UNIVERSIDAD DE EXTREMADURA

Departamento de Ingeniería Agronómica y Forestal

Material Vegetal y Tecnologías de Cultivo Frutales de Hueso

TESIS DOCTORAL

"Diseño de estrategias de riego y uso del modelo de simulación de cultivos CropSyst en ciruelo japonés"

Memoria presentada por Alberto Samperio Sainz-Aja para optar al Grado de Doctor por la Universidad de Extremadura

Badajoz, 2014

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Centro de Investigaciones Científicas y Tecnológicas de Extremadura (CICYTEX)

Instituto de Investigaciones Agrarias Finca "La Orden-Valdesequera"

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"Diseño de estrategias de riego y uso del modelo de simulación de cultivos CropSyst en ciruelo japonés"

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INFORMAN:

Que la Memoria titulada **"Diseño de estrategias de riego y uso del modelo de simulación de cultivos CropSyst en ciruelo japonés"**, que presenta el Ingeniero Agrónomo Alberto Samperio Sainz-Aja para optar al grado de Doctor, ha sido realizada bajo nuestra dirección en el Centro de Investigaciones Científicas y Tecnológicas de Extremadura (CICYTEX), Finca La Orden del Gobierno de Extremadura y en el Departamento de Ingeniería Agronómica y Forestal de la Universidad de Extremadura.

Considerando que se trata de un trabajo original de investigación que reúne todos los requisitos establecidos en el RD 99/2011, de 28 de enero, estimamos que puede ser presentado para su defensa ante el Tribunal nombrado al efecto.

Para que conste y preste los efectos oportunos lo firmamos, a petición del interesado, en Badajoz, el 8 de abril de 2014.

Fdo.: Dr. Mª Henar Prieto Losada Fdo.: Dr. Mª José Moñino Espino Fdo.: Dr. Abelardo García Martín

A mi familia

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RESUMEN

El uso eficiente del agua de riego es una prioridad para las plantaciones frutales de zonas áridas y semiáridas, que se debe compatibilizar con una producción comercial rentable. Diseñar programaciones de riego que contemplen estrategias de Riego Deficitario Controlado, exige disponer de conocimientos lo más ajustados posible para la especie y condiciones de cultivo.

En este trabajo se han determinado las necesidades hídricas en dos cultivares de ciruelo japonés (*Prunus salicina* Lindl.) de distinto ciclo de maduración: 'Red Beaut' (ciclo corto) y 'Angeleno' (ciclo largo), y los efectos del riego deficitario controlado (RDC) y de la carga de cosecha, tanto sobre la respuesta agronómica como sobre las relaciones hídricas, adaptando en cada caso las estrategias al ciclo de maduración de cada cultivar. Además, se ha evaluado la capacidad del modelo de simulación CropSyst para predecir el potencial hídrico de tallo al mediodía solar (Ψ_{stem}) y el coeficiente de cultivo (K_c), y la eficacia del balance de agua y de los flujos de savia para estimar las necesidades hídricas (ET_c) de ambos cultivares.

En 'Red Beaut' se establecieron tres estrategias de riego en el periodo post-cosecha, un Control regado con el 100% de la ET_c durante todo el ciclo; y dos estrategias de RDC en las que se aportaron el 60% y 30% de la ETc. El ahorro hídrico medio anual fue un 34% para la estrategia menos deficitaria y un 58% para la más severa, respecto al agua aplicada al tratamiento Control. Los resultados indicaron que un descenso progresivo de potencial hídrico de tallo al mediodía solar (Ψ_{stem}) en post-cosecha, hasta valores de -1.65 MPa a principios de agosto, con una disminución máxima de 0.014 MPa día^{-1}, podría ser una estrategia eficaz, no sólo para ahorrar agua, sino también como herramienta para controlar el crecimiento vegetativo (considerado como poda total) y mantener la producción y calidad del fruto en plantaciones comerciales.

En ‘Angeleno’ igualmente se establecieron tres estrategias de riego: un Control regado con el 100% de la ET_c durante todo el ciclo, y dos estrategias de RDC con restricciones hídricas durante la fase II de crecimiento del fruto y post-cosecha. En el tratamiento más moderado se aplicó un 20% y 60% de la ET_c durante fase II y post-cosecha, respectivamente. En el tratamiento de estrés más severo no se aplicó agua durante la fase II y se aplicó el 30% en post-cosecha. Fuera de estos periodos se aplicó el 100% de la ET_c. Durante dos campañas de riego cada estrategia se asoció a tres niveles de carga frutal: no aclareo, dejando todos los frutos cuajados; aclareo comercial, dejando el 75% de la carga frutal, y aclareo intenso, dejando el 50% de la carga frutal. El ahorro hídrico medio anual fue un 26% para la estrategia más moderada y un 34% para la más deficitaria. La restricción moderada del riego, antes y después de la cosecha, manteniendo Ψ_{stem} por encima de –1,75 MPa, con un descenso máximo de 0.019 MPa día^{-1} durante fase II y permitir un progresivo estrés hídrico después de recolección hasta Ψ_{stem} de -1.35 MPa, con un descenso máximo 0.008 MPa día^{-1}, podría ser una manera eficaz de ahorrar agua y controlar el vigor de los árboles, incrementando incluso el número de frutos por árbol y, por tanto, la producción y los rendimientos económicos. El nivel de carga frutal no afectó al estado hídrico del árbol ni al crecimiento vegetativo, sin embargo, un nivel de carga frutal superior a 1100 frutos por árbol produce una reducción del peso fresco del fruto en cosecha.

El ajuste de los parámetros del modelo CropSyst a los datos de campo permitió simular K_c y Ψ_{stem} para ‘Angeleno’ en otros años y árboles de menor tamaño que los empleados para la calibración. Sin embargo, el ajuste de estos parámetros no fue adecuado para simular el comportamiento en ‘Red Beaut’. El factor que determinó la necesidad de adoptar una nueva calibración para poder simular K_c y Ψ_{stem} en ‘Red Beaut’ fue el mayor vigor de los árboles y no el momento en que se realizó la cosecha.

La utilización del balance hídrico y los flujos de savia demostraron ser técnicas viables para determinar ET_c y K_c en 'Red Beaut' y 'Angeleno'. Los valores diarios de ET_c y K_c aumentaron en ambos cultivares desde el cuajado de frutos hasta cosecha, con un descenso progresivo después de esta. En 'Red Beaut' los máximos consumos suceden durante los meses de mayo y junio, por el contrario, en 'Angeleno' se producen en agosto y septiembre. Los valores de K_c obtenidos con ambas metodologías, mostraron una buena relación con la fracción de intercepción de radiación fotosintéticamente activa, sin embargo, estas relaciones fueron diferentes entre cultivares. Mientras para 'Red Beaut' la mejor relación se obtuvo con los valores de flujo de savia, para 'Angeleno' se obtuvo con los valores del balance hídrico.

Los trabajos, desarrollados en las condiciones de cultivo de las Vegas del Guadiana, suponen una contribución al conocimiento existente sobre esta especie, que puede incidir positivamente en la gestión de cualquier explotación de regadío, para realizar una óptima gestión del riego y del control del vigor de las plantaciones, manteniendo la producción y la calidad de la cosecha e incrementando el rendimiento económico.

SUMMARY

Irrigation water use efficiency is a priority for orchards in arid and semi-arid areas, which should be compatible with a profitable commercial yield. Designing irrigation schedules that include strategies as Regulated Deficit Irrigation requires have knowledge as adjusted as possible to the species and growing conditions.

In this work we have determined tree water needs in two cultivars of Japanese plum (*Prunus salicina* Lindl.) with different maturing time: 'Red Beaut' (early-maturing) and 'Angeleno' (late-maturing), and the effects of RDI and crop load, on both the agronomic response and water relations, adapting strategies in each case to maturing time of each cultivar. In addition, we examined the simulation capacities of CropSyst for determining midday stem water potential (Ψ_{stem}) and crop coefficient (K_c) and the effectiveness of the sap flow and soil water balance methods for determining crop evapotranspiration (ET_c) on both cultivars.

In 'Red Beaut', three irrigation treatments were applied during post-harvest season, Control was irrigated to replace the ET_c minus effective rainfall, and two RDI treatment applying 60% and 30% of water given to Control after harvest to onset leaf fall. The reduction in irrigation water in RDI treatments with respect to Control was on average 34% by moderate RDI treatment and reached up to 58% by the severe RDI treatment (Table 1.1). The results indicated that allow a progressive decrease in Ψ_{stem} from -0.76 MPa after harvest to -1.65 MPa at early August, with a maximum decrease of 0.014 MPa day^{-1}, could be an effective strategy not only to save water but also as a tool to control vegetative growth (considered as total pruning) and maintain yield and fruit quality in commercial orchards.

In 'Angeleno', three irrigation treatments were also applied: Control was irrigated to replace the ET_c minus effective rainfall, and two RDI treatments applying deficit

irrigation during stage II of fruit growth and during post-harvest. Moderate RDI treatment was irrigated at 20% of the Control during stage II and 60% during post-harvest. Severe RDI treatment received no irrigation during stage II and 30% during post-harvest. All trees were fully irrigated during stage I and III. During two seasons each irrigation strategy was associated with three crop load levels: no thinning, leaving all the fruit set; commercial thinning, leaving 75% of the crop load, and intense thinning, leaving 50% of the crop load. The total amount of water saved with RDI scheduling with respect to Control, was on average 26% by the moderate treatment and 34% by the severe treatment. Moderate deficit irrigation during stage II and post-harvest, maintaining Ψ_{stem} above -1.75 MPa, with a maximum decrease of 0.019 MPa day^{-1} during stage II and to -1.35 MPa with a maximum decrease of 0.008 MPa day^{-1} during post-harvest, could be an effective way to save water and control tree vigor, even increasing fruit number per tree and thus, yield and grower´s returns. Crop load did not affect tree water status and vegetative growth; however, a crop load higher than 1100 fruits per tree reduces fruit fresh weight at harvest.

The adjusted parameters CropSyst to field data was adequate to simulate K_c and Ψ_{stem} for ‘Angeleno’ in other seasons and smaller trees than those used for calibration. However, the setting of these parameters was not suitable to simulate the behavior in ‘Red Beaut’. The parameters adjusted in 2010 were not adequate to simulate the behavior of the more vigorous cultivar of ‘Red Beaut’. In ‘Red Beaut’, the factor that best explained the need to adapt CropSyst parameters was the difference in vigor but not the time of the removal of fruit sinks.

Both the sap flow and water balance methods seemed to provide useful ET_c and K_c values for ‘Red Beaut’ and ‘Angeleno’ plums, but there were notable differences in seasonal ET_c and K_c values between the two cultivars. Daily ET_c and K_c values

increased in both cultivars from fruit set to harvest, with a progressive decrease after this. The maximum K_c value was obtained from end-May to early-June for ‘Red Beaut’ and from end-August to early-September for ‘Angeleno’. Pre-harvest K_c showed a good correlation with daily fraction of Intercepted Photosynthetically Active Radiation which could be used as a tool to estimate water use for irrigation scheduling under our growing conditions and orchard managements. However, the relationships were different between cultivars; the best correlation was obtained with sap flow values for ‘Red Beaut’, but with water balance values for ‘Angeleno’.

The work developed in the growing conditions in Vegas del Guadiana, represent a contribution to existing knowledge on this species, which can impact positively on the management of any irrigation commercial orchard for optimal scheduling irrigation and control tree vigor, maintaining yield and fruit quality and increasing grower´s return.

INTRODUCCIÓN GENERAL

Existe una creciente preocupación social por el uso racional de los recursos naturales, y más concretamente de los recursos hídricos. La agricultura de regadío es la principal consumidora del agua dulce, con el 75% del total regulado (INE, 2008), siendo un recurso fundamental para incrementar y regularizar la producción agrícola en regiones áridas y semiáridas. Por otra parte, el aumento en la producción agrícola se ha convertido en una prioridad mundial para enfrentar la necesidad imperiosa de alimentar a una población mundial que en el año 2050 demandará un 70% más de alimentos (FAO, 2009), al tiempo que el destino de los cultivos podría tender hacia la producción de bioenergía y para otros fines industriales. En este panorama, la agricultura entrará en competición por la tierra y el agua con los núcleos urbanos en expansión, así como con las actuaciones llevadas a cabo para solventar las predicciones actuales sobre los efectos agroecológicos del escenario climático cambiante sobre el que nos encontramos.

Ambos aspectos convierten en prioritario el uso racional del agua en los regadíos, señalando como objetivo optimizar la productividad del agua, entendida como la cantidad de producto obtenido por cada metro cúbico consumido. A día de hoy, en algunas cadenas de comercialización se incluyen distintivos de calidad relativos a un uso eficiente del agua, como incentivo para un consumo responsable.

La importancia cuantitativa de la producción anual de ciruelas es de $10{,}7\text{x}10^6$ t (FAOSTAT, 2014). En el contexto mundial de producción de fruta fresca, es pequeña si se compara con otros frutales como el plátano ($102\ \text{x}10^6$ t), la manzana ($76\text{x}10^6$ t), o la naranja ($68\text{x}10^6$ t), pero es también la mitad que otros frutales de hueso como nectarino y melocotón ($21\text{x}10^6$ t). Si a esto unimos que bajo la denominación de ciruelo, a efectos de estadística, se incluyen tanto el ciruelo europeo, como el japonés y las endrinas, se entiende la escasa importancia relativa del ciruelo japonés en el mercado mundial de frutas. Sin embargo, la superficie dedicada al cultivo de ciruelo en España ha alcanzado 17.000 ha, con una producción de más de 230.000 t en 2012 (Magrama, 2014). Con estas estadísticas, España se sitúa como el 10º productor a nivel mundial y el 4º a nivel europeo por detrás de Rumanía, Serbia y Francia (FAOSTAT, 2014). La producción nacional está liderada por Extremadura, con 106.978 t en 2012 en una superficie de 5.319 ha (La agricultura y la ganadería extremeñas, 2012), en su mayoría de ciruelo japonés, que es el tipo producido en Extremadura. El 40% de esta producción se destina a exportación, con un valor de las exportaciones de 37,3 millones de euros en 2013 (FEPEX, 2014). Las condiciones agroclimáticas de las Vegas del Guadiana (Extremadura) son muy adecuadas para el cultivo del ciruelo japonés, permitiendo cultivares con un amplio rango de fechas de recolección, desde finales de mayo hasta septiembre, y que además cuentan con una gran aceptación comercial. Estos datos ponen de manifiesto que frente a la poca relevancia de este cultivo en el Mundo, en Extremadura ocupa una posición privilegiada dentro de una pujante fruticultura en el contexto de la producción agraria regional.

