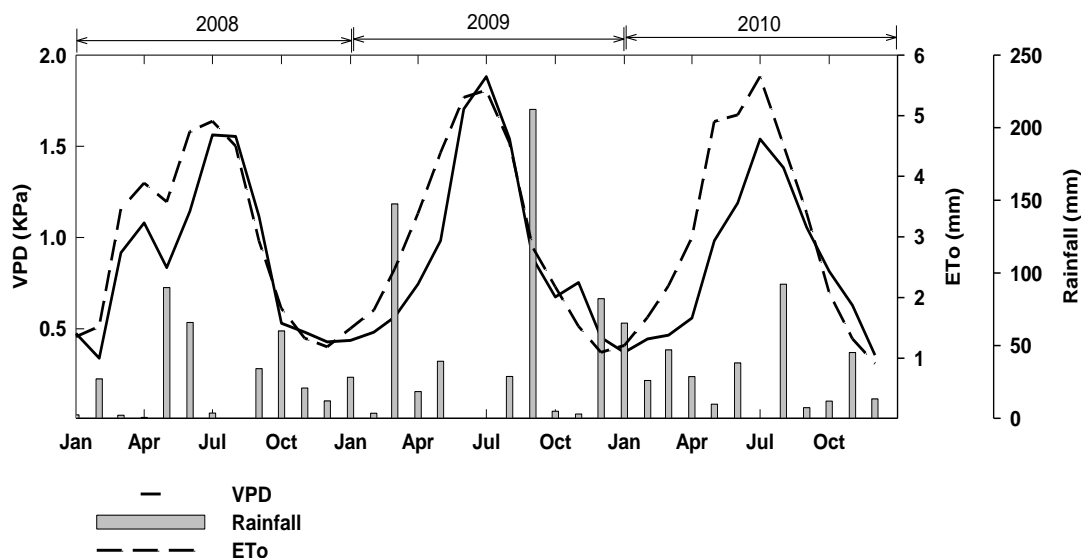
Figure 8.2. Reference evapotranspiration (ET_0), rainfall (mm) and VPD (KPa) at the experimental site. Monthly values from data collected during 2008, 2009 and 2010.

Soil water content

The volumetric soil water content (θ_v, m^3 m^{-3}) of the top 0.2 m 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 1.0 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 from the trees and beside the emitters. These probes were placed at 0.20 m from the emitter and next to TDR rods. Measurements using one neutron probe and TDR per experimental plot (4 replications per treatment) were taken in the morning, every 7 to 15 days, during the experimental period.

Stem and leaf water potential

Midday (12:00 h solar time) stem water potential (Ψ_s) was measured in one mature leaf per plant (4 trees per experimental plot), 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 with a pressure chamber (Soil Moisture Equip. Corp, model 3000, Santa Barbara, CA, USA). Leaf water potential (Ψ_l) was measured in the same trees used for Ψ_s measurements, sampling one mature and sunny-exposed leaf per plant. The water potential measurements were made according to Scholander et al. (1965) and following the recommendations of Turner (1988).

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Gas exchange parameters

Net photosynthesis (P_n) and stomatal conductance (g_s) were measured at solar midday, in one fully expanded sun-facing leaf in the four central trees of each experimental plot per treatment, in the same days that stem water potential was recorded, using a field-portable photosynthesis system (LI-6400, Li-Cor, Lincoln, NE, USA).

Vegetative and fruit growth

Trunk diameter was measured annually during the dormancy stage in 96 trees per treatment with a sliding caliper, 0.20 m above the soil surface. Trunk cross-sectional area (TCSA) was calculated from these data.

Over the growing season, fruit diameter was measured perpendicularly to the fruit suture on 200 fruits per treatment (50 fruits per replication). Each sampling was carried out every 7-10 days, randomly measuring 12-13 fruits in the four inner trees per experimental plot using a digital caliper (Powerfix model Nr Z22855F, Milomex Ltd, Bedfordshire, UK).

Yield and fruit quality

At harvest, 200 fruits per treatment (50 fruits per experimental plot) were randomly selected for quality assessment. Skin and flesh colour, firmness, pH, soluble solids content (SSC) and titratable acidity (TA) were evaluated as quality indices.

Colour values, on the surface (ground skin colour) and after peeling in the flesh, were measured with a Minolta chromameter (CR-300, Minolta, Ramsey, NJ) tristimulus colour analyzer calibrated with a white porcelain reference plate. The colour space coordinates L*, a*, and b*, hue angle [$H^o = arctg (a*/ b*)$], and chroma $(a*^2/ b*^2)^{1/2}$ were determined around the equatorial region in three different positions (with an average of nine times for each apricot).

Picture 8.2. Recently harvested apricots (Own Source).

Picture 8.3. Minolta chromameter (Own Source).

Fruit firmness was evaluated using a Durofel penetrometer DFT100 (Agro-Technologie S.A., Paris, France). Juice was extracted from combined samples of longitudinal unpeeled slices. Total soluble solids concentration (SSC) was determined with a hand-held refractometer (Atago, Co., Japan); and values were expressed as ºBrix. Titratable acidity (TA) was measured by titration of 5 mL of juice with 0.1 mol L^{-1} NaOH to pH 8.1 using an automatic titration system and expressed as g malic acid L^{-1}

(AOAC, 1984). The maturity index was calculated as the SSC TA^{-1} ratio. pH was measured using a pH-meter (Crison, Barcelona, Spain).

Water stress integral and water productivity

In order to evaluate the intensity of water stress, the water stress integral (MPa-days) was calculated from the Ψ_s data according to the following equation (Myers, 1988):

$$S_\Psi = \left| \sum_{i=0}^{i=t} \left(\overline{\Psi}_{i,i+1} - c \right) n \right|$$

where:

$\Psi_{i,i+1}$ (MPa) is the average Ψ_s for each time interval

c (MPa) is the value of the maximum Ψ_s in all seasons

n is the number of days in the interval.

Water productivity was calculated as the ratio between yield and total irrigation water applied (Kijne et al., 2003), expressed in Kg m^{-3}.

Statistical analysis

Statistical analysis was performed as a weighted analysis of variance (ANOVA; statistical software IBM SPSS Statistics v. 21 for Windows, Chicago). The Shapiro–Wilk test was used to evaluate the normality of the data. Tukey's HSD test was used for mean separation. Unless otherwise stated, the significance level was $p \leq 0.05$.

8.3. Results

Soil water content and irrigation

Volumetric soil water content during the 2008-2010 period (Figure 8.3), from 0 to 1 m depth, in the C treatment was nearly constant, with values close to field capacity. In the RDI treatment, θ_v decreased in all phenological periods before stage III of fruit growth, and recovered in this stage and early postharvest, when full irrigation was restored.

During the late postharvest period, the θ_v decreased because of the deficit irrigation applied. The soil moisture profile in the RDI treatment was characterized by the fact that during the water deficit periods, the θ_v values at depths greater than 0.6 m were clearly below field capacity, indicating the non-existence of drainage (data not shown).
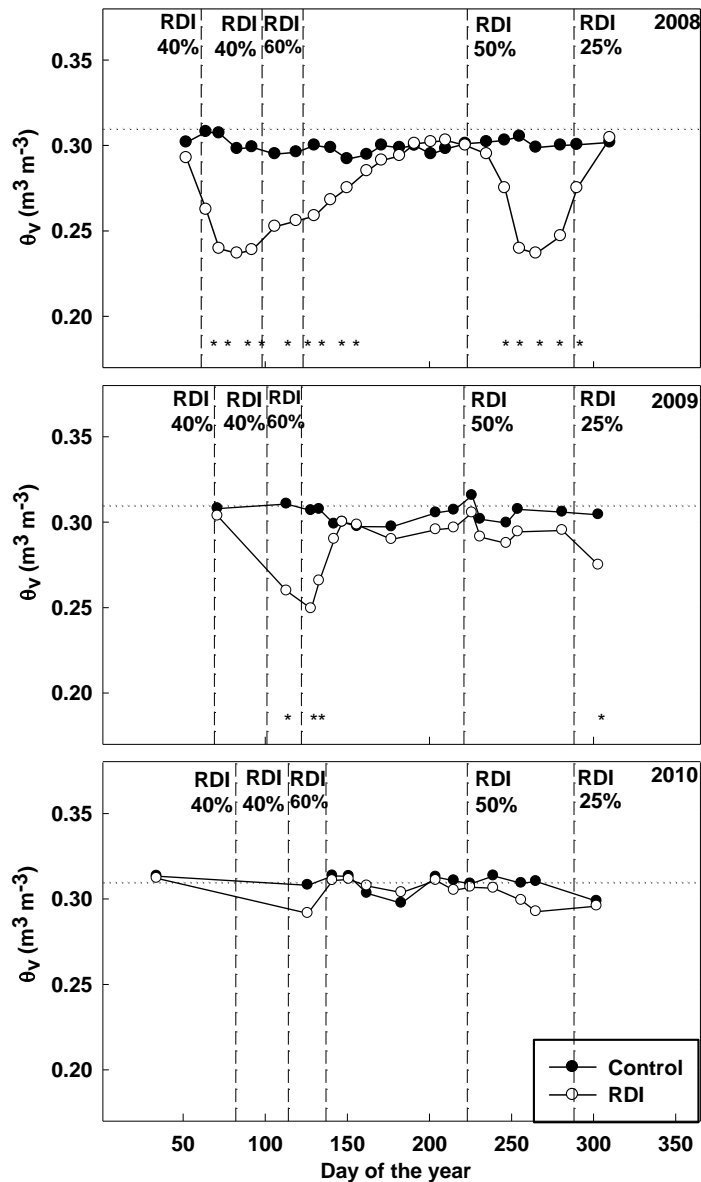
Figure 8.3. Volumetric soil water content down to 1 m depth (θ_v), in C (closed circles) and RDI (open circles) treatments for the three growing seasons studied (2008-2010). Each data point is the mean of four values. Asterisks indicate significant differences between treatments ($p < 0.05$). The intervals between vertical lines from left to right represent the beginning of the different phenological stages for apricot trees during the experimental period. Horizontal lines represent soil field capacity.