El ciruelo, pertenece al género *Prunus* de la familia de las Rosáceas. Bajo la denominación de ciruelo se conocen dos especies: ciruelo europeo (*Prunus domestica* L.), generalmente adaptados a regiones frías, y ciruelo japonés (*Prunus salicina* Lindl.), que incluye un amplio rango de cultivares desde precoces a tardíos adaptados a zonas templadas. Este último es originario de China, donde se ha cultivado tradicionalmente, y fue introducido en Estados Unidos a finales del s. XIX, en el que para adaptar el material a las condiciones de cultivo e introducir nuevas características a la especie, se realizaron cruzamientos de cultivares de *P. salicina* con otras especies americanas de ciruelo, como *P. simonii* Carrière o *P. americana* Marsh, que aportaron características diferenciales tanto a los frutos, como a los árboles del originario *P. salicina*. En el s. XX se continuó con el proceso de mejora mediante la hibridación de las especies anteriores, con otras nuevas como *P. cerasifera* Ehrh. y *P. angustifolia* Marsh. (Faust y Surányi, 1999). El resultado de todo este proceso de mejora varietal, es que en la actualidad, bajo la denominación de ciruelo japonés se recoge una gran complejidad genética que incluye híbridos interespecíficos obtenidos a partir de *P. salicina* y hasta otras 14 especies de *Prunus* (Okie y Hancock, 2008). Así, 'Red Beaut' es un híbrido complejo que viene del cruzamiento de las variedades: Eldorado (*P. Salicina x P. Simonii)* y Brumosa (Burbank (*P. Salicina* puro) x Formosa (origen genealógico desconocido)). En el caso de 'Angeleno', procede de polinización libre de la variedad QueenAnn (híbrido complejo) (Brooks and Olmo, 1997).

La situación de partida de este estudio es un cultivo de especial relevancia en Extremadura, con una gran complejidad intrínseca asociada a su origen genético, para el que apenas existe información disponible, por lo que a efectos de determinación de necesidades hídricas y estrategias de riego se ha tendido a asimilar a otros frutales de hueso "a priori" similares, como el melocotonero o la nectarina. Hasta la fecha se han realizado algunos estudios para evaluar el efecto del déficit hídrico sobre la producción y el tamaño del fruto (Johnson et al., 1994; Naor, 2004; Naor et al., 2004; Intrigliolo y Castel, 2005, 2010), además de estudios preliminares para determinar sus necesidades hídricas en plantaciones jóvenes (Martín-Vertedor, 2010), pero en ningún caso se ha evaluado el efecto de distintas estrategias de riego, así como la determinación de las necesidades hídricas en plantaciones adultas, en distintos cultivares en función del ciclo de maduración de los mismos.

El conocimiento de la fenología y fisiología de la especie y de los distintas cultivares dentro de la especie, es fundamental desde el punto de vista del manejo, tanto para el ajuste de sus necesidades de agua, fertilizantes y otros agroquímicos, como para la determinación de los períodos críticos al déficit de riego (Torrecillas et al., 2000). La presencia del fruto en el árbol tiene un papel fundamental en el ciclo anual de un frutal, ya que determina las relaciones fuente-sumidero, que a su vez condiciona aspectos fisiológicos como la estacionalidad del crecimiento vegetativo y el intercambio gaseoso en hoja. El número de frutos por árbol o nivel de carga, influyen, junto con otros condicionantes, en el tamaño que alcance el fruto en recolección (Forshey y Elfving, 1989; Ebel et al., 1995). En este sentido, existen determinadas prácticas de cultivo como el aclareo, que consiste en eliminar frutos del árbol para disminuir la competencia entre ellos, favoreciendo el crecimiento y la calidad de los que queden (Agustí, 2000).

Otro aspecto a tener en cuenta es que el estado hídrico del cultivo afecta a la capacidad de asimilación del árbol, e influye directamente en procesos fisiológicos como la expansión celular y consecuentemente en el crecimiento vegetativo y por último puede tener efectos directos sobre aspecto reproductivos como la inducción y diferenciación floral, posterior floración, cuajado y crecimiento del fruto (Hsiao, 1973).

La suma de estos dos factores, riego y carga, tienen la capacidad de influir en el crecimiento del árbol, y el nivel de carga puede condicionar la respuesta de la planta ante una situación de estrés hídrico (Berman y DeJong, 1996; Girona et al., 2004; Intrigliolo et al., 2004). Por tanto, delimitar y caracterizar las fases de crecimiento vegetativo y reproductivo, es fundamental para poder aplicar programas de riego que contemplen introducir periodos de déficit hídrico como es el Riego Deficitario Controlado (RDC) (Chalmers et al., 1981; Mitchell y Chalmers, 1982). Con esta técnica se persigue reducir la cantidad de agua de riego con un mínimo impacto sobre la producción, mejorando los rendimientos económicos y consiguiendo beneficios agronómicos adicionales, normalmente asociados al control del vigor (Behboudian et al., 2011). El éxito de la misma depende de tres factores: elegir el momento (o momentos) adecuado, la duración y la intensidad del estrés al que se somete a los árboles, y de la capacidad de recuperación del cultivo al terminar el RDC. Esto exige profundizar en la respuesta fisiológica de la planta frente al déficit hídrico en cada estado fenológico teniendo en cuenta la variabilidad de comportamiento entre especies e incluso de cultivares dentro de una misma especie. En numerosas especies frutales, se ha indicado que un buen manejo del RDC en ciertos períodos fenológicos de desarrollo del cultivo, no indujo pérdidas de producción o cualquier otra adversidad agronómica (Behboudian y Mills, 1997; Naor, 2006; Fereres y Soriano, 2007; Ruiz-Sánchez et al., 2010).

En cultivares de maduración temprana de frutales de hueso, el periodo post-cosecha parece el más adecuado para aplicar RDC, ya que al ser prologado, permite un considerable ahorro de agua sin interferir de forma directa sobre el crecimiento del fruto. Sin embargo, dado que en la fase post-cosecha tienen lugar procesos que determinan la producción del siguiente año, como la inducción y la diferenciación floral, y la acumulación de reservas para la brotación, un estrés hídrico severo puede tener un efecto negativo sobre la producción en la campaña siguiente, provocando una reducción del cuajado (Ruíz-Sánchez et al., 1999; Goldhamer y Viveros 2000; Torrecillas et al., 2000; Girona et al., 2003; Naor et al., 2005) y de la intensidad de la floración (Girona et al., 2003). Efectos que no se observa cuando el estrés post-cosecha es moderado (Larson, 1988; Johnson et al., 1992; Girona et al., 2005).

En cultivares de hueso de maduración media y tardía, se han propuesto estrategias de RDC con periodos de estrés coincidiendo con el fruto en el árbol. La fase definida como “poco sensible” al déficit hídrico, y por tanto susceptible a reducir el aporte de agua por debajo de las necesidades del árbol, es la de endurecimiento del hueso o fase II (Girona et al., 2004; Naor, 2006). En esta fase, el crecimiento del fruto es mínimo (Pavel y

DeJong, 1993) y su sensibilidad al estrés hídrico es menor que en otras fases. Coincide además con un periodo en que el crecimiento vegetativo es considerable, debido al menor efecto de competencia del fruto (Berman y DeJong, 2003), y puede ser controlado de manera efectiva por el déficit hídrico (Li et al., 1989; Girona et al., 2003). Sin embargo, el déficit hídrico debe aplicarse con precaución, porque si es severo y/o prolongado y el árbol no recupera el estado hídrico óptimo en el inicio de la fase final de crecimiento rápido del fruto, perderá calibre y descenderá la producción, pero sobre todo el valor de la misma (Intrigliolo y Castel, 2010). En este tipo de cv. se han propuesto estrategias combinadas con un segundo periodo de estrés tras la recolección de la fruta, destinado principalmente a incrementar el ahorro de agua, aunque con algún posible efecto positivo sobre la entrada en reposo del árbol (Girona et al., 2003).

Cualquier programación de riego, tanto si contempla cubrir las necesidades del árbol, como si plantea estrategias de RDC debe partir del conocimiento de las necesidades hídricas de la plantación a lo largo de todo su ciclo. La cuantificación de estas necesidades sigue siendo una ardua tarea en plantaciones frutales. El método mas extendido para calcular las necesidades hídricas de una plantación es el descrito en la sección de frutales de hueso por el manual FAO: Riego y Drenaje No. 56 (Allen et al., 1998), como: $ET_c = ET_o \times K_c$ (Allen et al., 1998), donde ET_c es la evapotranspiración del cultivo, ET_o es la evapotranspiración de referencia (Allen et al., 1998) y K_c es el coeficiente específico del cultivo. ET_o se calcula a partir de datos meteorológicos y K_c se determina empíricamente para un cultivo y lugar determinado. Sin embargo, este manual, en lo referente a ciruelo, no distingue entre ciruelo europeo y japonés, a pesar de que son especies diferentes y con diferente destino principal de la producción: en el caso del ciruelo europeo para secado, mientras que en ciruelo japonés el destino es el consumo en fresco. Una complejidad adicional para el cálculo de las necesidades hídricas, es que en plantaciones frutales el consumo de agua depende no solo de la especie y el cultivar, sino también de las condiciones concretas de la parcela, que incluye un conjunto de prácticas de manejo que influyen sobre el consumo de agua, y que puede variar considerablemente de una a otra parcela, como el sistema de formación, las podas (en verde e invernal), el nivel de carga frutal, natural o por aclareo de frutos.

La cuantificación directa de la ET_c de una plantación puede resultar muy compleja. Los diferentes métodos disponibles se basan en el balance de agua o de energía. El método considerado como referencia es el lisímetro de pesada, con el que se mide de forma precisa todas las entradas y salidas de agua, de forma que es posible despejar la ET_c en la ecuación de balance de agua $ET_c = P + I - D - R - \Delta S$, donde P es la lluvia efectiva, I es el riego, D es el drenaje, R es la escorrentía y ΔS es la variación en el almacenamiento del suelo (todo en mm día^{-1}). Sin embargo, este método requiere disponer de una instalación costosa, que exige un mantenimiento cuidadoso para que los datos sean fiables, limitándose a una determinación localizada en una plantación y condiciones concretas. Un método alternativo es la medida del contenido de agua en el suelo para determinar la variación en el contenido de agua en un periodo determinado, así como las pérdidas por lixiviación. Este método permitiría hacer determinaciones "in situ" en una plantación concreta, aunque solo es aplicable para estimar ET_c para períodos de tiempo superiores a un día, ha sido utilizado para cuantificar la ET_c estacional de cultivos, tales como almendros (Fereres et al., 1981a; 1981b; Andreu et al., 1997), olivo (Moreno et al., 1988), albaricoque (Abrisqueta et al., 2001) y citríos (Castel et al., 1987; García-Petillo y Castel, 2007) entre otros.

Con las medidas de ET_c y de ET_o se obtiene K_c como cociente entre ambas, siendo la forma más común de hacer extrapolables los cálculos de necesidades hídricas a otras plantaciones (Rana, 2000; Burt et al., 2005; Farahani et al., 2007; Li et al., 2009; Tanny, 2013). Sin embargo, también es posible determinar la ET_c a través de la medida o estimación de la evaporación (E) y la transpiración (T) de forma independiente (Allen et al., 1998). El empleo de métodos como los microlisímetros para medir la evaporación del suelo bajo la cubierta vegetal (Boast y Robertson, 1982; Shawcroft y Gardner, 1983; Walker, 1984; Bonachela et al., 1999, 2001) y medidas de flujo de savia para determinar la transpiración a través de los estomas de las plantas (Čermák et al., 1973; Granier, 1985) han allanado el camino para una verificación sólida para determinar estas componentes por separado. Esta separación de la ET_c a través de sus dos componentes, abre la puerta a un estudio directo de como influyen los factores agroclimáticos sobre cada uno de los componentes.

Se ha demostrado que K_c está bien relacionado con la intercepción de radiación fotosintéticamente activa (PAR) por parte de la cubierta vegetal (Johnson y Handley, 2000, Johnson et al., 2002; Ayars et al., 2003; Williams et al., 2003; Williams y Ayars, 2005; Consoli et al., 2006). Esta relación permite hacer ajustes de la T para árboles de diferentes edades, sistemas de formación, y marcos de plantación, que incluso podría ser válida para otras especies afines (Johnson et al., 2000). Sin embargo, experimentos realizados en manzano y peral indicaron que K_c mostró un descenso moderado después de la cosecha, sin cambios en la cubierta vegetal (Girona et al., 2011). Auzmendi et al. (2011) explicaron tales disminuciones después de la cosecha en manzano por una reducción en la tasa de transpiración respecto a la radiación interceptada.

La aplicación de estrategias de RDC supone reducir el volumen de agua a aplicar con el riego por debajo de las necesidades hídricas calculadas para la plantación en periodos concretos. La reducción que se haga de dicho caudal marcará la intensidad del estrés soportado por los árboles, que es uno de los aspectos críticos para obtener los resultados esperados. La forma más simple para establecer esta reducción es cuantificarla como un porcentaje de la ET_c. Este porcentaje dependerá del máximo estrés permitido durante ese período. No obstante, las condiciones de suelo y clima, así como los factores de cultivo interactúan con la reducción de riego, de forma que el estrés hídrico real soportado por las plantas dependerá de este conjunto de condiciones, y será por tanto variable entre plantaciones, e incluso en una misma plantación.