Significant differences in θ_v values were observed between treatments during flowering and fruit set, stage I and II and late postharvest until the end of the experiment in 2008; the following year, these differences were only observed in stage II and at the beginning of stage III until the soil water content was recovered due to the restoration of full irrigation in the RDI treatment and in the last point of measurements in late postharvest; during 2010, no significant differences between treatments were detected, although slightly lower soil water contents were measured in stage II of fruit development and early post-harvest stages (Figure 8.3).

The amounts of water applied during the 2008 growing season were 574 and 325 mm in C and RDI, respectively. In 2009, these amounts were 437 and 342 mm, whereas in 2010 they were 520 and 365 mm for C and RDI, respectively (Table 8.1). The average water saved over the three years in the RDI treatment was 57% (flowering and fruit set), 45% (stage I of fruit growth), 41% (stage II of fruit growth) and 56% during late postharvest period. Overall, for the entire growing season, RDI saved 33% water as compared to C.

Table 8.1. Cumulative applied water (mm) during the different stages of fruit growth for the three studied growing seasons, in C and RDI trees.

		Dormancy	Flowering & Fruit set	Stage I	Stage II	Stage III	Early Post-Harvest	Late Post-Harvest	Total
2008	Control	14.17	23.05	35.77	41.52	54.49	219.81	185.19	574.00
	RDI	10.57	8.74	15.65	22.91	48.45	150.19	68.90	325.40
2009	Control	12.15	11.68	11.99	17.70	48.50	189.06	145.93	437.00
	RDI	10.53	5.29	6.57	10.81	45.50	190.09	73.72	342.50
2010	Control	14.13	5.43	15.89	31.42	60.37	153.43	239.73	520.40
	RDI	12.20	3.35	12.52	19.52	57.41	151.36	109.25	365.60
2008-2010	Control	13.49	13.39	21.22	30.21	54.45	187.43	190.28	510.47
	RDI	11.10	5.79	11.58	17.75	50.45	163.88	83.96	344.50
Water Savings (%)		18	57	45	41	7	13	56	33

Plant water relations

The leaf water potential in both treatments was not significantly different in any period, except for isolated dates (five in 2008 and one in 2010) (Figure 8.4). In the second year of experiments (2009), the values of leaf water potential were more negative than those from the first and last years, probably due to higher temperatures, especially in the summer months.

The evolution of Ψ_s showed a decreasing trend in all treatments due to increased climate demand with the advent of warmer months (Figure 8.5). The RDI treatment induced significant reductions in Ψ_s in all the stages during which water deficit was imposed in 2008 and 2009. Nevertheless, during 2010, these differences were only significant in the postharvest period.
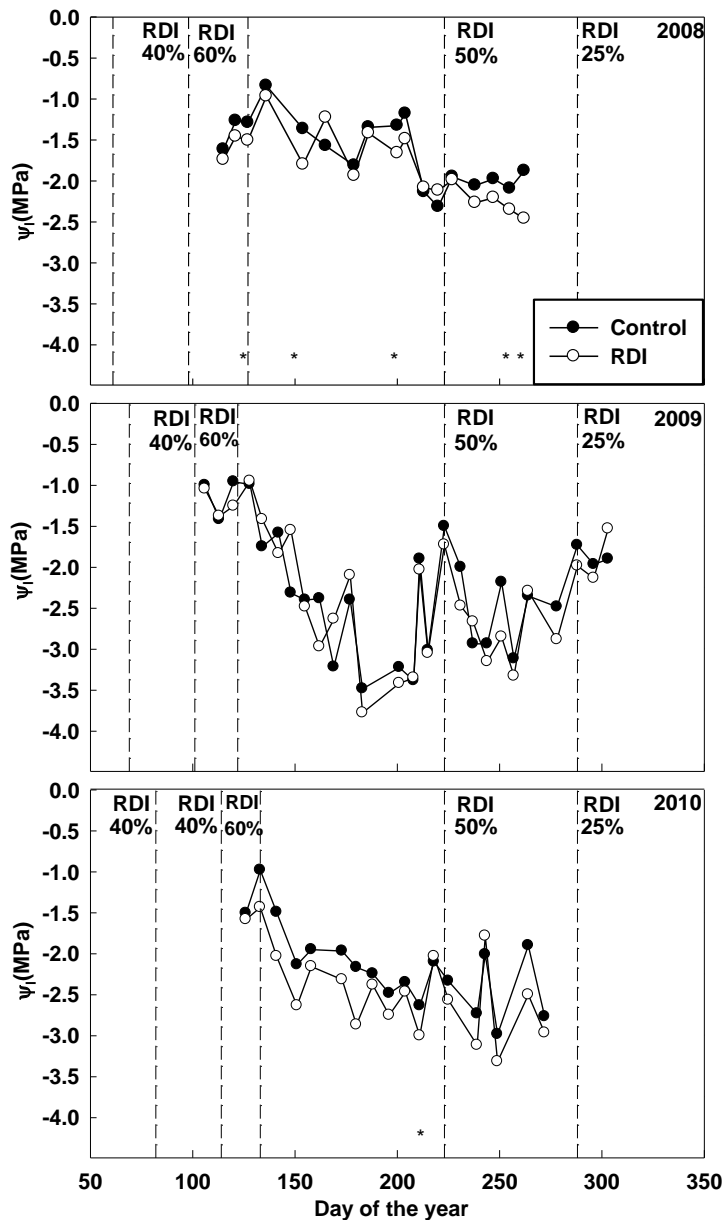
Figure 8.4. Midday leaf water potential in C (closed circles) and RDI (open circles) trees for the three studied growing seasons. Each data point is the mean of sixteen values. The intervals between vertical lines from left to right represent the beginning of the different phenological stages for apricot trees during the experimental period. Asterisks indicate significant differences between treatments ($p < 0.05$).

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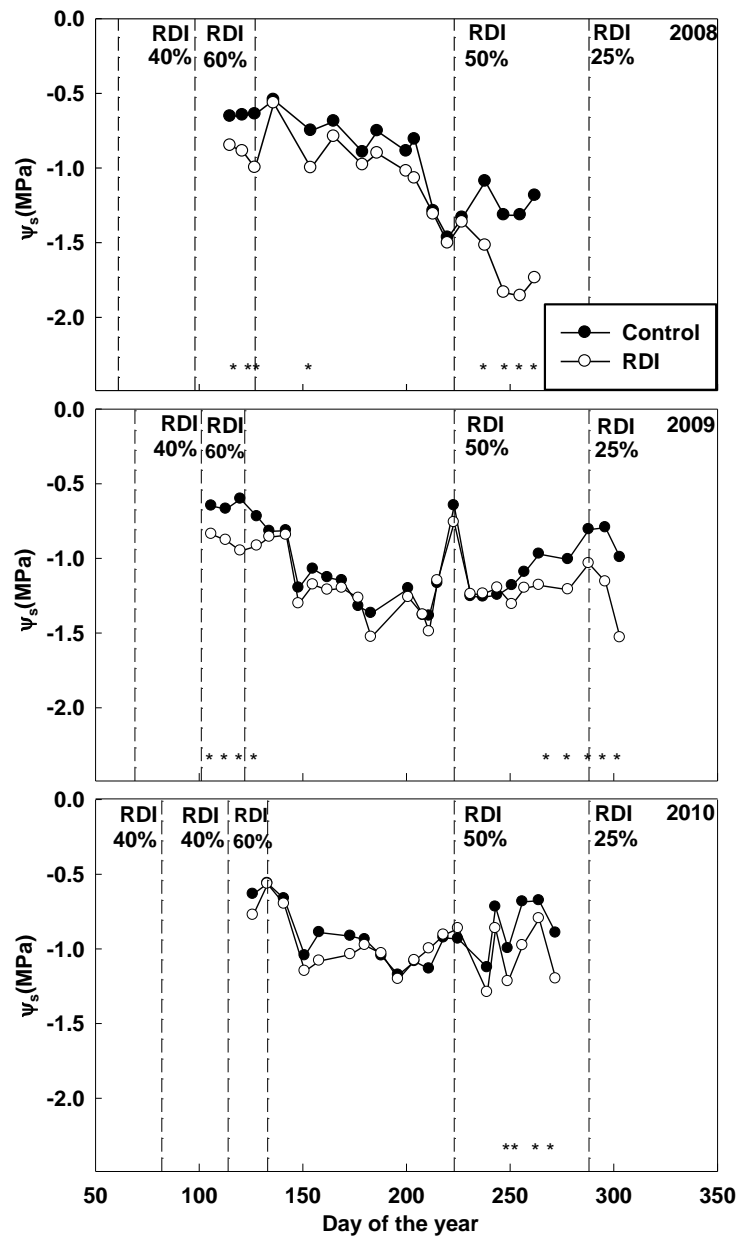
Figure. 8.5. Midday stem water potential in C (closed circles) and RDI (open circles) trees for the three studied growing seasons. Each data point is the mean of sixteen values. The intervals between vertical lines from left to right represent the beginning of the different phenological stages for apricot trees during the experimental period. Asterisks indicate significant differences between treatments ($p < 0.05$).

The RDI treatment induced significant reductions in the average values of midday Ψ_s in all the stages during which water deficit was imposed (Table 8.2). During fruit development, the values of Ψ_s were nearly constant in C treatment and were about –0.64 MPa in stage II. The reduction of Ψ_s in RDI treatment during this stage was significant and about 19% respect to C plants at stage II of fruit development (–0.79

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MPa). During postharvest period, Ψ_s values in C plants were lower due to increased evaporative demand, reaching an average of −1.04 MPa and −1.14 MPa during early and late postharvest periods, respectively.

The decrease of Ψ_s in RDI was significant and about 14% and 30% compared to C plants during the first and second period of late postharvest (−1.33 and −1.39 MPa), respectively. RDI showed the highest values of water stress integral (Figure 8.6), which coincides with the evolution of Ψ_s, with significant differences in 2008.

However, the RDI treatment induced significant reductions in the average values of midday Ψ_l only during stage II and the second period of late postharvest (Table 8.2).
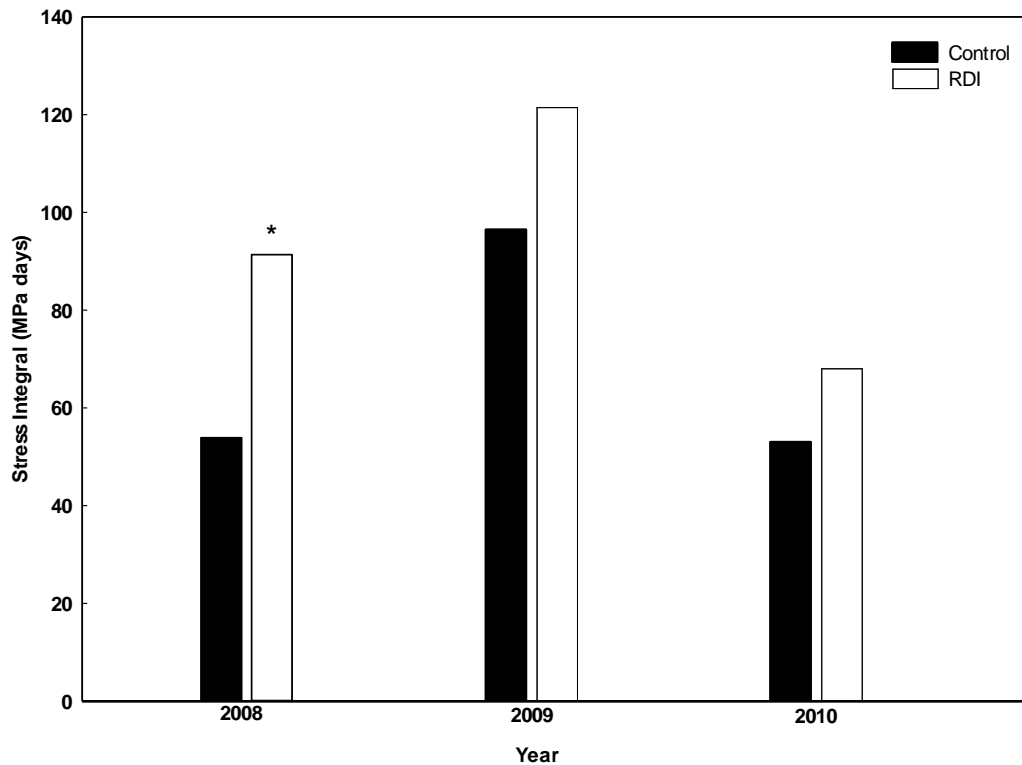
Figure. 8.6. Stress integral values for each irrigation treatment, control (black bars) and RDI (white bars) in the 2008, 2009 and 2010 growing seasons. Asterisks indicate significant differences between treatments ($p < 0.05$).

Similar behaviour to that observed in Ψ_l was also detected for gas exchange parameters during the postharvest period, with a significant reduction in P_n and g_s values only at the end of the second period of late postharvest. The decrease in P_n and g_s for the RDI treatment was 82 and 72%, respectively during this second period of late postharvest.

Table 8.2. Average values of midday stem water potential (Ψ_s, MPa), leaf water potential (Ψ_l, MPa), net photosynthesis (P_n, µmol m^{-2} s^{-1}) and stomatal conductance (g_s, mmol m^{-2} s^{-1}) for each phenological period during the three years of experimental period, in the control (C) and regulated deficit irrigation (RDI) treatments.

	Ψ_s (MPa)			Ψ_l (MPa)			P_n (µmol m^{-2}s^{-1})			g_s (mmol m^{-2}s^{-1})		
2008-2010	**Control**	**RDI**		**Control**	**RDI**		**Control**	**RDI**		**Control**	**RDI**	
Stage I	-0.61	-0.75	*	-1.26	-1.45	ns	10.20	8.10	ns	144.10	107.30	ns
Stage II	-0.64	-0.79	***	-1.24	-1.46	*	8.23	8.12	ns	100.74	92.71	ns
Stage III	-0.85	-0.98	ns	-1.74	-1.86	ns	9.42	9.64	ns	132.60	130.66	ns
Early Post-Harvest	-1.04	-1.10	ns	-2.22	-2.33	ns	6.07	5.14	ns	78.93	59.75	ns
Late Post-Harvest I	-1.14	-1.33	*	-2.40	-2.55	ns	6.71	5.14	ns	89.90	70.01	ns
Late Post-Harvest II	-0.98	-1.39	***	-2.19	-2.48	*	6.00	1.10	***	76.60	22.20	***

Values are the mean of all values in the different stages. ns: non-significant. * $p < 0.05$. *** $p < 0.001$.
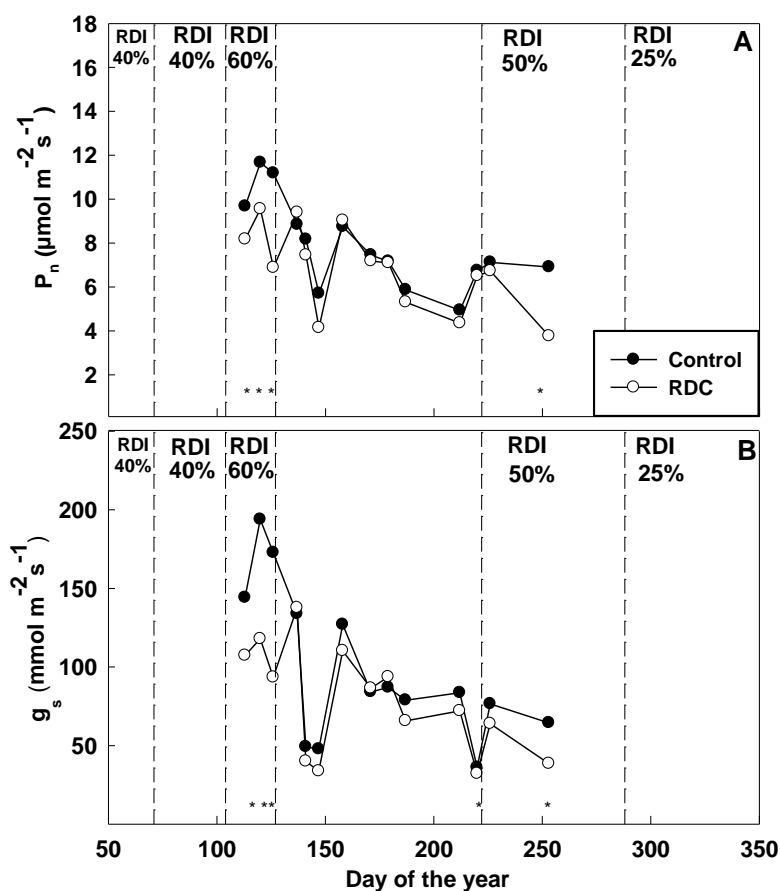
Figure. 8.7. Net photosynthesis (P_n, A) and stomatal conductance (g_s, B) values averaged for the three studied growing seasons in C (closed circles) and RDI (open circles) trees. Each data point is the mean of sixteen values. Asterisks indicate significant differences between treatments ($p < 0.05$). The intervals between vertical lines from left to right represent the beginning of the different phenological stages for apricot trees during the experimental period.

Similar behaviour to that of Ψ_s was also observed for gas exchange parameters averaged for the three growing seasons, with a significant reduction in net

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photosynthesis (P_n) (Figure 8.7A) and leaf stomatal conductance (g_s) (Figure 8.7B) due to water restrictions in the RDI treatment.

When each growing season is separately considered, lower values of both P_n and g_s were detected in all the stages during which water deficit was imposed in 2008. In 2009 and 2010, these differences were only significant for P_n in late postharvest in 2009 (data not shown).

Vegetative and fruit growth

Cumulative shoot growth was limited by water deficit with trees from RDI showing lower values than those observed in the control treatment (data not shown); however, this reduction was not significant. Similarly, no significant differences were observed for TCSA (Table 8.3).

However, fruit growth, measured as fruit diameter, followed a double sigmoid curve with the three characteristic stages of stone fruits (Figure 8.8). Fruits exposed to RDI had a lower but non-significant fruit diameter at the end of stage II of fruit development. When irrigation was restored in the RDI treatment, fruits rapidly reached similar diameter values to those obtained in the C treatment. At harvest, the fruit equatorial diameter was similar in both treatments for the three years.

Yield and fruit quality

No significant differences in yield were observed between treatments for the three growing seasons considered (Table 8.3).

Significantly lower values of fruit set were observed in RDI trees only during 2008. In contrast, water productivity was significantly higher for RDI in the three years considered in this study. Regarding water savings, the percentages were 43, 22 and 30% respect to ET_c (Control) for 2008, 2009 and 2010, respectively.

In relation to fruit quality, fruit firmness decreased significantly (30%) in fruits from the RDI treatment only in 2008, while SSC and maturity index values were significantly increased (8.6 and 18.3%, respectively) in this treatment with respect to C (Table 8.4).