En estas condiciones es fundamental disponer de un indicador del estado hídrico soportado por la planta, de forma que permita ajustar las dosis de riego para alcanzar en cada estado fenológico los estados hídrico objetivo. Se han propuesto diversas medidas como indicadores del estado hídrico de la planta como: variaciones del diámetro de tronco y fruto (Goldhamer et al., 1999; Fereres y Goldhamer, 2003; Naor y Cohen, 2003), crecimiento de los brotes (Hsiao, 1990; Moriana y Fereres, 2002; Nortes et al., 2005; Marsal et al., 2008), medida de la velocidad del flujo de savia (Smith y Allen, 1996; Green et al., 2003; Testi y Villalobos, 2009), temperatura de la cubierta vegetal (Jackson et al., 1977, 1981; Idso et al., 1981), conductancia estomática (Sellés y Berger, 1990), y potencial hídrico (Fereres y Goldhamer, 1990; McCutchan y Shackel, 1992; Shackel et al., 1997) son, hoy en día, los que se han propuesto como más aplicables para el ajuste de programaciones de riego (McCutchan y Shackel, 1992). En diferentes especies leñosas, se han planteado valores de referencia potencial hídrico tanto para condiciones de no estrés, como para indicar el máximo nivel de estrés recomendable en un determinado estado fenológico en melocotonero (Marsal et al., 2002), ciruelo (McCutchan y Shackel, 1992), almendro (Fereres y Goldhamer, 1990; Shackel et al., 1997), pera (McCutchan y Shackel, 1992), viña (Naor et al., 1997; Choné et al., 2001; William y Araujo 2002) y olive (Moriana et al., 2012).

Dada la multitud de factores que influyen en la respuesta de un árbol en una plantación frente al aporte de agua de riego, es difícil “a priori” conocer cuál va a ser la respuesta frente a una programación o estrategia de riego. Los modelos de simulación de cultivos son valiosas herramientas para representar el comportamiento de los sistemas agrícolas bajo una variedad de condiciones climáticas y geográficas. Su utilidad radica no sólo en reproducir la realidad, sino porque la simplifican y permiten que los procesos más importantes sean identificados, estudiados y pronosticados (Doorenbos y Kassam, 1979; De Wit, 1986). Disponer de un modelo de simulación de cultivo ajustado para las condiciones de la plantación, permitiría simular estrategias de riego para ajustar previamente los periodos de estrés en función de los resultados deseados. Para esta aplicación, el modelo debería ser capaz de simular de forma fiable condiciones de estrés hídrico. Los trabajos con modelos de simulación se iniciaron con cultivos herbáceos (Pala et al., 1996; Pannkuk et al., 1998), siendo más escasos en cultivos leñosos, además de más complejos debido al carácter interanual de los mismos. Entre los modelos de simulación más usados hoy en día para predecir el crecimiento diario de las plantas en función del clima, la disponibilidad de agua, nutrientes, manejo y la producción de cultivos, podemos citar: WOFOST (Van Diepen et al., 1989); PEACH (Grossman y DeJong, 1994); SWAP (Van Dam et al., 1997); CropSyst (Stöckle et al., 2003); MACRO (Larsbo and Jarvis, 2003) y AquaCrop (Steduto et al., 2009, Raes et al., 2009). Para nuestro conocimiento, el uso de modelos en plantaciones frutales ha sido menos frecuente que en cultivos herbáceos u hortícolas, y solo CropSyst ha sido utilizado con éxito en la simulación de estrés hídrico durante cortos períodos de tiempo en peral (Marsal y Stöckle, 2012), para predecir el coeficiente de cultivo en manzano (Marsal et al., 2013) y para producir información realista sobre el consumo de agua en diferentes especies frutales (Marsal et al., 2014).

El objetivo de este trabajo es proporcionar a los fruticultores de las Vegas del Guadiana la información necesaria para mejorar la gestión del riego en sus plantaciones de ciruelo japonés y contribuir a incrementar el conocimiento disponible sobre las necesidades hídricas y la respuesta al riego del ciruelo japonés. Estos objetivos generales se concretan en los siguientes puntos:

- Evaluar el efecto de diferentes estrategias de RDC aplicadas en post-cosecha en un cultivar de ciruelo japonés de maduración temprana.
- Evaluar el efecto de diferentes estrategias de RDC aplicadas en fase II de crecimiento del fruto y en post-cosecha en un cultivar de ciruelo japonés de maduración tardía.
- Evaluar la respuesta al uso de estrategias de RDC y distintos niveles de carga frutal en un cultivar de ciruelo japonés de maduración tardía.
- Ajustar el modelo de simulación CropSyst con los datos de campo, para obtener predicciones válidas de coeficiente del cultivo y potencial hídrico de tallo al mediodía solar, para usar CropSyst como herramienta de gestión del riego en plantaciones frutales de ciruelo japonés.
- Determinar las necesidades hídricas y los coeficientes de cultivo de dos cutivares de ciruelo japonés de distinto ciclo de maduración.

Chapter 1: Effect of post-harvest regulated deficit irrigation in 'Red Beaut' Japanese plum: tree water status, vegetative growth, fruit yield and quality

Abstract

In early maturing fruit crops, post-harvest is usually the preferred period to apply regulated deficit irrigation (RDI) because it offers the opportunity of reduce vegetative growth and saving water without interfere with fruit growth. RDI studies in Japanese plum are scarce compared with studies in other fruit crops. Therefore, we examined over the post-harvest seasons of 2009-2013 the effect of RDI on tree water status, vegetative growth, yield and fruit quality in an adult orchard of an early maturing 'Red Beaut' Japanese plum. The irrigation treatments had the same pre-harvest irrigation, receiving 100% of crop evapotranspiration (ET_c) and post-harvest irrigation treatments were: irrigated at 100% of ET_c (Control); applying 60% of water in Control (RDI-60); and applying 30% of water in Control (RDI-30). Maximum annual water saved respect to Control were 39% for RDI-60 and 70% for RDI-30. Intercepted photosynthetically active radiation displayed a similar pattern throughout the years without significant differences between irrigation treatments in any year. However, the RDI treatments were suitable for reduce trunk growth and total pruning weight. In the long-term (five seasons), the effect of post-harvest RDI did not produce a negative effect due to cumulative effects from one year to the next. Therefore, for early maturing Japanese plum it can be concluded that allow a progressive water stress after harvest that limits the decline in Ψ_{stem} to values of -1.65 MPa at early August, with a maximum decrease of 0.014 MPa day^{-1}, corresponding in this study to RDI-30, appears to be an effective way not only to save water, also as a tool to control vegetative growth (considered as total pruning), even increase yield and maintain fruit quality.

Key words: water stress; stem water potential; trunk growth; pruning; fruit weight; soluble solid concentration.

1.1. Introduction

World production of plum has experienced strong increase in recent years, with a global cultivated area in 2012 of 2.5 million ha, of which 69% are cultivated in China. Spain is the eighth producer on the world and the third main European Union producer (Faostat, 2014). The region of Extremadura, in south-western Spain, ranks first both in crop surface area as in production in the country with 5319 ha and 106.978 t per year (MAGRAMA, 2014).

Fruit yield in Mediterranean climates is dependent on irrigation in those moments where rainfall is scarce. Irrigation allows complementing crop water needs to achieve the yield and fruit quality desired. However, in these areas drought years are increased its frequent due to lack of rainfall in autumn and winter. The competition for water among agricultural, industrial and population areas, the rising costs associated with irrigation practices (electricity, water, labor, etc) and the increasingly limited availability of this resource exacerbated by climate change, require a rational use of water in agriculture. Therefore, it is necessary a sustainable, effective and equitable management of water both in agriculture as other productive sectors to minimize the negative impact on the environment and increase crop water use efficiency (Intrigliolo and Castel, 2010; Marsal et al., 2010; Intrigliolo et al., 2013; Vera et al., 2013). In this context, regulated deficit irrigation (RDI) could be useful tool to reduce water use in agriculture and to optimize grower's return.

RDI is a cultural practice that can be applied to reduce irrigation level during drought-tolerant phenological stages (Chalmers et al., 1981; Mitchell and Chalmers, 1982) and maintain full irrigation during drought-sensitive growth stages of a crop. In early maturing cultivar, the period between fruit set and harvest is short, with a rapid and continuous fruit growth in which it is difficult to identify growth stages. On the contrary, the post-harvest period is long, and thus it may be a more adequate period for irrigation restriction (Johnson et al., 1994; Naor et al., 2006; Marsal et al., 2010). It offers the opportunity to reduce vegetative growth and saving water without interfere with fruit growth in the current season (Chalmers et al., 1981; Behboudian and Mills 1997; Naor, 2006; Fereres and Soriano, 2007). However, it must be applied with caution as severe water stress during post-harvest could have a detrimental effect on yield and fruit disorders in following year like in peach (Girona et al., 2003, 2005; Naor et al., 2005; Lopez et al., 2007), apricot (Ruiz-Sanchez et al., 1999; Torrecillas et al., 2000) and almond (Goldhamer and Viveros 2000; Marsal et al., 2008). The decrease in yield caused by severe post-harvest water stress in the previous year has been attributed to lower fruit set (Ruiz-Sanchez et al., 1999; Goldhamer and Viveros, 2000; Torrecillas et al., 2000; Girona et al., 2003; Naor et al., 2006). The lower fruit set has been attributed to a reduced of pollen viability (Ruiz-Sanchez et al., 1999) and reduced of winter starch concentration (Lopez et al., 2007). In contrast, a moderate level of post-harvest water stress did not affect final fruit size, fruit number per tree or yield in peach tree (Larson, 1988; Johnson et al., 1992; Girona et al., 2005). Another factor that can explain the reductions in fruit set following water stress late in the season are the effects in the long-term due to carry-over effects from one year to the next, with a reduction in crop load the following year due to smaller tree sizes (Johnson and Handley, 2000; Girona et al., 2003; Intrigliolo and Castel, 2005; Naor et al., 2005; Goldhamer et al., 2006;

Intrigliolo et al., 2013). A recent research that evaluating carry-over effect in mid-maturing Japanese plum (Intrigliolo et al., 2013) concluded that RDI impaired the fruit bearing capacity, but not impair yield because the cultivar employed in that study required intense thinning.

However, and unlike the above mentioned crops, studies on post-harvest RDI in Japanese plum are scarce when compared to other fruits (e.g. peach) that normally tend to be related. Most of the research works on plum trees have been developed in middle and late maturing cultivars, applied deficit irrigation during stage II, stage III and post-harvest or combined deficit irrigation during stage II and post-harvest (Naor, 2004; Naor et al., 2004; Intrigliolo and Castel, 2005, 2010), while only few of them have been developed in early maturing cultivars. Some previous studies shows behavior differences between cultivars into the same specie (Martin-Vertedor, 2010, Samperio et al., submitted to Agricultural Water Management), which highlights the need for specific studies. These researches indicated that tree growth, CO_2 assimilation and water use of several plum cultivars are different according the maturing time. The study of Johnson et al. (1994) on 'Red Beaut' plum shows some negative effect of post-harvest RDI, because the trees were extensively defoliated at the end of the season, also reveals some shoot and scaffold dieback, and reduced yield in the following season. The objective of this work was to assess the effect of different post-harvest RDI strategies on stem water potential, vegetative growth and its subsequent yield and fruit quality in early maturing 'Red Beaut' Japanese plum trees.

1.2. Material and methods

1.2.1. Experimental plot and climatic conditions

The experiment was performed over five years (2009-2013) in a 1.0 ha orchard of an early maturing Japanese plum (*Prunus salicina* Lindl. ‘Red Beaut’), located on “Finca La Orden” experimental farm, Badajoz (38°51'N, 6º40'W, elevation 184 m), Spain. Plum trees were planted in spring 2005 at a spacing of 6 x 4 m, in an east-west row orientation (5º towards north). Trees were grafted on *Mariana* 2624 rootstock and were trained to an open vase system with four main scaffold branches per tree. *P. salicina* ‘Black Diamon’ and ‘Ambra’ were planted in guard rows in a sufficient number as pollinizers. Bee hives were used at flowering to ensure optimal pollination. At the beginning of the experiment in 2009, trees had similar average trunk perimeter of 0.53 m and canopy volume of 5.60 m^3.

The climate of the area is Mediterranean with mild Atlantic influence, dry and hot summers, with high daily irradiance and evaporative demand. The average annual temperature was 16.2 °C (1992-2013) and average annual rainfall and reference evapotranspiration (ET_o) were 428 mm and 1293 mm, respectively. The soil was in the order Alfisol, suborder Xeral and in the major Haploxeralf group, with mainly acid pH, low organic matter content and high bulk density, light colors, moderate to weak structure, with normal and even very high content of P_2O_5, low content of Na^+ and K^+ and low cation exchange capacity. The texture was loam, with low stone content and depth greater than 2.5 m. Fertilization practices and pest control were those commonly used in commercial orchards, and weeds were eliminated by chemical treatment. Fruit thinning was only done during 2011 due to a high cropping level of that year.

1.2.2. Irrigation management

The trees were irrigated on a daily basis by a drip irrigation system with four pressure-compensated emitters per tree (4 l h^{-1} for each dripper) set 1-m apart tree, which was located close to the tree trunk. Trees fully irrigated received full replacement crop evapotranspiration (ET_c) minus effective rainfall. ET_c was calculated by multiplying reference evapotranspiration (ET_o) by the crop coefficient (K_c) (Allen et al., 1998). The Penman-Monteith method was used to determine ET_o. ET_c was obtained from Allen et al. (1998), except in 2010 and 2013, where crop water needs were adjusted through soil water content measures calculated weekly by soil water balance. Weather data were obtained from an automated weather station located ~ 600 m from the plum orchard.

1.2.3. Irrigation treatments

Irrigation treatments started after the harvest of 2009 and ended on onset leaf fall of 2013. Three irrigation treatments were applied during season 2009-2011: Control, RDI-60, and RDI-30, and two treatments were maintained during season 2012-2013: Control and RDI-30. All trees were fully irrigated before harvest. The Control treatment was irrigated to replace the ET_c minus effective rainfall. RDI-60 received 60% of water given to Control after harvest to onset leaf fall and RDI-30 received 30% of water given to Control for the same period.

1.2.4. Experimental design

Treatments were distributed in a randomized complete block design with four replications per treatment. Each experimental plot consisted of four adjacent rows of four trees. The four central trees in the second and third rows were used for data collection and the other trees in the plot were guard trees, including four trees located in the first and fourth row-column which was of a different cultivar.