However, there were no significant differences between treatments for pH and TA. In the other two years, no significant differences among treatments were detected in

any parameter with the exception of maturity index in 2009 (12.8% increased under RDI) (Table 8.4).
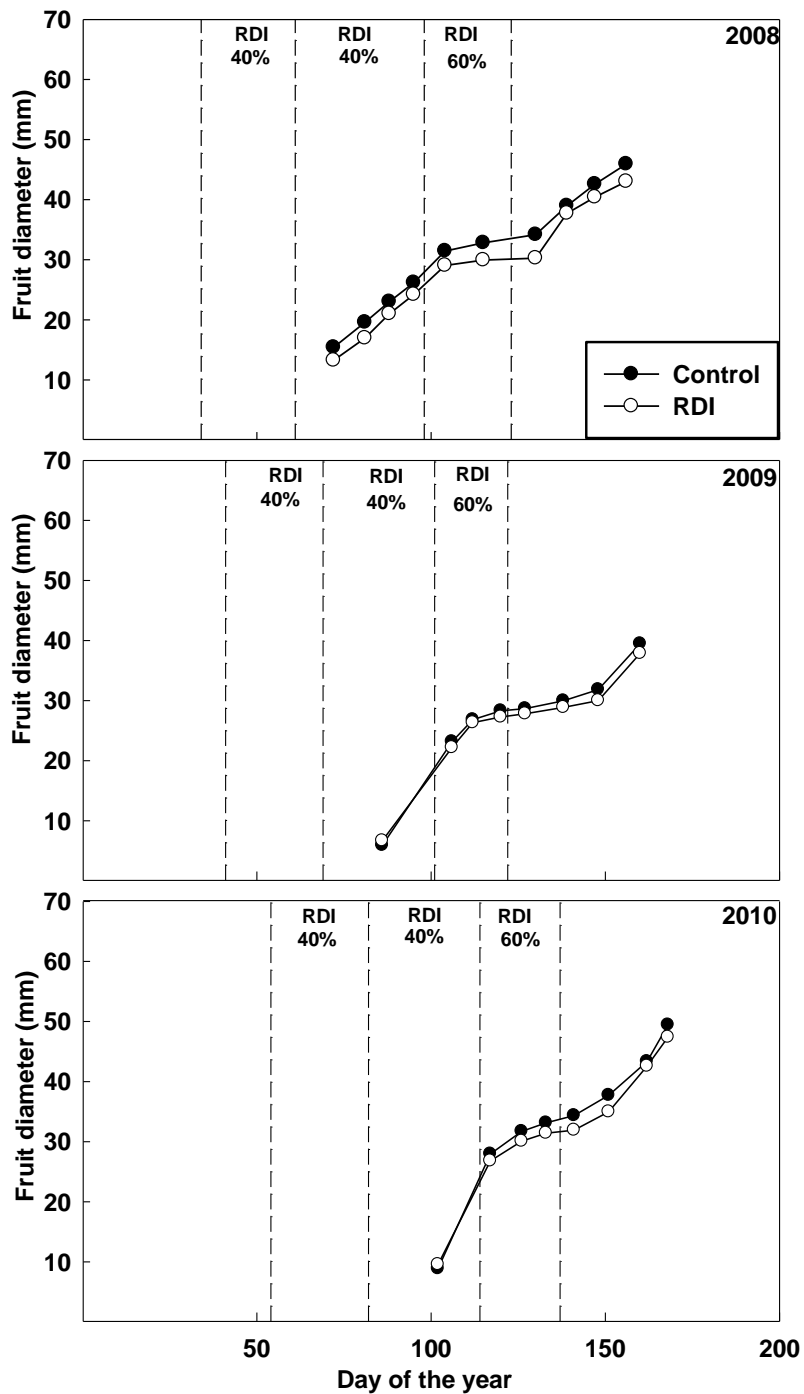
Figure. 8.8. Fruit diameter (mm) evolution in C (closed circles) and RDI (open circles) trees for the three studied growing seasons. Each data point is the mean of 200 values. The intervals between vertical lines from left to right represent the beginning of the different phenological stages for apricot trees during the experimental period.

Table 8.3. Fruit set (%), trunk cross sectional area (TCSA, cm^2), yield (kg tree^{-1}), water productivity (WP, kg m^{-3}) and water savings as a function of the irrigation treatments for the experimental period 2008-2010.

	Fruit set (%)	TCSA (cm^2)	Yield (Kg tree^{-1})	WP (Kg m^{-3})	Water savings (%)
2008					
Control	35.86	308.17	157	5.70	
RDI	19.71	270.88	153	9.79	43
	*	ns	ns	*	
2009					
Control	37.19	345.45	104	4.96	
RDI	38.46	301.33	106	6.45	22
	ns	ns	ns	*	
2010					
Control	45.97	375.88	92	3.68	
RDI	41.31	311.88	89	5.07	30
	ns	ns	ns	*	
2008-2010					
Control	39.67	343.17	118	4.78	
RDI	33.16	294.68	116	7.10	33
	ns	ns	ns	*	

Values are the mean of 160 (fruit set), 96 (TCSA) and 16 measurements (yield). ns: non-significant. * $p < 0.05$.

The analysis of the colour values showed that the lightness factor, $L*$, in flesh was similar for both treatments during the three years (Table 8.5). However, in the skin significantly higher values were observed for the RDI treatmet in 2009 and 2010.

The hue angle (H^o) in skin and flesh was significantly higher in the fruits from the RDI treatment during 2008, whereas it was significantly greater for skin in 2009 and for the flesh in 2010. Respect to chroma ($C*$), the fruits from the RDI treatment showed significantly higher values in both skin and flesh than those from C during 2008 and 2009. These differences were not significant in 2010.

Table 8.4. Fruit firmness (N), pH, soluble solids content (SSC, ºBrix), tritratable acidity (TA, g 100 mL^{-1}) and SSC/TA ratio at harvest as a function of the treatment for the three experimental seasons.

	Firmness (N)	pH -	SSC (ºBrix)	TA (g 100 ml^{-1})	Maturity Index (SSC/TA)
2008					
Control	52.90	3.71	9.47	1.07	9.02
RDI	36.50	3.75	10.28	0.98	10.67
	**	ns	*	ns	**
2009					
Control	52.53	3.60	10.56	1.21	8.81
RDI	49.39	3.62	11.28	1.17	9.94
	ns	ns	ns	ns	***
2010					
Control	69.97	3.94	10.33	0.96	10.89
RDI	71.83	3.94	10.53	0.95	11.15
	ns	ns	ns	ns	ns
2008-2010					
Control	58.47	3.75	10.12	1.11	9.38
RDI	52.57	3.77	10.70	1.06	10.42
	ns	ns	*	ns	***

Values are the mean of 200 measurements. ns: non-significant. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Table 8.5. Skin and flesh fruit colour values (reflectance measurements L^*, H^o, C^*) at harvest in the control (C) and regulated deficit irrigation (RDI) treatments, for the three experimental seasons.

		L^*		H^o		C^*	
		Skin	Flesh	Skin	Flesh	Skin	Flesh
2008	**Control**	67.1	62.6	78.8	78.6	48.1	44.7
	RDI	69.2	63.9	85.3	82.9	50.6	46.6
		ns	ns	**	**	**	*
2009	**Control**	64.7	61.4	71.6	72.5	44.5	41.2
	RDI	66.1	61.7	77.1	73.0	47.9	43.9
		***	ns	***	ns	***	***
2010	**Control**	62.7	59.6	65.4	65.6	43.4	40.0
	RDI	63.8	59.5	67.3	63.2	44.2	40.8
		*	ns	ns	***	ns	ns
2008-2010	**Control**	64.8	61.2	71.9	72.2	45.3	42.0
	RDI	66.4	61.7	76.6	73.0	47.6	43.8
		***	ns	***	ns	***	***

L^*: lightness factor. H^o: Hue value. C^*: colour intensity (chroma). Values are the mean of 200 measurements. ns: non-significant. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

8.4. Discussion

The amount of water applied in the C treatment maintained high values of θ_v, close to field capacity, indicating that plants under this treatment did not suffer from water deprivation (Figure 8.3). Similar values were measured in the RDI treatment during periods of full irrigation, being the drainage low in both treatments indicating that a suitable irrigation scheduling in C treatment was applied (Abrisqueta et al., 2001). Soil water profiles for the deficit irrigation treatment presented a high degree of uniformity respect to C, from the end of April to the beginning of August. During the phenological periods of water deficit in the RDI treatment, θ_v decreased significantly, reaching values which caused stress conditions for apricot trees (Ruiz-Sánchez et al., 2000b), especially in 2008. The higher spring rainfall amount caused that in 2010 no differences were observed between treatments during flowering and fruit set, stage I and stage II of fruit development.

The annual water savings averaged 33% for the three-year study period and were in accordance with those reported by Pérez Pastor et al. (2009) and Pérez-Sarmiento et al. (2010) for the same cultivar. Although Pérez-Pastor et al. (2009) observed significant reductions in plant production, in our case yield was similar between treatments for the three years of the study (Table 8.3). This aspect can be explained by the highest water reductions designed by Pérez-Pastor et al. (2009) during fruit development in the initial two years (75% until the end of stage II) in contrast with our experimental conditions (50%), which were based on the last two years designed by those authors (Figure 8.1). Apart from this, the RDI treatment was more efficient than the control, as observed from the values of water productivity. These results are in agreement with those indicated by other authors for different fruits under water deficit conditions (e.g. Romero et al., 2004; Perez-Pastor et al., 2009).

Water savings during fruit development did not affect fruit growth in the RDI treatment, since fruits from this treatment had a slightly lower but non-significant fruit diameter at the end of the stage II of fruit development, which were more marked in 2008 (Figure 8.8). When irrigation was restored in the RDI treatment, a compensatory fruit growth was observed which allowed the fruit to reach a similar diameter to fruits from the C treatment (Chalmers et al., 1986) and at harvest apricot fruits were of «extra» size in both treatments (> 40 mm in diameter). This can be explained by the fact

that fruits act as strong sinks of photosynthates, which become available when irrigation is restored, promoting higher fruit growth rates (Torrecillas et al., 2000). This behaviour has been observed in other stone fruit trees such as peach (Mitchell and Chalmers, 1982). This compensatory fruit growth during a recovery period of water deficit and the relative separation between shoot and fruit growth periods in apricot plants (Torrecillas et al., 2000) are essential for the successful application of RDI strategies (Goldhamer, 1989), indicating that deficit irrigation may be applied to limit shoot growth without detrimental effects on fruit growth and yield (Chalmers et al., 1981; Mitchell and Chalmers, 1982).

Our results showed that stress imposed did not significantly reduce vegetative growth (data not shown) and TCSA compared to trees under full irrigation conditions. The reduction of vegetative growth is of great interest for controlling canopy size and for reducing the costs associated with specific agricultural practices (Ruiz-Sánchez et al., 2010), such as pruning.

Although plant water status (Ψ_s and Ψ_l) and gas exchange (P_n and g_s) parameters were affected by the RDI treatment, not all these discontinuous water stress indicators performed in the same way. Thus, only Ψ_s reflected well the effects on plant water status of the different water restrictions even under mild levels of water deficit associated with low VPD (stage I of fruit growth) (Table 8.2). For this reason, the use of Ψ_s has been adopted for irrigation scheduling because of its high sensitivity to water deprivation (Remorini and Massai, 2003) and its good prediction of the yield response to deficit irrigation (Intrigliolo and Castel, 2006). The remaining water stress indicators (Ψ_l, P_n and g_s) depend more on the meteorological conditions (Ruiz-Sánchez et al., 2004) and in our case only presented significant differences when the water reductions in RDI treatment were very high with respect to the C treatment (25% ET_c).

Despite being higher in the deficit treatment over the 3 years, the values of S_ψ were only significant in 2008. Pérez-Pastor et al. (2014) confirmed that RDI led to yield reductions when water deficits were severe (>140 MPa-days of water stress integral) during non-critical periods. The maximum value obtained in the current study was, approximately, 120 MPa-days. For this reason, reductions in yield might have not been detected in our experiment.

One of the benefits of RDI is an improvement in fruit taste and quality due to the increasing in SSC (Mpelasoka et al., 2000; López et al., 2011). In the present study, SSC values increased in all years for the RDI treatment although this difference was significant only in 2008. No differences were found in pH and tritratable acidity. Our data showed a similar fruit hardness in both treatments, with the exception of 2008, indicated by the significant differences in firmness. Higher ratios of SSC/TA (maturity index) were observed for RDI during the three years, being significant in 2008 and 2009. This ratio affects taste perception (sweetness and acidity) by the consumer, thereby influencing buying decisions (Scandella et al., 1997). Thus, fruits from the RDI treatment can be considered of high quality since SSC increased without affecting acidity (Scandella et al., 1997).

These significant differences in fruit quality were in accordance with the previous figures in which no differences were observed neither in yield, or reproductive and vegetative growth, although the average water savings were close to 40% in the RDI treatment. These savings and the absence of impacts on fruits and trees reinforce the idea that the irrigation strategy used is optimal from an environmental and economic standpoint.

As for other parameters of fruit quality, lightness factor was significantly affected by RDI in 2009 and 2010 only for fruit skin. The H^o has been described as a suitable and intuitively understandable colour index (Arias et al., 2000). The increase in this parameter in apricot fruits from RDI plants can be associated to a reduction in carotenoids accumulation attributed to the oxidation by exposure to light (Ruiz et al., 2005). This exposure to light in the fruits from the RDI treatment is usually related to a significant reduction in the vegetative growth of the trees during fruit development (Gelly et al., 2003; Buendía et al., 2008).

In summary, the results indicated that the apricot tree is an appropriate species to apply RDI because of its clear separation between vegetative and reproductive growths and its ability to recover the fruit diameter reduction suffered during RDI application. Furthermore, some qualitative characteristics such as the level of soluble solids, fruit taste and the colour of the fruit are enhanced. These reasons, together with average water savings of 33%, emphasize the RDI strategies as a possible solution in areas with water shortage, like the south-eastern region of Spain.

Acknowledgements

8.5. References

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CONCLUSIONES/CONCLUSIONS

9. Conclusiones

Conclusiones generales

A) Las ecuaciones de referencia realizadas con las medidas de la máxima contracción diaria (MCD) en melocotoneros adultos fueron dependientes de las variables climáticas usadas, la etapa fenológica del cultivo, así como de su carga productiva. Por tanto, estos factores deben tenerse en cuenta para ser utilizadas en la programación automática del riego por parte de los productores.

B) El riego deficitario controlado (RDC) fue programado con éxito utilizando la intensidad de la señal de la MCD (IS_{MCD}) en melocotoneros adultos. Además, estos valores de IS_{MCD} han demostrado su utilidad para poder determinar de manera precisa las necesidades hídricas de este cultivo.

C) El potencial hídrico de tallo a mediodía ha demostrado ser un indicador en planta del estado hídrico adecuado para poder establecer una programación del RDC en melocotonero adulto, a pesar de que sus medidas no pueden ser automatizadas.

D) Las estrategias de RDC utilizadas en el presente estudio han demostrado su utilidad para ahorrar agua (más del 30% comparado con el riego al 100% de la ET_c), sin comprometer el rendimiento tanto en melocotonero como en albaricoquero. Por lo tanto, esta estrategia de riego podría suponer una solución para áreas con infradotación hídrica como es el caso del sureste español.

Conclusiones parciales

1) Las medidas de las fluctuaciones de la MCD, estuvieron mejor relacionadas con la temperatura máxima y al mediodía que con otras variables meteorológicas durante el crecimiento del fruto y, con el DPV durante el período de post-cosecha. Sin embargo, estas relaciones estuvieron muy influenciadas por las condiciones de cada año, el estado fenológico del cultivo y la carga productiva en melocotonero.

2) No se detectó una relación única entre MCD y Ψ_t que fuera válida para todo el periodo, sino que esta relación varió cada año durante el período de crecimiento del fruto, mientras que en postcosecha las relaciones obtenidas fueron similares entre años.

3) La ET_0 diaria mostró una baja correlación con los registros de la MCD, sugiriendo que para especies leñosas, la ET_0 puede no ser el mejor criterio para determinar los requerimientos hídricos del cultivo utilizando estas ecuaciones de referencia.

4) La aplicación de estrategias de programación del riego en melocotonero a partir de valores umbrales de la IS_{MCD} fue llevada a cabo con éxito. En este sentido, la programación del RDC no afectó la producción ni la calidad de la cosecha. Además, la reducción del crecimiento vegetativo observado se puede considerar beneficiosa ya que permite la entrada de luz en el interior del árbol y además reduce el tiempo de poda, con el consiguiente ahorro económico para el agricultor.

5) La programación del riego realizada manteniendo los valores de IS_{MCD} cercanos a la unidad durante todo el período de cultivo nos permite cuantificar los requerimientos hídricos del cultivo y determinar, de esta manera, el coeficiente de cultivo (K_c) en melocotonero.

6) Las estrategias de RDC utilizadas en este estudio fueron capaces de reducir el agua aplicada entre un 43-65% sin afectar la producción, aumentando así la productividad del agua. Estos resultados confirmaron la posibilidad de programar el riego basándose en medidas de IS_{MCD}. Sin embargo, la sostenibilidad de estos resultados debe ser estudiada a medio-largo plazo.

7) La aplicación de estrategias de programación del riego en melocotonero a partir de valores umbrales de Ψ_t fue llevada a cabo con éxito. En este sentido, la programación del RDC no afectó la producción ni la calidad de la cosecha. y constituyen una opción viable para ahorrar agua sin comprometer la producción.

8) Desde el punto de vista de la sostenibilidad de los recursos hídricos, la programación del RDC en base a valores umbrales de Ψ_t permitió reducir de media los aportes hídricos en un 55%, para los tres años estudiados. Sin embargo, estos ahorros fueron dependientes del valor umbral de Ψ_t utilizado, los cuales deben estudiarse más a fondo con el fin de adaptarlos a las condiciones específicas del lugar donde van a ser utilizados.

9) El albaricoquero es una especie adecuada para aplicar estrategias de RDC debido a su clara separación entre crecimientos vegetativo y reproductivo y su capacidad para recuperar la reducción del diámetro de fruto sufrida durante la aplicación de esta estrategia de riego.

10) La producción no se vio afectada significativamente por el RDC impuesto, mientras que los parámetros de calidad mejoraron, especialmente el índice de madurez, el cual afecta a la percepción del gusto y puede influir en las decisiones de compra de los consumidores.

11) La aplicación del protocolo de RDC aplicado supuso un ahorro medio de agua del 33%, durante el período de estudio, lo que demuestra que esta estrategia de riego puede ser una alternativa viable en áreas con escasez hídrica, como es el caso de las condiciones semiáridas del sureste de España.

9. Conclusions

General conclusions

A) Reference equations established using maximum daily trunk shrinkage (MDS) measurements for adult peach trees were dependent on the climate variable used, crop phenological stages as well as crop load. Therefore, these factors must be accounted for by growers when using these equations for automated irrigation scheduling.

B) Regulated deficit irrigation (RDI) was successfully sheduled using MDS signal intensity (MDS SI) in adult peach trees. Moreover, these MDS SI values proved useful for precisely estimating peach water requirements.

C) Midday stem water potential proved to be an adequate plant-based water status indicator to establish RDI schedulings in adult peach trees, although its measurements cannot be automated.

D) The RDI strategies used in the current study proved useful for saving water (more than 30% water when compared to irrigation to the 100% ET_c) without compromising yield in both apricot and peach trees. Therefore, this irrigation strategy could be a solution in areas with water shortage, such as the south-eastern region of Spain.

Partial conclusions

1) The MDS fluctuations measured were better related to midday and maximum temperature than to other meteorological variables during fruit growth; and to VPD during the postharvest period. However, these relationships were greatly affected by the conditions of each year, tree phenological stage and crop load in adult peach trees.

2) There was not a single unique relationship between MDS and Ψ_s that was valid for the whole period, but this relationship varied each year during the period of fruit growth, while at postharvest, the relations obtained were similar between years.

3) Daily ET_0 showed the poorest correlation with the MDS records suggesting that, for woody species, ET_0 would not be the best criterium for determining crop water requirements by using reference equations.

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4) The feasibility of rrigation scheduling in peach based on the MDS SI thresholds was demonstrated. In this sese, the irrigation scheduling used in this study did not affect yield and fruit quality. In addition, the reduction of vegetative growth observed under the RDI strategy can be considered beneficial because it allows light to enter inside the tree and reduce pruning time, with the consequent economic savings for the farmer.

5) The irrigation strategy of maintaining MDS SI values close to unity during peach crop growth allowed for quantifying crop water requirements and thus to determine the crop factor (K_c) for peach

6) The RDI strategies employed in this study were able to reduce the seasonal water applied around 43-65% without affecting yield components and thus increasing water productivity. These results confirmed the possibility of irrigation scheduling based on MDS SI. Nevertheless, sustainability of these results must be studied at the medium-long term.