1.2.5. Measurements

1.2.5.1. Applied water and water status

The irrigation volumes were recorded daily by digital water meters (CZ2000-3M, Contazara, Zaragoza, Spain), installed on each replicate. Midday stem water potential (Ψ_{stem}) was measured with a pressure chamber (Model 3005; Soil Moisture Equipment, Santa Barbara, CA, USA.) from two shaded-leaves per tree, from north face situated near the base of the trunk. Selected leaves were covered with aluminum foil at least two hours before the measurement (Shackel et al., 1997), which were carried out between 12:00 and 13:00 h solar time. Determinations were carried out in eight trees per treatment. In 2009 and 2010, measurements were made weekly, while the rest of the years was measured on a weekly basis until harvest and then was measured approximately every 15 days.

1.2.5.2. Phenology and vegetative growth

The growth stages were determined weekly from bud-break to leaf fall using the Baggiolini scale (Baggiolini, 1952). A visual inspection of the orchard was performed once a week to determine the most representative stage at that time (the stage showed by at least 80% of flowers) as well as the most backward and the most advanced stages in the sample. The base and cut-off temperature used to calculate degree-days were 6 and 25 ºC, respectively (Tabuenca and Herrero, 1966). Temperature data used for calculating degree days were obtained from the weather station mentioned previously.

Trunk cross sectional area (TCSA) were determined by measuring the trunk perimeter with a tape measure, about 10 cm above ground level, as: $((Ø/(2 \times \Pi))^2 \times \Pi)$, where Ø is the trunk perimeter, and Π is the number pi = 3.1416. Canopy volume at harvest was calculated assuming a conical shape from telescopic pole measures with two diameters at right angles and the height of the canopy, as: $(\Pi \times r^2 \times h)/3$ where r is the mean canopy diameter (average of S-N diameter and E-W diameter) and h the canopy height.

Summer pruning was applied from 2010 to 2013. Winter pruning was carried out in December, separating each tree pruning in wood of one year (new wood), and wood of more than one year (old wood). The vegetation removed by pruning was weighed. A sample of known fresh weight was dried at 65ºC in a forced air oven (DryBig 250, Borel Fours Industriels & Etuves, S. A., Neuchâtel, Switzerland) and the dry weight was then recorded. The dry/fresh ratio was calculated for the sample and this ratio was then applied to the total fresh weight of pruning to determine the total dry weight.

The percentage of photosynthetically active radiation (PAR) intercepted at solar noon by the canopy measured on clear days was measured with a digital image analyzer for canopy and solar radiations analysis (WinSCANOPY, Regent Instruments Inc., Quebec, Canadian). On each experimental plot, intercepted PAR was obtained from ten measurements taken at fixed positions by placing the digital image analyzer below the canopy of the trees at the soil level in the centre of a ten-quadrant grid into which the planting frame was divided, between the second and third rows of the trees. The grid consisted of two parallel lines 1 m apart from each other and perpendicular to the line of drip tubing and tree trunks. Each line had 5 equidistant measuring points which were 1 m apart, with the first measuring point 1 m from the drip tubing, the 2nd 2 m from the drip tubing, etc.

1.2.5.3. Yield and fruit quality determinations

Fruit were harvested at 2-3 picking dates during late May and early June. Fruit were picked at commercial maturing as determined by ground color, fruit size and soluble solid concentration. Fruit from each tree was harvested, and average fruit weight and fruit number per tree were determined using a commercial grading machine (Greefa Machinebouw B.V., Tricht, Holland). Mean fresh fruit weight at harvest was estimated by dividing the total yield per tree by fruit number per tree. From harvest data several harvest index were determined: water use efficiency (WUE, kg m^{-3}) calculated as yield divided by irrigation applied plus effective rainfall, fruit number per canopy volume at harvest and yield divided by pruning weight.

To assess fruit quality thirty representative fruits per replication were used for the fruit quality assessments in each picking date. Fruit sampled were carried to a laboratory for the automatic control of fruit quality (Pimprenelle, Setop Giraud Technologie, Cavaillon, France). The parameter measured for individual fruit were: soluble solid concentration (SSC, ºBrix) and firmness (FR, kg cm^{-2}). The juice of all the fruit was gathered, weighed and compared to the cumulative weight of all the fruit, determining juiciness (JI, %).

1.2.6. Economic indices

Crop accounting was established for a cultivated area of 1 ha in which all the commercial agricultural practices of the study area are carried out. This is a comparative analysis of income and costs for different irrigation treatments over 2009 and 2013. We used cost-benefit analysis proposed by Ballesteros, (2000) to calculate the economic indices and following the procedure used in an experiment done with different irrigation treatments and fruit thinning levels in our experimental orchard (Samperio et al, submitted to Irrigation Science). Briefly, the following economic indices were calculated: Gross income, calculated for each treatment bearing in mind the prices received by farmers per kilogram of fruit of each commercial category and discounting costs for loading and unloading of the goods. Gross margin, as the difference between gross income and production costs. Productive efficiency, as yield divided by irrigation applied plus effective rainfall until harvest Water economic efficiency, as GM per irrigation applied to each treatment. Irrigation applied per unit of plum calculated as irrigation applied to each treatment per fruit number per tree.

1.2.7. Statistical analysis

Data were analyzed by analysis of variance and regression analysis. Means that differed significantly were separated according to Duncan's new multiple range test at $P < 0.05$. Statistical analyses were performed using version 2.10.1 of the R statistical package (R Development Core Team, 2009) aided by the version 1.5-4 of R Commander package (Fox et al., 2009).

1.3. Results

1.3.1. Climatic conditions and applied water

The cumulative rainfall, annual ET_o, the volume of applied water to each irrigation treatment from 2009 to 2013 and the dates of start and end of irrigation period are given in Table 1.1. The average annual rainfall during the experimental period was 542 mm, varying between the 420 mm of the driest year (2009) to the 685 mm of the wettest year (2010). The average ET_o during the experimental period was 1268, ranged from 1140 mm (2010) to 1357 mm (2009) with the highest level generally recorded in June, July and August (about 200 mm month^{-1}). Average daily values of ET_o increased to reach a peak in July, then remained relatively stable during July (around 7.0 mm d^{-1}), and then decreased until the end of the irrigation period (Fig. 1.1). It should be noted that from June to September, there was no significant amount of rainfall. In the post-harvest period occurred 14% and 54% of the total annual rainfall and annual ET_o, respectively. The average daily temperature in July and August were above 25 ºC (Fig. 1.1).

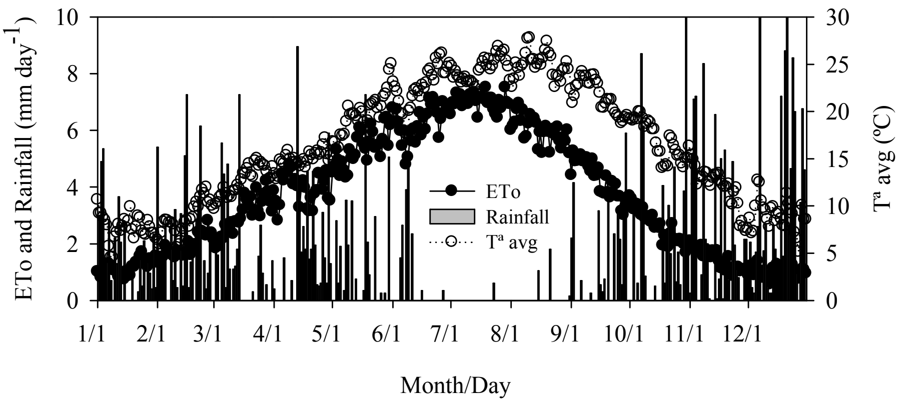


Fig. 1.1 Average daily rainfall, reference evapotranspiration (ET_o) and daily air temperature from January 1 to December 31 during the five experimental years.

The quantity of applied water during the five experimental years slightly varied from year to year due to the length of the irrigation period (Table 1.1). The average annual amounts of water applied in the Control treatment during pre and post-harvest period of 2009-2011 were 95 and 492 mm, respectively (Table 1.1). The corresponding values in the deficit irrigation treatments were 104 and 325 mm in RDI-60 and 101 and 165 mm in RDI-30. The reduction in irrigation water in RDI treatments with respect to Control in these years was on average 34% by the RDI-60 treatment and reached up to 66% by the RDI-30 treatment (Table 1.1). During seasons 2012-2013, applied water during pre-harvest was similarly between Control and RDI-30 (213 and 216 mm, respectively) and during post-harvest the reduction in irrigation water in RDI-30 with respect to Control was on average 46%.

Table 1.1 Annual rainfall, annual reference evapotranspiration (ET_o), irrigation period, and applied water to each irrigation treatment during the five experimental years.

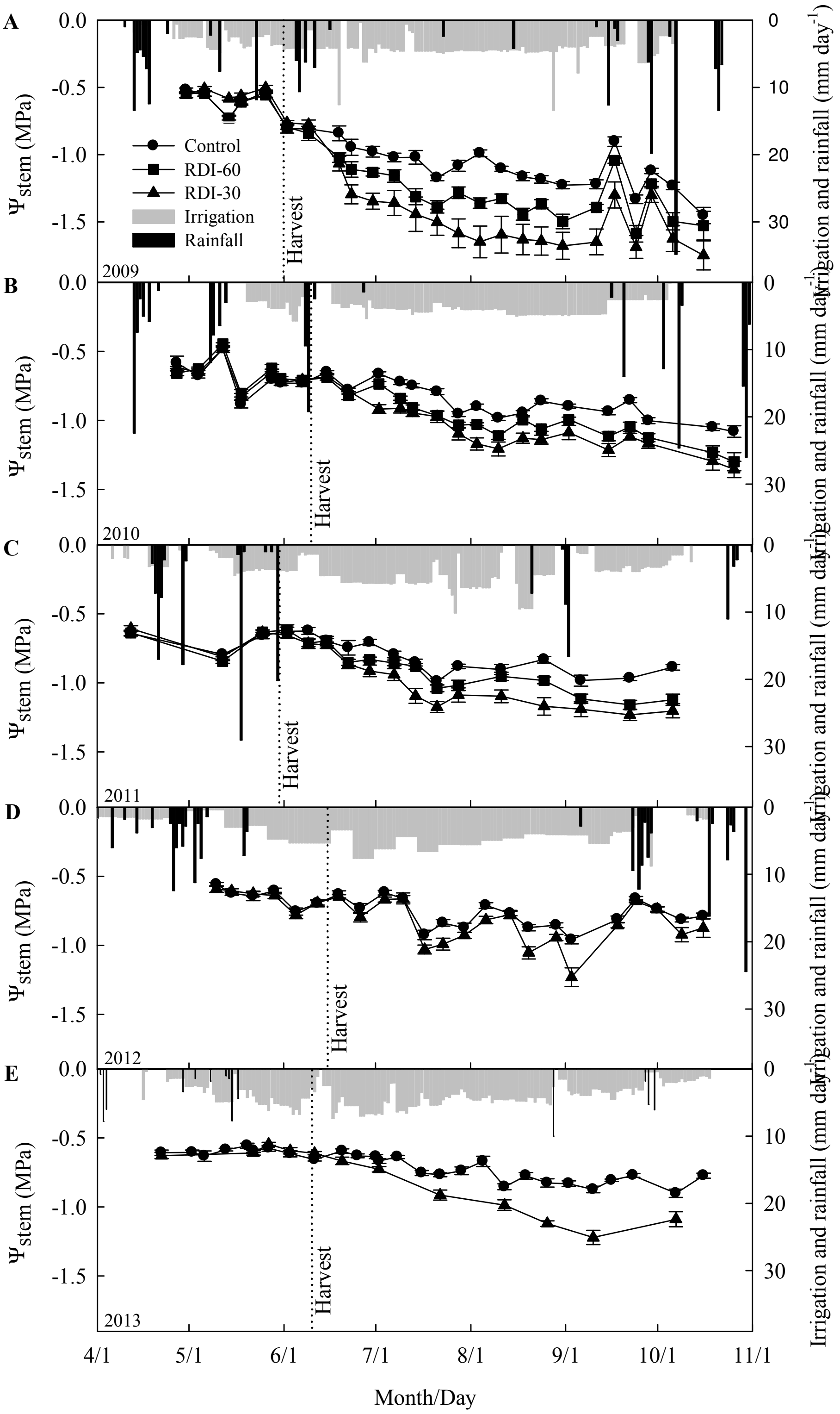
	Annual Rainfall mm			Annual ETo mm			Irr. Period month/day	Irrigation treatments					
								Control		RDI-60		RDI-30	
Year	Pre[1]	Post[2]	Annual[3]	Pre	Post	Annual		Pre	Post	Pre	Post	Pre	Post
2009	75	126	420	403	775	1357	04/14-10/06	108	525	114	320 (39)	113	156 (70)
2010	94	58	685	271	648	1140	05/24-10/06	69	426	72	284 (33)	73	151 (65)
2011	114	33	522	359	720	1308	04/08-10/23	109	526	126	371 (29)	117	187 (64)
2012	87	48	267	434	642	1354	02/26-10/18	231	515			240	321 (38)
2013	36	78	613	318	665	1215	04/17-10/20	194	494			192	225 (54)

[1]From fruit set to harvest of the current year
[2]From harvest to onset leaf fall of the current year
[3]From onset leaf fall of the previous year to onset leaf fall of the current year
In parentheses % savings compared to the Control, calculated as: ((applied water in the Control - applied water in the RDI treatment)/applied water in the Control) x 100

1.3.2. Plant water status

Measurements of the Ψ_{stem} reflected a decreasing trend as the irrigation season progressed in all treatments (Fig. 1.2). No significant differences in Ψ_{stem} were found during the pre-harvest period in the five experimental years. The Ψ_{stem} values were more negative in 2009 than in other years for all treatments (Fig. 1.2) and the minimum differences between treatments were obtained during 2012. In 2009, the Ψ_{stem} values for the Control fell from an initial value of -0.5 MPa during the fruit growth stages to -1.2 MPa in last August. In the RDI-60, the Ψ_{stem} showed minimum values of -1.5 MPa, whereas reductions in the RDI-30 were more pronounced, with minimum values of -1.7 MPa (Fig. 1.2). Significant differences in Ψ_{stem} between Control and deficit irrigation trees were observed between two-four weeks after the onset of post-harvest period in all years (Fig. 1.2A-E). Maximum differences between deficit irrigation treatments appeared normally from early August to mid-September (Fig. 1.2A-E).

Fig. 1.2 Seasonal variations in midday stem water potential (Ψ_{stem}) of 'Red Beaut' plum trees in response to different irrigation treatments during the years 2009 (A), 2010 (B), 2011 (C), 2012 (D) and 2013 (E). Each value is the mean of 8 trees ± standard error. Verticals bars indicate daily rainfall and daily irrigation for Control trees.



Average Ψ_{stem} values in the pre-harvest period ranged from -0.59 to -0.70 MPa (Table 1.2). In post-harvest period, average values for the first three years of the experiment were -0.96, -1.09, and -1.19 MPa for Control, RDI-60 and RDI-30, respectively, with significant differences in tree water potential between all irrigation treatments (Table 1.2). Also during 2012-2013 post-harvest, a significant difference was found between Control and RDI-30.

Table 1.2 Average value of midday stem water potential for each irrigation treatment during the five experimental years.

Treatments	2009		2010		2011		2012		2013	
	Pre[1]	Post[2]	Pre	Post	Pre	Post	Pre	Post	Post	Pre
Control	-0.61	-1.11 a	-0.69	-0.90 a	-0.68	-0.86 a	-0.65	-0.79 a	-0.61	-0.77 a
RDI-60	-0.62	-1.26 b	-0.70	-1.04 b	-0.68	-0.96 b				
RDI-30	-0.61	-1.38 c	-0.68	-1.12 c	-0.66	-1.06 c	-0.66	-0.87 b	-0.59	-0.93 b
ANOVA	n.s.	***	n.s.	***	n.s.	***	n.s.	***	n.s.	***

[1]From fruit set to harvest of the current year
[2]From harvest to onset leaf fall of the current year
Values within columns followed by different letters are significantly different according to Duncan´s Multiple Range test (P=0.05). *, **, ***, n.s., Significant at P = 0.05, 0.01, 0.001, or non-significant, respectively. Each value is the mean of 8 trees.

1.3.3. Fruit and vegetative growth

Table 1.3 shows the development stages of plum trees during the five experimental years (2009-2013). Irrigation did not affect flower phenology in any year (data not shown). As an average, fruit set was established between 37-60 days after bud-break and commercial harvest ranged from 23 May (first harvest) to 13 June (last harvest) (Table 1.3). Fruit growth in the cv. Red Beaut is continuous from fruit set until harvest, resulting in a period of 57-70 days (Table 1.3). Not significant differences between treatments were found in fruit growth (data not shown). This cultivar shows a post-harvest period of about 155-175 days (Table 1.3), with a significant vegetative activity, developing the fully irrigation treatment about the 68% of canopy volume in this period (data not shown).

Table 1.3 Mean onset of phenological stages, total growing period and the accumulation of degree-days (base 6 ºC) from bud-break to leaf fall during the five experimental years.

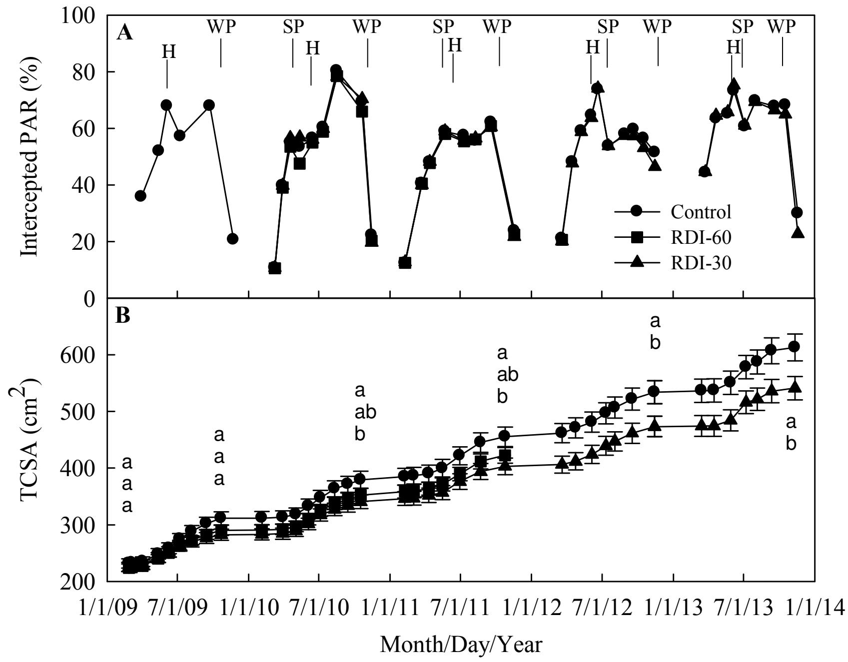
Year	Bud-break[1]	Full Bloom[2]	Fruit set[2]	First Harvest[2]	Last Harvest[2]	Leaf fall[2]	Degree-day accumulation
2009	2/4	23	53	110	117	289	3582
2010	2/11	18	47	111	117	278	3384
2011	1/25	28	49	118	125	299	3613
2012	2/14	21	37	107	119	274	3300
2013	1/31	28	60	124	130	288	289

[1]Indicates date (month/day)
[2]Days after bud-break

Intercepted PAR displayed a similar pattern throughout the years and not significant differences were found between irrigation treatments in any years (Fig. 1.3A). The values of intercepted PAR increased from bud-break to harvest, except in 2010 and 2011, where summer pruning was done before harvest. The highest value of intercepted PAR was reached on August 17, 2010, indicating that the trees were completely developed during the second year of this study. In following years due to summer pruning was severe, intercepted PAR was reduced.

Deficit irrigation did not reduce trunk growth the first experimental year (Fig. 1.3B). In 2010 and 2011 there were not significant different in trunk growth between Control and RDI-60, but from 2010 to the end of 2013 trunk growth was significantly inhibited in the RDI-30 (Fig. 1.3B). The total reduction of TCSA, with respect to Control, was on average 17% by the RDI-30 treatment for the years 2009-2013 and 11% by the RDI-60 treatment during seasons 2009-2011 (Fig. 1.3B).

Fig. 1.3 Seasonal variations in intercepted PAR (A) and trunk cross sectional area (TCSA) (B) of ‘Red Beaut’ plum trees in response to different irrigation treatments during the five experimental years. Each value is the mean of 16 trees ± standard error. For each irrigation treatment, different letters are significantly different at P < 0.05 according to Duncan´s test. SP, WP and H indicate summer pruning, winter pruning and harvest, respectively.



Water stress did not significantly reduce summer pruning (data not shown), however there was a trend toward a significant reduction in the total pruning weight in deficit irrigation treatments compared to Control, with average reductions over the years 2009-2013 close to 22% in RDI-30 and 18% in RDI-60 during seasons 2009-2011 (Table 1.4). The results of winter pruning wood were different among years and between types of wood. There were more differences in new wood, with significant differences among all three treatments except during 2010, where not significant difference between treatments were found. Regarding the old wood, deficit irrigation treatments had only lower amount than Control treatment in 2009, and in 2013 there were significant difference between Control and RDI-30. Generally, of the total wood pruning 62% belong to new wood, 22% to old wood, and the rest to summer pruning in all treatments (Table 1.4). Averages reductions in accumulated pruning of new and old wood for 2009-2013 were about 27% and 24% respectively, for RDI-30 compared to Control

(Table 1.4). The corresponding reductions during 2009-2011 for RDI-60 were 16% and 24%. In total pruning per TCSA the results were similar than in winter pruning of old wood, with significant differences among Control treatment and RDI treatments, except in 2010 and 2013 (Table 1.4).

Table 1.4 Effects of irrigation on annual and accumulated winter pruning of new wood, winter pruning of old wood, total pruning and total pruning per TCSA during the five experimental years.

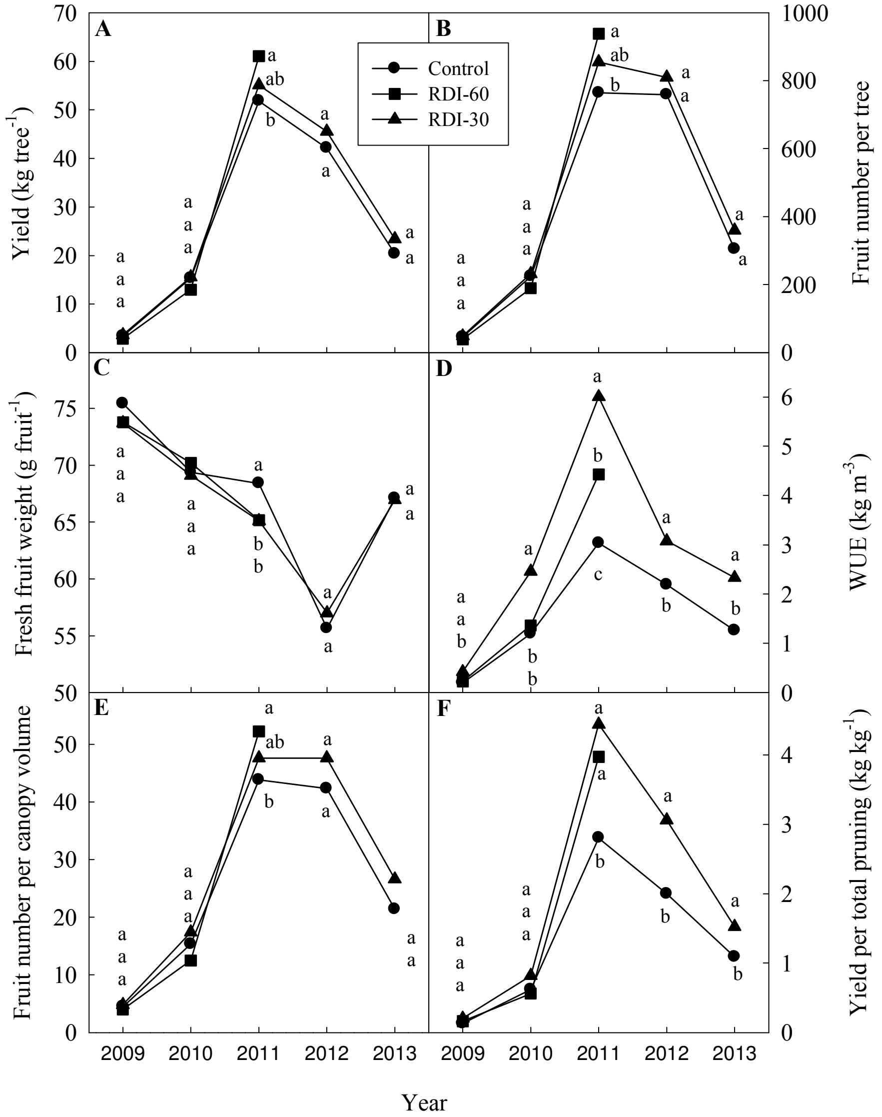
Parameters	Treatments	2009		2010		2011		2012		2013	
Winter pruning of new wood (kg tree^{-1})	Control	19.2	a	19.0		15.1	a	7.4	a	10.2	a
	RDI-60	14.5	b	17.9		12.3	b				
	RDI-30	13.6	b	16.1		9.9	c	4.4	b	8.5	b
	ANOVA	***		n.s.		***		***		***	
Winter pruning of old wood (kg tree^{-1})	Control	8.9	a	6.5		2.1		3.7	a	3.3	a
	RDI-60	5.2	b	5.6		1.8					
	RDI-30	6.6	b	5.6		1.8		1.8	b	2.8	b
	ANOVA	**		n.s.		n.s.		*		*	
Total pruning (kg tree^{-1})	Control	28.1	a	25.8	a	18.9	a	21.5	a	19.7	a
	RDI-60	19.7	b	23.8	ab	15.6	b				
	RDI-30	20.2	b	22.0	b	13.0	c	16.2	b	17.0	b
	ANOVA	***		*		***		***		**	
Total pruning per TCSA (g cm^{-2})	Control	90.1	a	67.9		41.4	a	40.4	a	32.1	a
	RDI-60	67.9	b	67.6		37.0	b				
	RDI-30	71.4	b	64.6		32.2	c	34.3	b	31.5	ab
	ANOVA	**		n.s.		***		*		*	

Total pruning is the sum of summer pruning and winter pruning (new + old wood). Values within columns followed by different letters are significantly different according to Duncan´s Multiple Range test (P=0.05). *, **, ***, n.s., Significant at P = 0.05, 0.01, 0.001 or non-significant, respectively. Each value is the mean of 16 trees.

1.3.4. Yield and quality determinations

In 2009, 2010 and 2013 there was no significant effect of irrigation on yield parameter (Fig. 1.4). During these years, fruit number per tree was low (with 40, 224 and 300 fruit tree^{-1} respectively, averaged over Control trees) and as consequence yield was also low (Fig. 1.4A and B). In comparison to these years, fruit number per tree was higher in 2011 and 2012 (with 760 fruit tree^{-1}, averaged over Control trees). In 2011, deficit irrigation treatments had higher yield, fruit number per tree, fruit number per canopy volume and yield per total pruning than Control treatment with significant differences between RDI-60 and Control, but in 2012 there was no significant effect of irrigation on most of yield parameter (Fig. 1.4A, B, E). Since fruit load changed among years, fruit weight was higher in 2009 than in other years. In 2011, as a result of the higher fruit number per tree for RDI treatments, fruit fresh weight was also the lower for these treatments (Fig. 1.4C). As a consequence the important water savings obtained (Table 1.1) water use efficiency from RDI treatments was significantly higher than Control treatment and significant differences were found among Control and RDI-30 in water use efficiency over the five years of experiment (Fig. 1.4D).

Fig. 1.4 Effects of irrigation on yield (A), fruit number per tree at harvest (B), fruit fresh weight (C), water use efficiency (WUE) (D), fruit number per canopy volume at harvest (E) and yield per total pruning weight (F) during the five experimental years. Each value is the mean of 16 trees. For each irrigation treatment, different letters are significantly different at P < 0.05 according to Duncan´s test.