7) The irrigation scheduling strategies application in peach from Ψ_s threshold values was carried out successfully. In this sense RDC scheduling did not affect the production and quality of the harvest and constitute an option viable to save water without compromising production.

8) From the sustainability of water resources viewpoint, RDI scheduling based on Ψ_s thresholds, allowed to reduce water consumption around 55%, in average for the three studied years. However, these water savings were dependent on the Ψ_s threshold used, which must be further explored in order to adapt them to the specific conditions of the site where they will be used.

9) Apricot tree is an appropriate species to apply RDI because of its clear separation between vegetative and reproductive growths and its ability to recover the fruit diameter reduction suffered during RDI application.

10) Fruit yield was not significantly affected by the RDI imposed, whereas fruit quality attributes improved, especially the maturity index which affects taste perception and may influence consumer's buying decisions.

11) The RDI protocol applied supposed average water savings of 33%, during the study period, indicated that the RDI strategy used in the current experiment may be a solution in areas with water shortage, such as the semi-arid conditions of the southeast of Spain.

ANEXOS/ANNEXES

10. Anexos/Annexes

Effects of regulated deficit irrigation on physiology and fruit quality in apricot trees

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Abstract

The effects of regulated deficit irrigation (RDI) were studied on 9 year-old apricot-trees (*Prunus armeniaca* L. cv. 'Búlida') grafted on 'Real Fino' rootstock. Two irrigation treatments were established. The first, a control treatment, was irrigated to fully satisfy the crop water requirements (100% ETc) and the second, a RDI treatment, was subject to water shortage during the non-critical periods of crop development, by reducing the amount of applied irrigation water to: a) 40% of ETc from flowering until the end of the first stage of fruit growth; b) 60% of ETc during the second stage of fruit growth and c) 50% and 25% of ETc during the late postharvest period (that starts 60 days after harvesting), for the first 30 days and until the end of tree defoliation, respectively. The results indicated that the apricot tree is an appropriate species to apply RDI thanks to the clear separation between their vegetative and reproductive growths and its ability to recover the fruit diameter reduction suffered during RDI application. Furthermore, some qualitative characteristics such as the level of soluble solids, fruit taste and the colour of the fruit are enhanced. These two reasons, together with irrigation water savings of 39%, emphasize the RDI strategies as a possible solution in areas with water shortages, like the south-eastern region of Spain.

Additional key words: fruit growth, photosynthesis; *Prunus armeniaca* L.; regulated deficit irrigation; stomatal conductance; water relations; water stress.

Resumen

Efectos del riego deficitario controlado sobre la fisiología y la calidad de fruto en albaricoquero

Se estudiaron los efectos de estrategias de riego deficitario controlado (RDC) sobre albaricoqueros de 9 años de edad (*Prunus armeniaca* L. cv. 'Búlida') injertados sobre patrón franco de 'Real Fino'. Para ello, se establecieron 2 tratamientos de riego, uno de riego control, que se regó satisfaciendo los requerimientos hídricos del cultivo (100% ETc) y un tratamiento de RDC, que consistió en reducir los aportes de agua con respecto a la ETc en los períodos no críticos en este cultivo: a) 40% de la ETc desde floración hasta el final de la primera fase de crecimiento del fruto; b) 60% de la ETc durante la segunda fase de crecimiento del fruto y c) 50% y 25% durante la post-cosecha final (60 días después de recolección), diferenciando 2 períodos de 30 días, el primero al 50% de la ETc, y otro hasta la caída de hojas al 25% de la ETc. Los resultados obtenidos indican que el albaricoquero es una especie adecuada para realizar estrategias de RDC, debido principalmente a la clara separación entre el crecimiento vegetativo y reproductivo y, también al efecto de crecimientos compensatorios que se producen en los frutos que han estado bajo RDC, lo cual hace que finalmente no se produzcan mermas significativas de calibre. Además, ciertas características cualitativas, como el nivel en sólidos solubles, sabor y coloración de la fruta, se ven incrementadas. Estas dos razones, junto con ahorros de agua vía riego, del 39%, conducen a que estrategias de RDC puedan suponer una clara alternativa en zonas con infradotación hídrica, como es el sureste español.

Palabras clave adicionales: conductancia estomática; crecimiento del fruto; estrés hídrico; fotosíntesis; *Prunus armeniaca* L.; relaciones hídricas; riego deficitario controlado.

Introduction

Apricot trees (*Prunus armeniaca* L.) are widely cultivated in Mediterranean countries, with the Murcia Region being Spain's leading apricot producer with an average annual yield in the last few years of about 85,000 tonnes of apricots, from a cultivation area of 10,500 ha (MARM, 2009); these figures represent ~66% and ~60% of the Spanish total apricot production and cultivation area of apricots, respectively. The most important cultivar of apricot in Spain is 'Búlida', which represents ~50% and ~66% of the total production of apricots in Spain and the Murcia Region, respectively (CARM, 2009).

Apricot trees are highly sensitive to drought stress at particular phenological stages, such as stage III of fruit growth and during the 2 months after harvest (early postharvest) (Torrecillas *et al.*, 2000; Pérez-Pastor *et al.*, 2007, 2009). Apricot drought tolerance is mainly based on avoidance mechanisms, such as stomatal control, epinasty and limitation transpiration by reducing leaf area (Torrecillas *et al.*, 1999; Ruiz-Sánchez *et al.*, 2000a), together with some degree of osmotic adjustment in young apricot trees although this adjustment is not observed in adult trees (Ruiz-Sánchez *et al.*, 2007).

Regulated deficit irrigation (RDI) is the practice of reducing applied water at selected phenological stages less sensitive to water deficit, thus imposing plant water stress in a controlled manner, and can be a feasible water saving practice for arid areas with a minimum impact on yield and fruit quality (Chalmers *et al.*, 1981; Goldhammer, 1989; Naor, 2006). The success of RDI strongly depends on the appropriate use of microirrigation techniques, which allows the control of soil water content (Dichio *et al.*, 2007). RDI has been used successfully maintaining yield and fruit quality in many fruit species (Ebel *et al.*, 1995; Girona *et al.*, 2003; Buendía *et al.*, 2008; López *et al.*, 2008), nut species (Goldhamer *et al.*, 2000; Goldhamer and Beede, 2004; Romero *et al.*, 2004; Girona *et al.*, 2005) citrus species (Sánchez-Blanco *et al.*, 1989; Castel and Buj, 1990; Domingo *et al.*, 1996; González-Altozano and Castel, 1999, 2000; Goldhamer and Salinas, 2000), wine grapes (Bravdo and Naor, 1996; McCarthy *et al.*, 2002) and olives (Moriana *et al.*, 2003). The most important research studies related to the application of RDI strategies in apricot trees has been done by Ruiz-Sanchez *et al.* (1999, 2000b, 2004, 2007), and Pérez-Pastor *et al.* (2004, 2007, 2009). These authors have found benefits such as higher values of total soluble solids, tritratable acidity and hue angle in apricots obtained from RDI strategies (Pérez-Pastor *et al.*, 2007).

The aim of this paper was to evaluate the effect of RDI on plant-water relations, yield and fruit quality in adult apricot trees (*Prunus armeniaca* L. cv. 'Búlida'). The RDI treatment was scheduled to reduce water applications during non-critical periods, satisfying the crop water requirements during the critical periods, which corresponded to the second rapid fruit growth period (stage III) and the early postharvest period (Pérez-Pastor *et al.*, 2009).

Material and methods

Experimental conditions and plant material

The experiment was performed during 2008, in a 1-ha plot of a commercial orchard, located in Mula valley, Murcia, Spain (37°55' N, 1°25' W, 360 m above sea level). The soil is a clay-loam texture and classified as a Xeric Torriorthent. It is highly calcareous, has a pH of 7.8, and a low organic matter content and cationic exchange capacity. The available water capacity is about $0.31 \ m^3 \ m^{-3}$. The climate is semiarid Mediterranean with hot and dry summers; annual evaporation calculated from reference crop evapotranspiration (ET_0) and rainfall was 1,055 and 318 mm, respectively.

The plant material consisted of 9-year-old apricot trees (*Prunus armeniaca* L. cv. Búlida, on Real Fino apricot rootstock), spaced 8×6 m, with an average height of 3.9 m, trunk diameter of 0.19 m, and ground cover of about 65%. Trees were drip irrigated using one drip irrigation line for each row, with five emitters per tree, each with a flow rate of 4 L h^{-1}.

Crop irrigation requirements were scheduled weekly according to daily ETo, calculated using the Penman-Monteith equation (Allen *et al.*, 1998), and a local crop factor based on the time of the year (Abrisqueta *et al.*, 2001): 0.5 February, 0.75 March, 0.8 April, 0.9 May, 0.6 June, 0.5 July-November. The correction coefficient for ground cover was 1 according to Fereres and Goldhmaer (1990). All trees received the same quantity of nutrients through the irrigation system: 110 kg N, 62 kg P_2O_5 and 117 kg K_2O ha^{-1} $year^{-1}$. Pest control was that commonly used by growers, and no weeds were allowed to develop within the orchard.

A total of 192 trees were used in this study. The experimental design of each irrigation treatment was

4 standard experimental plots distributed randomly in blocks. The standard plot was made up of 24 trees, organized in 4 adjacent rows. The 8 central trees of the middle row were used for measurements, and the other 16 trees were guard trees.