There was an exponential correlation between canopy volume at harvest and yield or fruit number per tree (Fig. 1.5). Fruit number per tree and yield increased with increases in the canopy volume. Moreover, there was a significantly negative linear correlation between fruit number per tree and fruit fresh weight (Fig. 1.6). The increase in fruit number per tree decreased the fruit fresh weight (Fig. 1.6).

Fig. 1.5 Relationship between yield (A) and fruit number per tree at harvest (B) and canopy volume at harvest during the five experimental years. Each data point is the average value per each experimental plot.

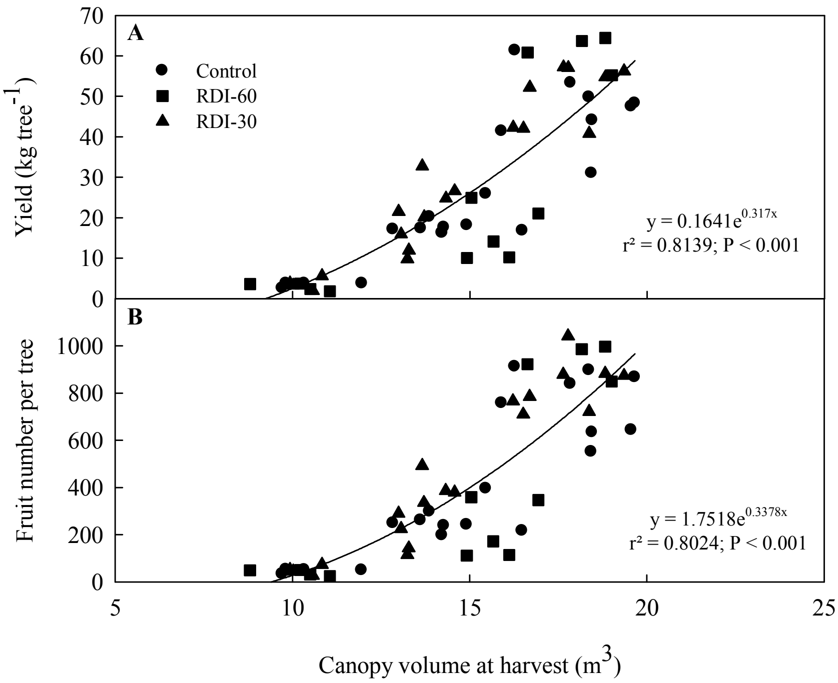
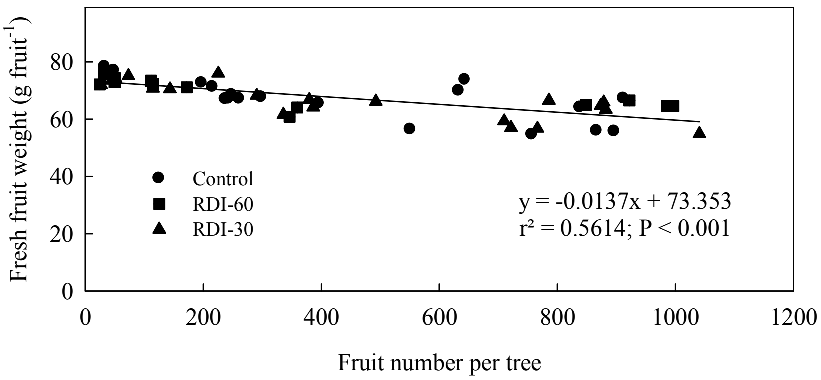


Fig. 1.6 Relationships between fruit fresh weight and fruit number per tree during the five experimental years. Each data point is the average value per each experimental plot.



There were no significant differences among the treatments in SSC and JI in any seasons (Table 1.5). Among the measured fruit quality attributes, there were only differences in FR in 2009 and 2012 with deficit irrigation treatments showing significantly lower values than in Control, whereas in 2010, 2011 and 2013, there were no differences between treatments (Table 1.5). Average values over the five years were 11.8 ºBrix for SSC and 27.7% for JI (Table 1.5).

Table 1.5 Effects of irrigation on soluble solids concentration (SSC), firmness (FR) and juice index (JI) at harvest during the five experimental years.

Parameters	Treatments	2009	2010	2011	2012	2013
SSC (ºBrix)	Control	12.0	12.4	11.6	11.0	11.8
	RDI-60	11.7	12.7	11.6		
	RDI-30	11.5	12.4	11.6	11.7	11.7
	ANOVA	n.s.	n.s.	n.s.	n.s.	n.s.
FR (kg cm^{-2})	Control	2.2 a	1.4	1.5	1.6 a	1.6
	RDI-60	1.5 b	1.5	1.3		
	RDI-30	1.6 b	1.4	1.4	1.3 b	1.5
	ANOVA	*	n.s.	n.s.	**	n.s.
JI (%)	Control	29.6	29.9	25.8	25.6	26.4
	RDI-60	29.8	28.2	26.0		
	RDI-30	29.7	27.6	25.8	27.9	26.7
	ANOVA	n.s.	n.s.	n.s.	n.s.	n.s.

Fruit quality data for 2009 were obtained before the post-harvest application of irrigation treatments. Values within columns followed by different letters are significantly different according to Duncan´s Multiple Range test (P=0.05). *, **, ***, n.s., Significant at P = 0.05, 0.01, 0.001 or non-significant, respectively. Each value is the mean of 120 fruits.

1.3.5. Economic assessment

Tables 1.6 and 1.7 show the absolute costs and economic indices for Control and RDI-30 treatments. Winter pruning, irrigation and electricity costs were significantly higher in Control than in RDI-30 (Table 1.6), but the costs of other cultural operations were similar in both treatments. Gross income was not significant difference between treatments (Table 1.7), however, due to the cost reduction in RDI-30, gross margin was higher in this treatment. Bearing in mind the water saving obtained in RDI-30 (Table 1.1), and the fact that plum yield did not affected (Fig. 1.4), the productive efficiency increased notably in this treatment: 3.4 kg of plums were produced per a cubic meter of water provided in RDI-30, compared to 1.8 kg in Control (Table 1.7). IAUP was lower in RDI-30 than in Control: RDI-30 needed 36.3 liters of irrigation for obtain one fruit, compared to 18.4 liters in Control (Table 1.7).

Table 1.6 Annual absolute cost for a 1 ha plum orchard in the experimental period (2009-2013).

Parameters (€ ha^{-1})	Treatments Control		RDI-30		ANOVA
Winter pruning	1055	a	747	b	***
Summer pruning	151		134		n.s.
Harvesting	1056		1135		n.s.
Irrigation	140	a	77	b	***
Electricity	367	a	204	b	***
Machinery	559		559		n.s.
Crop insurance	377		377		n.s.
Phytosanitary	452		452		n.s.
Herbicides	72		72		n.s.
Fertilizers	376		376		n.s.
Total	4604	a	4133	b	***

Values within columns followed by different letters are significantly different according to Duncan´s Multiple Range test (P=0.05). *, **, ***, n.s., Significant at P = 0.05, 0.01, 0.001 or non-significant, respectively. Each value is the mean of 16 trees.

Table 1.7 Indices of economic evaluation and water use efficiency for a 1 ha plum orchard in the experimental period (2009-2013).

Parameters	Treatments Control		RDI-30		ANOVA
Gross incomes (€ ha^{-1})	4684		4935		n.s.
Gross margin (€ ha^{-1})	80	b	802	a	***
Productive efficiency (kg m^{-3})	1.8	b	3.4	a	***
Gross margin per applied water (€ m^{-3})	0.01	b	0.23	a	*
Irrigation applied per unit of plum (l $fruit^{-1}$)	36.3	a	18.4	b	*

Values within columns followed by different letters are significantly different according to Duncan´s Multiple Range test (P=0.05). *, **, ***, n.s., Significant at P = 0.05, 0.01, 0.001, or non-significant, respectively. Each value is the mean of 16 trees. *, ***, n.s., Significant at P = 0.05, 0.001, or non-significant, respectively. Each value is the mean of 16 trees.

1.4. Discussion

The effect of water stress on yield and quality in the following seasons and the long-term effect on orchard productivity are two aspects that can determine how to apply RDI strategies. In this experiment we evaluated the effect of applying during five experimental years, different RDI treatments as a tool to reduce excessive vegetative growth of Japanese plum trees and saving water during post-harvest period. In the following discussion the effect of irrigation on tree water status, vegetative growth, yield and fruit quality are discussed into different sections to facilitate the presentation.

1.4.1. Effect of irrigation on plant water status

Measurements of the Ψ_{stem} reflected a decreasing trend along the irrigation season progressed in all treatments (Fig. 1.2). In Control trees, the Ψ_{stem} followed the same seasonal pattern and attained similar values (except in 2009) among the five experimental years (Fig. 1.2). The range in Ψ_{stem} of the Control treatment (-0.55 MPa at the beginning of the season, -0.75 MPa before harvest and -1.10 MPa at the end of the season) agree quite well with published values for peach (Garnier and Berger, 1985), European plum (McCutchan and Shackel, 1992) and Japanese plum (Johnson et al., 1994; Intrigliolo and Castel, 2010). Therefore, the ranged suggested may provide a tool to assist in the irrigation scheduling in early maturing Japanese plum orchard under well-watered conditions. Moreover, within this range can be considered that there are no restrictions on vegetative growth of the year and yield in following year (Table 1.4 and Fig. 1.4). Deficit irrigation treatments had lower Ψ_{stem} after water restriction started. In 2009, the Ψ_{stem} of treatment RDI-30 dropped from 0.76 MPa after harvest to -1.65 MPa at early August, with a maximum decrease of 0.014 MPa day^{-1}, and -1.75 MPa the end of the season and no reduction of yield resulted in 2010 (Fig. 1.4). Differences among deficit irrigation treatments in Ψ_{stem} seemed most apparent in 2009 (Fig. 1.2A), probably because the applied water in RDI treatments respect to ET_o was lower in that year (Table 1.1), and also this year was no summer pruning so the trees had more vegetative growth than in other years, except than in 2010 (Table 1.4). In the remaining years, differences between the RDI-60 and RDI-30 treatments and Control were relatively minor, especially during 2012, because the applied water was higher than in previous seasons (Fig. 1.2D and Table 1.1).

The average Ψ_{stem} obtained for RDI-30, that showed no reduction in yield, was of -0.55 to -0.70 MPa over the fruit growth and -0.80 to -1.40 MPa over entire post-harvest period (Table 1.2). Lower and upper limit in post-harvest period were lower (0.2 and 0.1 MPa, respectively) than reported for 'Red Beaut' under similar growing conditions (Johnson et al., 1994). These values could be also used as guidelines to help an orchard manager regulate the degree of stress imposed on his plum orchard. Moreover, in mid-season 'Black-Gold' plum, Intrigliolo and Castel (2005) obtained for Control treatment an average Ψ_{stem} of -0.7 to -1.2 MPa during fruit growth and -1.2 to -1.8 MPa after harvest and did not affect flowering, fruit set or fruit growth the next season.

1.4.2. Effect of irrigation on vegetative growth

The consistent pattern in intercepted PAR in post-harvest period over the 5 years provides more evidence that no negative effects in the long-term due to carry-over effects from one year to the next was inflicted by the RDI treatments, because intercepted PAR along the seasons was similar for all treatments (Fig. 1.3A). Moreover, summer pruning weight was not affected by the previous year's deficit irrigation, which is other evidence that deficit irrigation in post-harvest period did not affect pre-harvest vegetative growth in the next year. Summer pruning is a common practice in our area to promote the inner zone lighting tree to enhance flower buds quality, but it reduces the effect of water deficit on vegetative growth. Therefore, summer pruning decreases intercepted PAR (Fig. 1.3A), which may reduces the water requirements of the trees and delays the appearance of leaf wilting symptoms. On the contrary, the effect of deficit irrigation was more important on vegetative growth. A decrease in vegetative growth (both shoot elongation and trunk growth) due to reduced irrigation water is one of the most sensitive processes to water stress (Hsiao, 1990; Moriana and Fereres, 2002;

Nortes et al., 2005; Marsal et al., 2008). Total pruning weight was reduced in RDI treatments (Table 1.4), contrary to found with the same cultivar by Johnson et al. (1994) which indicated that deficit irrigation caused no reduction in winter pruning weight compared with the Control treatment. This was probably because the shoots have reached their maximum length when the stress treatments were imposed. However, in our experiment canopy volume continued growing after harvest (data not shown) and deficit irrigation could reduce the growth of water sprouts respect Control treatment. This led to shorter shoots in deficit irrigation treatments and therefore lowers wood removal during winter pruning (Table 1.4).

1.4.3. Effect of irrigation on yield and quality parameters

Overall, we found that reducing the amount of applied water after harvest of early maturing plum has shown no negative effect in following years on yield and fruit quality in the five experimental years (Fig. 1.4 and Table 1.5). These results were similar to those obtained in plum (Johnson et al., 1994) and in peach (Johnson et al., 1992) where in both cases with early maturing cultivars not significant differences in yield and a reduction of tree vigor where found during four years of study. In this sense, the temporal coincidence between floral differentiation and period in which occurs the severe post-harvest water stress could have a key role. However, yield decreases with deficit irrigation in the previous year in pome fruits (Naor et al., 2006) and stone fruits (Johnson et al., 1994; Ruiz-Sanchez et al., 1999; Torrecillas et al., 2000; Girona et al., 2003; Naor et al., 2005), probably due to a more severe effect of deficit irrigation, because Ψ_{stem} in post-harvest period were more negative than in our experiment. The decrease in yield has been attributed to reduced flowering intensity (Ruiz-Sanchez et al., 1999; Goldhamer and Viveros, 2000; Torrecillas et al., 2000; Girona et al., 2003; Naor et al., 2006). Deficit irrigation of previous season did not impair the fruit bearing capacity quantified as the number of fruit per tree at harvest (Fig. 1.4B). This result was similar to those obtained in sweet cherry (Marsal et al., 2010). On the contrary, deficit irrigation of previous years impaired the fruit bearing capacity in plum, due to a decrease in the concentration of starch reserves in the root system during the previous season (Intrigliolo et al., 2013). These differences between experiments could be due to long-term effect of water stress because in this last experiment RDI was applied during seven consecutive seasons. Moreover, in this experiment was not observed the occurrence of double fruits and deep suture, similarly at found in Red Beaut, Ambra, Durado, Black Amber or Black-Gold cultivars (Johnson et al., 1994; Naor et al., 2004; Intrigliolo and Castel, 2005). This suggests that plum cultivars are less sensitive at these disorders as reported for peaches and nectarine (Johnson et al., 1992; Handley and Johnson, 2000; Naor et al., 2005).

Favorable soil water conditions were maintained during the whole period of fruit development. However, yield parameters were different between years. Yield was lower in 2009, 2010 and 2013 than in 2011 and 2012, due to changes in fruit number per tree (Fig. 1.4). The lower yield in 2009 was related to the low flower density in that year (visual observation) while in 2010 and 2013 probably was due to rainfall, cloudy and windy days during the flowering period which did not allow the flight of bees required for the establishment of the fruit set (Calzoni and Speranza, 1998). The rainfall from full bloom to fruit set was 8, 84, 57, 0 and 194 mm for 2009, 2010, 2011, 2012 and 2013, respectively. In 2011, over 50% (29 mm) of rainfall took place a day before the end of this period, so fruit set was not affected. Moreover, 'Red Beaut has been identified as a male sterile cultivar having anthers without pollen grains or very few pollen grains small and unable of germinate (Herrero and Salvador, 1980). RDI treatments had significantly higher fruit number per tree and yield than Control in 2011, but conversely RDI treatment had significantly lower fruit fresh weight than Control (Fig. 1.4). Moreover in this year, fruit thinning was done due to high cropping level of that year (with 216, 347 and 333 fruit tree^{-1} removed for Control, RDI-60 and RDI-30, respectively). In cherry (Marsal et al., 2010), peach (Girona et al., 2003), nectarine (Naor et al., 2005) and pear (Marsal et al., 2012), fresh fruit weight in the stressed trees was higher than the unstressed trees, probably because the higher crop load in the unstressed trees caused a significant reduction in fruit-to-fruit competition in carbon availability (Grossman and DeJong, 1995; Berman and DeJong, 1996; Naor et al., 2001). The lower fresh fruit weight in 2012 in both irrigation treatments respect to any years might be due to multiple reasons. Firstly, this could be due higher growing degree hours accumulations during the first 30 days after bloom (5500 degree hours in 2012 versus about 4000 degree hours in other years), result in smaller fruit at harvest because trees cannot supply resources rapidly enough to support the potential growth associated to high rates of phenological development (Lopez and DeJong, 2007). Secondly, the higher crop load of 2011 and water stress post-harvest in that year could significantly reduce the concentration of winter root starch concentration (Lopez et al., 2007). Thirdly, we hypothesized that year with high crop load and summer pruning after harvest would result in smaller fruit fresh weight due to the competition between shoot and fruit growth for assimilates.

Canopy volume at harvest is highly correlated with yield (Fig. 1.5A) and fruit number per tree (Fig. 1.5B). Yield and fruit number per tree increase with canopy volume, up to a threshold of 20 m^3 tree^{-1}. A lower increase in yield and fruit number per tree is noticeable when canopy volume at harvest is increased further, probably because of increasing source limitation (Johnson and Hanley, 1989), and therefore may serves as a practical indicator for grower's return. In addition, high fruit numbers per tree tend to reduce fruit fresh weight (Fig. 1.6), due to an increase on the sensitivity of fruit growth (Berman and DeJong, 1996). Any factor that reduces the tree transpiration during fruit growth period, have a greatest influence on fruit size, because the fruits are the major sink of assimilates (Chalmers et al., 1983).

The values of SSC for Control ranged between 11 and 12 ºBrix, TA between 3.4 and 5.1 g malic acid l^{-1} and FR between 1.4 and 2.2 kg cm^{-2}. These values of SSC and FR agreement with values reported by Daza et al. (2012) in 'Red Beaut', within an experiment with several plums cultivars. However, the TA values did not coincide with those published by Daza et al. (2012) because they determined TA on homogenized samples of whole fruit by Official Methods of Analysis of AOAC International (AOAC, 2002), while our automatic laboratory determined TA over a set quantity of each fruit's juice. To compare the laboratory results with those obtained by Daza et al. (2012), in 2013 we made the TA determination following the AOAC method and the results gave an average value for the Control and RDI-30 treatments of 14.5 and 13.9 g malic acid l^{-1} respectively, and therefore were similar to those reported by Daza et al. (2012) for well-watered treatment. Deficit irrigation did not induce any significant changes in fruit quality parameters except to produce fruit with lower firmness (Table 1.6). However, in the years with high fruit number per tree (2011 and 2012), were reduced SSC and JI in all treatments. In a previous reports in sweet cherry (Neilsen et al., 2007; Marsal et al., 2010) and Japanese plum (Intrigliolo and Castel, 2010), low crop level has been associated with a greater SSC. This could be due to a dilution effect because fruit from years with higher fruit number per tree had lower fruit fresh weight (Fig. 1.4).

1.4.4. Effect of irrigation on economic assessment

According to the a comparative analysis of absolute cost (Table 1.6) and economic indices (Table 1.7) for Control and RDI-30 treatments, we can conclude that gross incomes in both treatments were similar (Table 1.7). On the contrary, absolute costs, gross margin, gross margin per applied water and irrigation applied per unit of plum were significantly higher in RDI-30 than in Control (Tables 1.6 and 1.7). The increase in gross margin was due to lower production cost, mainly due to a reduction in annual pruning costs, applied water and electricity consumption compared to Control (Table 1.6). The results agree with those obtained in late-maturing peach, apricot, pear and Japanese plum (García-García, 2007) and lower than obtained in almond (García-Garcia et al., 2004) and early maturing peach and apricot (García-García and García, 2012).

1.5. Conclusions

The application of post-harvest RDI saved water, reduced vegetative growth (considered as total pruning) and maintained yield and fruit quality. Moreover, in the long term (five seasons) the effect of deficit irrigation post-harvest did not produce a negative effect due to cumulative effects from one year to the next on vegetative growth and yield, however, increase gross margin compared to a well-watered treatment. Therefore, according to our data allow a progressive water stress after harvest that limits the decline in Ψ_{stem} to values of -1.65 MPa at early August, with a maximum decrease of 0.014 MPa day^{-1}, and minimum Ψ_{stem} values of -1.75 MPa at the end the season, corresponding in this study to RDI-30, appears to be an effective way to assist for the deficit irrigation scheduling in early maturing Japanese plum.

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Chapter 2: Response of regulated deficit irrigation during stage II and post-harvest on tree water status, vegetative growth, yield and economic assessment in 'Angeleno' Japanese plum.

Abstract

This paper examined during 2009-2013 the effect of stage II of fruit growth and post-harvest regulated deficit irrigation (RDI) techniques for its potential of vigor control, save water and maintaining yield and grower's return in 'Angeleno' Japanese plum in south-western Spain. Irrigation treatments were: Control, to cover 100% of crop water requirements during the whole season; RDI-20-60, applying 20% and 60% of Control during stage II and post-harvest, respectively; and RDI-0-30 received no irrigation during stage II and 30% of Control during post-harvest. Otherwise deficit irrigation trees received 100% of crop water requirements. Midday stem water potential (Ψ_{stem}), vegetative and fruit growth, yield and grower´s return were measured in the different treatments. Average water saving over the five years of experiment was 26% for RDI-20-60 and 34% for RDI-0-30. RDI reduced Ψ_{stem}, trunk cross sectional area (TCSA) and pruning weight in any year and fruit fresh weigh when deficit irrigation applied during stage II lasted more than two months. The cost-benefit analysis was an average 46% and 30% higher for RDI-20-60 respect to Control and RDI-0-30 respectively, due to an increase in yield and a reduction in annual pruning costs, applied water and electricity consumption. Therefore, from this result it can be concluded that allow some degree of deficit irrigation during stage II of fruit growth, Ψ_{stem} above -1.75 MPa, with a maximum decrease of 0.019 MPa day^{-1} and allow a progressive water stress after harvest that limits the decline in Ψ_{stem} to values of -1.35 MPa, with a maximum decrease

of 0.008 MPa day^{-1}, appear to be an effective way not only for save water, but also as a tool to control vegetative growth and maintain yield and economic return.

Key words: water deficit, stem water potential, intercepted radiation, trunk growth, pruning, wood, water economic efficiency.

2.1. Introduction

Water is a scarce resource in dry areas of the Mediterranean region, and in the Southwestern Spain, the 75% of the freshwater demand is consumed by irrigated agriculture (INE, 2008). Considering the prospect for the future includes a sharp increase in average temperature and a decrease in rainfall events (Intergovernmental Panel on Climate Change, 2013), and therefore an increase in global agricultural evapotranspiration (Playán and Mateos, 2006), it is thus adequate irrigation water management used to increases water productivity and profits (Fereres and Soriano, 2007). One of the most promising techniques that would help attain this objective is the use of regulated deficit irrigation (RDI). RDI is an irrigation strategy developed to control vegetative growth and to save water (Chalmers et al., 1981; Mitchell and Chalmers, 1982; Behboudian and Mills 1997) with minimum impact on yield and quality (see reviews of Naor, 2006; Fereres and Soriano, 2007; Ruiz-Sánchez et al., 2010).

Clearly in stone fruit trees the imposition of RDI at certain stages of fruit growth can therefore benefit vigor control, yield, quality and grower's return. Moreover, very important is the duration of RDI program, because in the short-term, RDI applied during four years did not reduce yield and tree vigor (Johnson et al., 1992; Intrigliolo and Castel, 2005). On the other hand, in the mid-long term, RDI applied during more than four years had a negative impact on yield in almond (Goldhamer et al., 2006; Girona et al., 2005a) and apricot trees (Torrecillas et al., 2000). As a result of applying regulated deficit irrigation (RDI), a reduced in vegetative growth has been obtained in many fruit trees (Hsiao, 1990; Moriana and Fereres, 2002; Girona et al., 2005a; Intrigliolo and Castel, 2005; Marsal et al., 2008; Pérez-Pastor et al., 2009). On the other hand, fruit growth response to RDI is different during different fruit growth stages (Larson et al., 1988; Li et al., 1989). For example, in stone fruits, moderate RDI during initial stage of fruit growth (stage I and II of fruit growth) does not necessarily reduces fruit size and yield compared with fully irrigated trees (Caspari et al., 1994; Ebel et al., 1995; Torrecillas et al., 2000; González-Altozano and Castel, 2000; Girona et al., 2003, 2004, 2005b; Naor, 2006). However, RDI during the critical period (stage III of fruit growth) cause a reduction of fruit diameter, which adversely affects production (González-Altozano and Castel, 2000; Torrecillas et al., 2000; Girona et al., 2004). RDI may also be imposed in post-harvest period, when water stress has no influence on fruit growth but may offer the opportunity saving water without interference with fruit growth (Johnson et al., 1992). To attain the maximum benefits of such strategies, RDI has been combined during phase II and post-harvest in peach (Gelly et al., 2003, 2004), apricot (Pérez-Pastor et al., 2009) and Japanese plum (Intrigliolo and Castel, 2005, 2010).

However, and unlike the above mentioned crops, studies of combined RDI during stage II and post-harvest in Japanese plum are scarce when compared to other fruits (e.g. peach) that normally tend to be related. Nowadays, most of fresh-market plums are complex hybrids developed by intercrossing various diploid species, such as *Prunus simonii*, *Prunus americana*, *Prunus cerasifera* or *Prunus angustifolia,* with *Prunus salicina* or other complex hybrids (Okie and Hancock, 2008). Therefore, the diverse genetic origin can make difficult to assimilate this specie to another stone fruits, because of their differential responses to environmental variables, such as water. Some previous studies showed behavior differences between cultivars within the same specie (Martin-Vertedor, 2010, Samperio et al., submitted to Agricultural Water Management). These researches indicated that tree growth, CO_2 assimilation and water use of several plum cultivars were different according to time to maturity. For ‘Black-Gold’ Japanese plum, Intrigliolo and Castel (2005) reported that water deficit during fruit growth reduced average fruit weight, but a moderate level of post-harvest water stress did not affect yield, in the short-term. However, in the last year of that experiment, yield was reduced compared with well watered trees because they were smaller. Moreover, a severe post-harvest water stress in stone fruit decreased yield in following season (Girona et al., 2003; Naor et al., 2005).

To evaluate the usefulness of these strategies is essential to evaluate the effect in the medium and long term, because their application can cause progressive weakening trees due to the detrimental effects of water stress on vegetative growth, and therefore might be detrimental to the tree productivity and reduce the useful life of a plantation. The main propose of this study was to understand the limits and possibilities of using combined RDI techniques in Japanese plum taking into account physiological responses, tree growth, yield and grower’s return. This will allow determining the most suitable RDI strategy in late maturing Japanese plum orchards.

2.2. Materials and methods

2.2.1. Experimental plot and climatic conditions

The experiment was performed during five consecutive seasons (2009-2013) in a 1.0-ha experimental orchard located on experimental station “Finca La Orden” (Centro de Investigaciones Científicas y Tecnológicas de Extremadura, Badajoz, Spain). The farm is located in the middle of the irrigation area of the Vegas Bajas del Guadiana (38º51'N, 6º40'W, elevation 184 m). The plant material consisted of late maturing Japanese plum (*Prunus salicina* Lindl. cv. Angeleno, on *Mariana* 2624 rootstock), planted in the spring 2005 at a spacing of 6 x 4 m, in an East-West row orientation (5º towards North), with an average trunk perimeter of 0.51 m and ground cover of 27%. Trees were trained to an open vase system with four main branches per tree. *P. salicina* cv. Larry Ann and cv. Fortune were planted in guard rows in a sufficient number as pollinizers, and at flowering were placed bee hives to ensure pollination. Fruit thinning was done, 65 days after full bloom, only during 2011 due to a high cropping level of that year.