Irrigation treatments

Two irrigation treatments were applied: (C), irrigated daily satisfying the estimated crop evapotranspiration (ETc) and RDI irrigated at 100% ETc during the critical periods (stage III of fruit growth and 2 months after harvest period) and was subjected to water shortage during the non-critical periods of crop development by reducing the amount of applied irrigation water to: a) 40% of ETc from flowering until the end of the first stage of fruit growth; b) 60% of ETc during the second stage of fruit growth and c) 50% and 25% of ETc during the late postharvest period (that starts 60 days after harvesting), for the first 30 days and until the end of tree defoliation, respectively (Fig. 1). This distribution of water applied during non-critical periods was based on studies by Torrecillas *et al.* (2000). The irrigation water was considered to be of good quality with a very low electrical conductivity (0.6 dS m^{-1}). Irrigation was controlled automatically by a head unit programmer and the amounts of water applied for each irrigation treatment were measured with in-line flowmeters placed in each standard experimental plot.
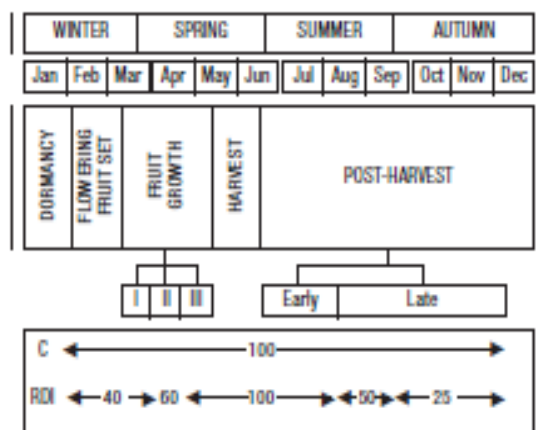
Figure 1. Percentages of crop evapotranspiration (ETc) applied in the regulated deficit irrigation (RDI) treatment during the phenological stages for 'Búlida' apricot trees during the experimental period.

Measurements

The soil volumetric water content (θ_v) of the top 0.2 m of the soil profile was measured by time-domain-reflectrometry probes (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 1.0 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 beside the emitters. Measurements using one neutron probe per each standard experimental plot (4 per treatment) were taken every 7 to 15 days in the morning, during the experimental period. Two TDR probes were used for each neutron probe.

Midday (12:00 h solar time) stem water potential (Ψ_s) was measured in one mature leaves per plant (6 trees per each experimental plot), 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 with a pressure chamber (Soil Moisture Equip. Corp, model 3000, Santa Barbara, CA, USA). Leaf water potential (Ψ_l) was measured in the same trees used for Ψ_s measurements, sampling one sunny mature leaves per plant. The water potential measurements were made according to Scholander *et al.* (1965) and following the recommendations of Turner (1988).

The gas exchange parameters (net photosynthesis, P_n, and stomatal conductance, g_s) were measured at solar midday, in a similar number and type of leaves, and in the same days and trees respectively, as for leaf water potential readings, using a field-portable photosynthesis system (LI-6400, Li-Cor, Lincoln, NE, USA).

Fruit growth was measured perpendicular to the fruit suture on 200 fruits in each treatment (50 fruits per experimental plot). Each sampling was carried out every 7-10 d from a fruit diameter minimum of 1 cm and sampling randomly 10 fruits in the canopy of 5 trees per experimental plot using digital callipers.

At harvest, 200 fruits in each treatment (50 fruits per experimental plot) were selected for their quality assessment. Skin and flesh colour, firmness, tritable acidity (TA), pH, and soluble solids content (SSC) were evaluated as quality indices. Colour values, on the surface (ground skin colour) and after peeling in the flesh, were measured with a Minolta chromameter (CR-300, Minolta, Ramsey, NJ) tristimulus colour analyzer calibrated with a white porcelain reference plate. The colour space coordinates L^*, a^*, and b^*, hue angle [H° = arctg

($a*/ b*$)], and chroma ($a*^2/ b*^2)^{1/2}$ were determined around the equatorial region in three different positions (with an average of nine times for each apricot). Fruit firmness was evaluated by compression test using a Lloyd instrument (model LR10K, Fareham Hants, UK) equipped with two flat plates (12×18 cm²). The maximum force required to deform the fruit 5 mm at a speed of 25 mm min⁻¹ was determined. TA was measured by titration of 5 mL of juice with 0.1 mol L⁻¹ NaOH to pH 8.1 by an automatic titration system (AOAC, 1984). The pH values were measured using a pH-meter, and SSC was determined with an Atago N1 hand-held refractometer (Tokyo, Japan).

Statistical design and analysis

Statistical analysis was performed by weighted analysis of variance (ANOVA) using general linear model of SPSS software (version 17.0, SPSS Inc., Chicago).

Results

During the experimental period, the average values of volumetric soil water content (θ_v) from 0 to 1 m depth in C treatment was nearly constant, with values always close to field capacity (95.8% of θ_v value at field capacity) (Fig. 2a). RDI treatment presented different θ_v values (82.5% of θ_v value at field capacity) between day of year (DOY) 64 and 152 and between DOY 240 and 290, both being lower than those of C treatment (Fig. 2b). The soil moisture profile in RDI treatment was characterized by the fact that during the water deficit periods, the θ_v values beyond 600 mm were clearly below field capacity, indicating the non existence of drainage (data not shown). The amount of water applied was 574.0 mm and 352.4 mm in C and RDI treatments, respectively. The water saved in RDI treatment was 28.5% and 50% during the fruit development and late postharvest period, respectively (Fig. 2c).

Fruit growth, measured as fruit diameter, followed a double-sigmoid pattern (Fig. 3a). Fruits exposed to RDI had a lower but non-significant fruit diameter at the end of stage II of fruit development. When irrigation was restored in the RDI treatment, fruits of this treatment rapidly reached similar diameter values to those obtained in the C treatment due to a significant
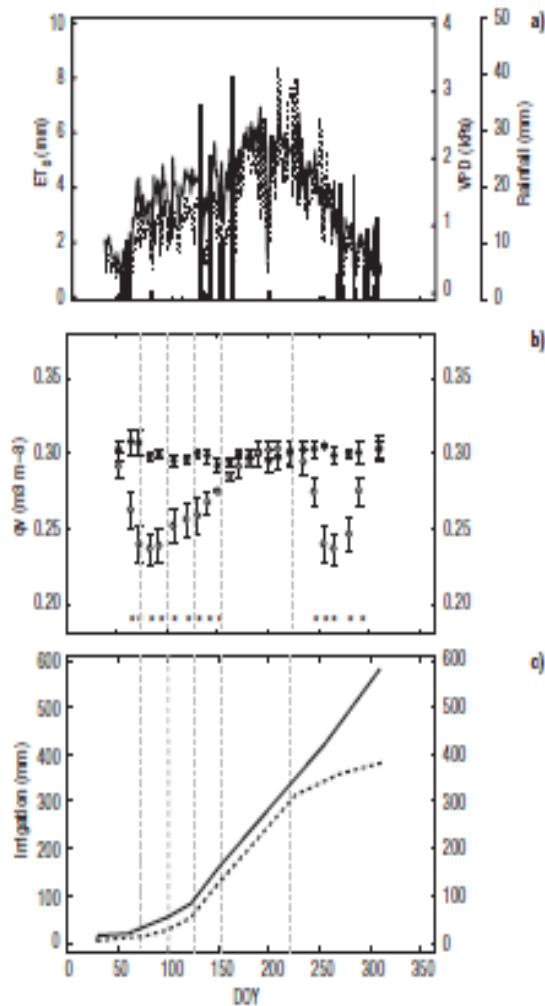
Figure 2. (a) Daily crop reference evapotranspiration (ET₀, mm) (solid line), mean air vapour pressure deficit (VPD, kPa) (dotted line) and rainfall (mm) (vertical bars); (b) soil volumetric water content (θ_v) to a depth of 1 m in the control (●) and RDI (○) irrigation treatments; (c) cumulative irrigation water applied (mm) in the control (solid line), and RDI (discontinuous line) plants along the season (DOY-day of year). The interval between vertical dotted lines from left to right represent the beginning of phases I, II and III of fruit growth, early- and late postharvest. Each value of θ_v is the mean of four measurements ± SE. Asterisks indicate statistically significant differences between treatments ($p < 0.001$).

increase in the fruit growth rate (Fig. 3b). At harvest the fruit equatorial diameter was similar in both treatments and around 45 mm (Fig. 3a).

The RDI treatment induced statically significant reductions in Ψ_s in all the stages during which the water deficit was imposed (Table 1). During the fruit development the values of Ψ_s were nearly constant in C treatment and were about –0.65 MPa. The reduction of
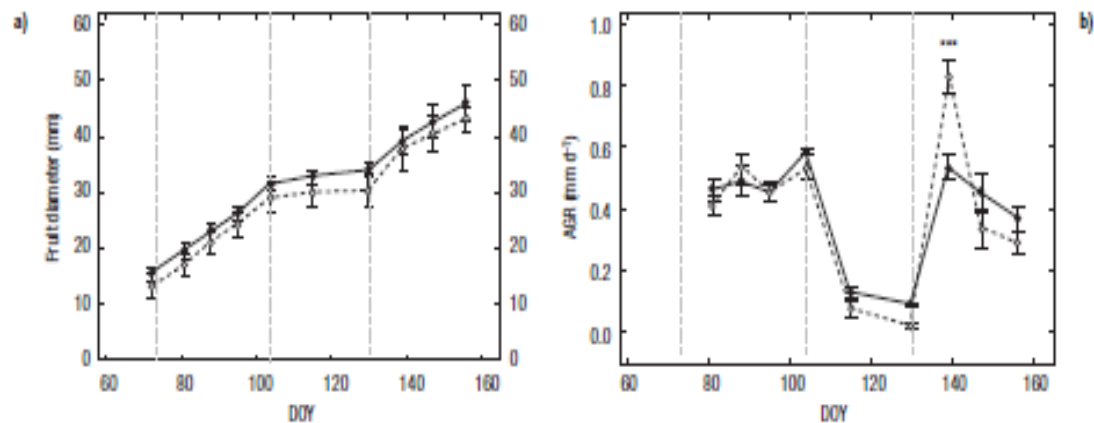
Figure 3. (a) Fruit diameter (mm) and (b) absolute fruit growth rate (AGR, mm d⁻¹) evolution in the C (solid line, ●) and RDI (discontinuous line, ○) irrigation treatments during the fruit growth period (DOY-day of year). The interval between vertical dotted lines from left to right represent the beginning of phases I, II and III of fruit growth. Each value is the mean of 200 measurements $\pm$ SE. Asterisks indicate statistically significant differences between treatments ($p < 0.001$).

Ψ_s in RDI treatment during this period was significant and about 47% respect to C plants at the end of stage II of fruit development (–0.94 MPa). During postharvest period, Ψ_s values in C plants were lower due to increased evaporative demand, reaching an average of –0.91 MPa and –1.24 MPa during early and late postharvest periods, respectively. The decrease of Ψ_s in RDI was significant and about of 26% and 18% compared to C plants during the first and second period of late postharvest respectively (–1.55 and –1.81 MPa, respectively). However, RDI treatment induced statically

significant reductions in Ψ_l only during the second period of late postharvest when the water deficit was more important (25% ETc). As in the case of Ψ_s values, Ψ_l showed a decreasing tendency as vapour pressure deficit (VPD) increased in both treatments (Fig. 2a). The average values of Ψ_l for both treatments were about –1.36 MPa, –1.65 and –2.11 MPa during fruit development, early- and late-postharvest periods, respectively. Similar behaviour to that observed in Ψ_l was also shown in gas exchange parameters with a significant reduction in P_n and g_s values only being ob-

Table 1. Average values of stem (Ψ_s, MPa) and leaf (Ψ_l, MPa) water potential, net photosynthesis (P_n, μmol m⁻² s⁻¹) and stomatal conductance (g_s, mmol m⁻² s⁻¹) in each phenological period in the control (C) and regulated deficit irrigation (RDI) treatments

Phenological period	Ψ_s			Ψ_l			P_n			g_s		
	C		RDI	C		RDI	C		RDI	C		RDI
Stage I	–0.61	*	–0.75	–1.26	ns	–1.45	10.2	ns	8.1	144.1	ns	107.3
Stage II	–0.64	**	–0.94	–1.28	ns	–1.48	11.3	ns	9.4	167.6	ns	128.3
Stage III	–0.66	ns	–0.70	–1.36	ns	–1.52	12.3	ns	12.7	196.3	ns	193.0
Early Postharvest	–0.91	ns	–1.03	–1.65	ns	–1.66	7.6	ns	7.9	99.9	ns	78.3
Late Postharvest I	–1.23	**	–1.55	–2.11	ns	–2.12	6.2	ns	5.8	91.9	ns	72.1
Late Postharvest II	–1.25	***	–1.81	–1.98	*	–2.34	6.0	***	1.1	76.6	***	22.2

Values are the mean of 24 measurements. ns: non-significant. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Table 2. Skin and flesh fruit colour values (reflectance measurements L^*, H^o, C^*) at harvest in the control (C) and regulated deficit irrigation (RDI) treatments

Treatment	L^*		H^o		C^*	
	Skin	Flesh	Skin	Flesh	Skin	Flesh
C	67.1	62.6	78.8	78.6	48.1	44.7
RDI	69.2	63.9	85.3	82.9	50.6	46.6
	ns	ns	**	**	**	*

L^*: lightness factor. H^o: Hue value. C^*: colour intensity (chroma). Values are the mean of 200 measurements. ns: non-significant. * $p < 0.05$. ** $p < 0.01$.

served at the end of the second period of late postharvest. The decrease in P_a and g_a was 82 and 72%, respectively during this second period of late postharvest RDI treatment. C plants had average values of 11.3 and 167.6 in P_a and g_a during fruit development, respectively. These values were decreased nearly by half in the postharvest period (Table 1).

The yield and fruit number per tree were similar between treatments (156.7 and 153.5 kg tree^{-1} and 2,906.7 and 3,038.4 fruits per tree^{-1} for C and RDI treatments, respectively). Irrigation treatment affected to the main quality indices of apricot fruits. The analysis of the colour values showed that the lightness factor, L^*, was similar in both treatments although slightly higher in the RDI treatment. The hue angle (H^o) in skin and flesh was significant higher in the fruits of RDI treatment. Similar behaviour observed in H^o was shown in the chroma (C^*), and the fruits from the RDI treatment showed significant higher values in skin and flesh than those obtained in C treatment (Table 2). Fruit firmness significantly decreased (30%) in fruits from the RDI treatment, while SSC values were increased (9%) significantly in this treatment with respect to C treatment. However, there were no statistically significant differences between treatments as regards pH and TA (Table 3).

Table 3. Fruit firmness (N), pH, soluble solid content (SSC,%), tritratable acidity (TA, g 100 mL^{-1}) and SSC/TA ratio at harvest in the control (C) and regulated deficit irrigation (RDI) treatments

Treatment	Firmness	pH	SSC	TA	SSC/TA
C	52.9	3.71	9.47	1.19	7.96
RDI	36.5	3.75	10.28	1.14	9.02
	**	ns	*	ns	*

Values are the mean of 200 measurements. ns: non-significant. * $p < 0.05$. ** $p < 0.01$.

Discussion

The amount of water applied in the C treatment maintained high values of θ_v, nearest to field capacity (Fig. 2b). Similar values of θ_v were measured in the RDI treatment during periods of full irrigation, being in both treatments the drainage low (lower than 10%) (data not shown) indicating that a suitable irrigation scheduling in C treatment was applied (Abrisqueta *et al.*, 2001). During the phenological periods of water deficit in the RDI treatment, θ_v decreased significantly, reaching values which provoke significant stress conditions in apricot trees (Ruiz-Sánchez *et al.*, 2000). The annual water saving achieved in RDI treatment was 39% (Fig. 2c). This amount of water is similar to that obtained from RDI strategies during the two initial years by Pérez-Pastor *et al.* (2009). Although these authors observed significant reductions in plant production for both years, in our case the yield and fruit number per tree were similar between treatments. This aspect can be explained by the highest water reductions designed by Pérez-Pastor *et al.* (2009) during the fruit development in the initial two years (75% until the end of stage II) in contrast with our experimental conditions (50%) based on the last two years designed by those authors (Fig. 1).

The water saving during fruit development did not affect fruit growth in RDI treatment, since fruits from this treatment had a slightly lower but non-significant fruit diameter at the end of stage II of fruit development (Fig. 3a). When irrigation was restored in the RDI treatment, a compensatory fruit growth was observed (Fig. 3b) which allowed the fruit to reach a similar diameter to fruits from the C treatment (Chalmers *et al.*, 1986) and at harvest apricot fruits were of «extra» size in both treatments (> 40 mm in diameter). This can be explained by the fact that fruit acts as strong sinks of photosynthates. These reserves are available when

irrigation is restored, promoting higher fruit growth rates (Cohen and Goell, 1984; Mills *et al.*, 1996; Torrecillas *et al.*, 2000). This behaviour has been observed in other fruit trees such as lemon (Cohen and Goel, 1984), peach (Mitchell and Chalmers, 1982) and pear (Caspari *et al.*, 1994). This compensatory fruit growth during a recovery period of water deficit and the relative separation between shoot and fruit growth periods in apricot plants (Torrecillas *et al.*, 2000) is essential for the successful application of RDI strategies (Goldhamer, 1989), which indicates that deficit irrigation may be applied to limit shoot growth without detrimental effects on fruit growth and yield (Chalmers *et al.*, 1981; Mitchell and Chalmers, 1982).

Plant water status (Ψ_s and Ψ_l) and gas exchange parameters (P_n and g_s) were affected by the RDI treatment, but not all these discontinuous water stress indicators performed in the same way. Thus, only Ψ_s reflected well the effects on plant water status of the different water restrictions even under mild levels of water deficit associated at low VPD (stage I of fruit growth) (Table 1 and Fig. 2a). For this reason, the use of Ψ_s has been adopted because of its high sensitivity to water deprivation (McCutchan and Shackel, 1992; Naor *et al.*, 1995; Remorini and Massai, 2003) and its good prediction of the yield response to deficit irrigation (Naor, 2000; Intrigliolo and Castel, 2006). The remaining water stress indicators (Ψ_l, P_n and g_s) depend more on the meteorological conditions (Ruiz-Sánchez *et al.*, 2004) and in our case only presented significant differences when the water reductions in RDI treatment were very high with respect to the C treatment (25% ETc).

The water deficit imposed also affected fruit quality indices. Significant differences in fruit skin and flesh colour were found. Fruits from RDI treatment showed higher values of hue angle ($H°$) and chroma ($C*$) (Table 2). The $H°$ has been described as a suitable and intuitively understandable colour index (Arias *et al.*, 2000). The increase in this parameter in apricot fruits from RDI plants can be associated to a reduction in carotenoids accumulation attributed to the oxidation by exposure to light (Ruiz *et al.*, 2005). This exposure to light in the fruits from RDI treatment is related to a significant reduction in the vegetative growth of the trees during fruit development (data not shown), implying a high exposure to light of fruits. Similar behaviour was observed in peach fruits under RDI (Gelly *et al.*, 2003; Buendía *et al.*, 2008).

One of the benefits of RDI is an improvement in fruit taste and quality (Li *et al.*, 1989; Mills *et al.*, 1996;

Mpelasoka *et al.*, 2000). Soluble solids content (SSC) and titratable acidity (TA) warrant particular attention due to their importance in fruit taste (Crisosto *et al.*, 1994). In our case, SSC values were increased significantly in RDI treatment whereas TA was equal in both treatments, and therefore the SSC/TA ratio was increased significantly in RDI treatment (Table 3). This ratio affects the perception of taste (sweetness and acidity) by the consumer, thereby influencing decisions to buy again or not (Crisosto *et al.*, 1997; Scandella *et al.*, 1997). Thus, fruits from RDI treatment can be considered of high quality since SSC increased nearly 1° without affecting acidity (Scandella *et al.*, 1997).

In conclusion, the results indicated that the apricot tree is an appropriate species to apply RDI thanks to the clear separation between their vegetative and reproductive growths and its ability to recover the fruit diameter reduction suffered during RDI application. Furthermore, some qualitative characteristics such as the level of soluble solids, fruit taste and the colour of the fruit are enhanced. These two reasons, together with irrigation water savings of 39%, emphasize the RDI strategies as a possible solution in areas with water shortage, like the south-eastern region of Spain.

Acknowledgments

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