The climate of the area is Mediterranean with mild Atlantic influence, dry and hot summers, with high daily irradiance and evaporative demand and rainfalls occurring mainly during winter and spring. The average annual temperature is 16.2 °C (1992-2013), average annual rainfall and reference evapotranspiration (ET_o) is 428 mm and 1293 mm, respectively.

The soil is into the order Alfisol, suborder Xeral and into the great group Haploxeralfs, with mainly acid pH, with low organic matter content and high bulk density, light colors, moderate to weak structure, with normal and even very high content of P_2O_5, with low content of Na^+ and K^+ and low cation exchange capacity. The texture was loam, with low stone content and depth greater than 2.5 m. Fertilization practices and pest control were those commonly used in commercial orchards, and weeds were eliminated by chemical treatment.

2.2.2. Irrigation management

Irrigation treatments started on stage II of fruit growth of 2009 and ended at mid October of 2013. The trees were irrigated on a daily basis by a drip irrigation system with four pressure-compensated emitters per tree (4 l h^{-1} for each dripper) set 1-m apart tree, which was located close to the tree trunk. Trees fully irrigated received full replacement crop evapotranspiration (ET_c) minus effective rainfall. ET_c was calculated by multiplying reference evapotranspiration (ET_o) by the crop coefficient (K_c) (Allen et al., 1998). The Penman-Monteith method was used to determine ET_o. ET_c was obtained from Allen et al. (1998), except in 2010 and 2013, where crop water needs were adjusted through soil water content measures calculated weekly by soil water balance. Weather data were obtained from an automated weather station located ~ 600 m from the plum orchard.

2.2.3. Irrigation treatments

Three irrigation treatments were applied: Control, RDI-20-60, and RDI-0-30. All trees were fully irrigated during stage I and III. The Control treatment was fully irrigated to replace 100% of crop evapotranspiration (minus any effective precipitation). RDI-20-60 treatment was irrigated at 20% of the Control during stage II and 60% during post-harvest (from harvest until the end of the irrigation season). RDI-0-30 received no irrigation during stage II and 30% during post-harvest. During post-harvest 2013, both RDI treatments were irrigated applying 100% of water given to Control.

2.2.4. Experimental design

Treatments were distributed in a randomized complete block design with four replications per treatment. Each experimental plot consisted of four adjacent rows of four trees. The four central trees in the second and third rows were used for data collection and the other trees in the plot were guard trees, including four trees located in the first and fourth row-column which was of a different cultivar.

2.2.5. Measurements

2.2.5.1. Applied water and water status

The irrigation volumes were recorded daily by digital water meters (CZ2000-3M, Contazara, Zaragoza, Spain), installed on each replicate. Midday stem water potential (Ψ_{stem}) was measured weekly with a pressure chamber (Model 3005; Soil Moisture Equipment, Santa Barbara, CA, USA). Eight trees per treatment were selected (two per replicate), and two leaves per tree were measured. The leaves were selected from the north face near the base of the trunk. Selected leaves were covered with aluminum foil at least two hours before the measurement (Shackel et al., 1997), which were carried out between 12:00 and 13:00 h solar time.

2.2.5.2. Phenology, reproductive and vegetative growth

The growth stages were determined weekly from bud-break to leaf fall using the Baggiolini scale (Baggiolini, 1952). The base and cut-off temperature used to calculate degree-days were 6 and 25 ºC, respectively (Tabuenca and Herrero, 1966).

Fruit growth was measured in the years 2010, 2012 and 2013, from fruit set to harvest, on sixteen fruits per plot, and selecting and labeling four fruits per tree in different positions and orientations, and once a week they were measured the equatorial diameter using a digital caliper (IP 67, Vogel Germany GmbH & Co. KG, Kevelaer, Germany). In 2009 fruit growth was not measured. In 2011 fruit growth was assessed in destructive samples of 30 fruit per treatment. These fruits were individually weighed and then equatorial diameter was measured.

Annual increases in trunk cross sectional area (TCSA) were determined by measuring the trunk perimeter with a tape measure, about 10 cm above ground level, as $((Ø/(2 \times \Pi))^2 \times \Pi)$, where Ø is the trunk perimeter, and Π is the number pi = 3.1416. Canopy volume in harvest was calculated assuming a conical shape from telescopic pole measures with two diameters at right angles and the height of the canopy, as $(\Pi \times r^2 \times h)/3$ where r is the mean canopy diameter (average of S-N diameter and E-W diameter) and h the canopy height. Summer pruning was applied in 2010, 2011, 2012 and 2013. Winter pruning was carried out in December. The vegetation removed by pruning was weighed. A sample of known fresh weight was dried at 65ºC in a forced air oven (DryBig 250, Borel Fours Industriels & Etuves, S. A., Neuchâtel, Switzerland) and the dry weight was then recorded. The dry/fresh ratio was calculated for a sample and this ratio was then applied to the total fresh weight of pruning to determine the total dry weight.

The percentage of intercepted photosynthetically active radiation (PAR) by tree canopy was determined at solar noon on cloudless days with a digital image analyzer for solar radiations analysis (WinSCANOPY, Regent Instruments Inc., Quebec, Canadian). On each experimental plot, Intercepted PAR was obtained from ten measurements taken at fixed positions by placing the digital image analyzer below the canopy of the trees at soil level in the centre of a ten-quadrant grid into which the planting frame was divided, between the second and third rows of the trees. The grid consisted of two parallel lines 1 m apart from each other and perpendicular to the line of drip tubing and tree trunks. Each line had 5 equidistant measuring points which were 1 m apart, with the first measuring point 1 m from the drip tubing, the 2nd 2 m from the drip tubing, etc. In 2009, was only measured in Control treatment.

2.2.5.3. Yield determinations

Fruits were harvested at a single commercial picking during late-August and early-September, depending on the year, following normal commercial practice. Fruit from each tree was harvested and average fruit mass and fruit numbers per tree were determined using a commercial grading machine (Greefa Machinebouw B.V., Tricht, Holland), separating fruit into five categories (<53; 53-56; 56-59; 59-61; >61 mm). Mean fruit fresh weight at harvest was estimated by dividing the total yield per tree by fruit number per tree. From harvest data were determined: yield per canopy volume at harvest, fruit number per canopy volume at harvest and yield per pruning weight.

2.2.6. Economic indices

Crop accounting was established for a cultivated area of 1 ha in which all the commercial agricultural practices of the study area are carried out. This is a comparative analysis of income and costs for different irrigation treatments over 2009 and 2013. We used cost-benefit analysis proposed by Ballesteros, (2000) to calculate the economic indices which allow the treatments to be compared and any differences to be identified from an economic point of view: gross margin, water economic efficiency, break-even point and irrigation applied per unit of plum. Gross margin (GM, € tree^{-1}) was calculated as the difference between gross income and production costs. Water use efficiency (WUE, kg m^{-3}) was calculated as the ratio between yield and the irrigation applied in each treatment; water economic efficiency (WEE, € m^{-3}) was calculated as GM per irrigation applied to each treatment; and irrigation applied per unit of plum

(IAUP, l fruit^{-1}) indicates the ratio between irrigation applied to each treatment and fruit number per tree. Gross income (GI, € tree^{-1}) was calculated for each treatment bearing in mind the prices received by farmers per kilogram of fruit of each commercial category and discounting costs for loading and unloading of the goods (0.01 € kg^{-1}), cold storage (0.02 € kg^{-1}) and marketing (0.19 € kg^{-1}). Final prices in € kg^{-1} were 0.29, 0.43, 0.47, 0.51 and 0.56 for commercial category <53, 53-56, 56-59, 59-61 and >61 mm, respectively. Production costs (PC, € tree^{-1}) were calculated considering those costs that *a priori* are considered differential between treatments, namely electricity (0.057 € m^{-3}), irrigation (0.022 € m^{-3}), annual pruning (0.099 € kg^{-1}), thinning (0.004 € fruit^{-1}) and harvest (0.094 € kg^{-1}). The following costs were considered common to all treatments because they were commonly applied: plant protection products (502 € ha^{-1}), herbicides (72 € ha^{-1}), fertilizers (418 € ha^{-1}), crop insurance (500 € ha^{-1}), and fixed personnel (2100 € ha^{-1}). Similarly, the fixed assets and overheads associated with the regular workforce of the orchard are common to the treatments and therefore not included. We use data from the experiment and other data referring to irrigated plum production in the orchard in the Vegas Bajas del Guadiana, Badajoz, Spain.

2.2.7. Statistical analysis

Data were analyzed by analysis of variance and regression analysis. Means that differed significantly were separated according to Duncan's new multiple range test at $P < 0.05$. Statistical analyses were performed using version 2.10.1 of the R statistical package (R Development Core Team, 2009) aided by the version 1.5-4 of R Commander package (Fox et al., 2009).

2.3. Results

2.3.1. Climatic conditions and applied water

Annual rainfall, annual crop reference evapotranspiration (ET_o), the dates of start and end of irrigation period and the volume of applied water to each irrigation treatment during the five experimental years (2009-2013) are given in Table 2.1. The average annual rainfall was 519 mm, which is above the average range of the area, with great year-to-year deviations from this value, varying between 352 mm the driest year (2012) and 739 mm the wettest year (2010). Rainfall was principally during spring and autumn (Fig. 2.1). The average ET_o during the experimental period was 1310 mm, with minor year-to-year variations, and the highest level was generally recorded in June, July and August (about 200 mm month^{-1}). The average rainfall and ET_o (2009-2013) during stage II were 38 and 366 mm, respectively. The corresponding values during post-harvest were 34 and 153 mm. The longer irrigation period occurred in 2012, while the shorter occurred in 2010. The average daily temperature in June and September were 22 ºC and in July and August were 25ºC (Fig. 2.1).

Table 2.1 Annual rainfall, annual reference evapotranspiration (ET_o), irrigation period, and applied water during each stage of fruit growth and post-harvest to each irrigation treatment during the five experimental years.

	Ann.	Ann.	Irrigation	Irrigation treatments											
	Rainfall	ET_o	period	Control				RDI-20-60				RDI-0-30			
Year	mm	mm	month/day	S I	S II	S III	P-H	S I	S II	S III	P-H	S I	S II	S III	P-H
2009	556	1391	04/14-10/06[1]	6	199	229	158	7	51	231	97	6	5	246	59
2010	739	1318	05/24-10/06[1]	41	211	338	52	35	45	348	32	44	3	354	17
2011	379	1314	04/08-10/23[1]	31	230	299	135	32	58	315	83	33	3	303	43
2012	352	1325	02/26-10/18[1]	88	276	306	107	86	79	292	91	86	39	325	74
2013	355	1071	04/16-10/20[1]	23	138	476	133	28	30	479	140	29	4	492	144
Avg.	507	1337	04/06-10/15[1]	38	211	330	113[2]	38	53	333	76[2]	40	11	344	48[2]

S I, S II, S III and P-H indicates fruit growth stages (I, II, and III) and post-harvest.
[1] Period free of rainfall from harvest until indicated date.
2 Post-harvest applied water during 2013 were not included

The average annual amount of water applied in the Control during 2009-2013 was 695 mm, whereas trees in the RDI-20-60 during 2009-2012 received 470 mm and trees in the RDI-0-30 received 410 mm (Table 2.1). The average amounts of water applied in stage II of fruit growth were 211, 53 and 11 mm for Control, RDI-20-60, and RDI-0-30, respectively and in post-harvest were 113, 76, and 48 mm, respectively (Table 2.1). The total amount of water saved with RDI scheduling during stage II and post-harvest period over the years 2009-2012, with respect to Control, was on average 31% by the RDI-20-60 treatment and reached up to 40% by the RDI-0-30 treatment (Table 2.1).

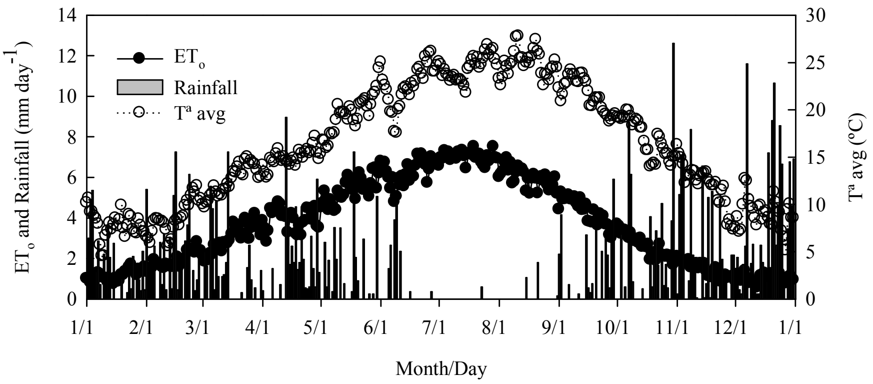

Fig. 2.1 Average daily rainfall (verticals bars), reference evapotranspiration (close circles), and temperature (open circles) over the five experimental years.

2.3.2. Plant water status

The Ψ_{stem} values in RDI periods were more negative in 2009 and 2012 during stage II than in other years for all treatments (Fig. 2.2). Overall, in the second or third weeks of RDI application during stage II were established differences between Control treatment and RDI strategies and by mid-stage II were established between RDI strategies. The minimum values for RDI strategies in stage II were reached at the end of the stage, at which point the maximum differences between treatments. Minimum values in stage II were -1.05 MPa to Control (Fig. 2.2A), -1.75 MPa to RDI-20-60 (Fig. 2.2A) and -2.60 MPa to RDI-0-30 (Fig. 2.2D). When water was returned to full irrigation during phase

III differences in Ψ_{stem} disappeared between treatments, reaching Control values in about 3 weeks, and at harvest all trees had the same water status (Fig. 2.2). Following harvest, there was a decrease of Ψ_{stem} in the all three irrigation treatments. This decrease, although it was more pronounced in RDI strategies, did not give significant differences between the Control and RDI-20-60 in any year. However, RDI-0-30 presented differences compared with Control and RDI-20-60 treatments from 2009 to 2012 (Fig. 2.2). Minimum Ψ_{stem} values in post-harvest were -1.35 MPa for Control and RDI-20-60 in 2010 in both treatments and -1.97 MPa for RDI-0-30 in 2009 (Fig. 2.2A).

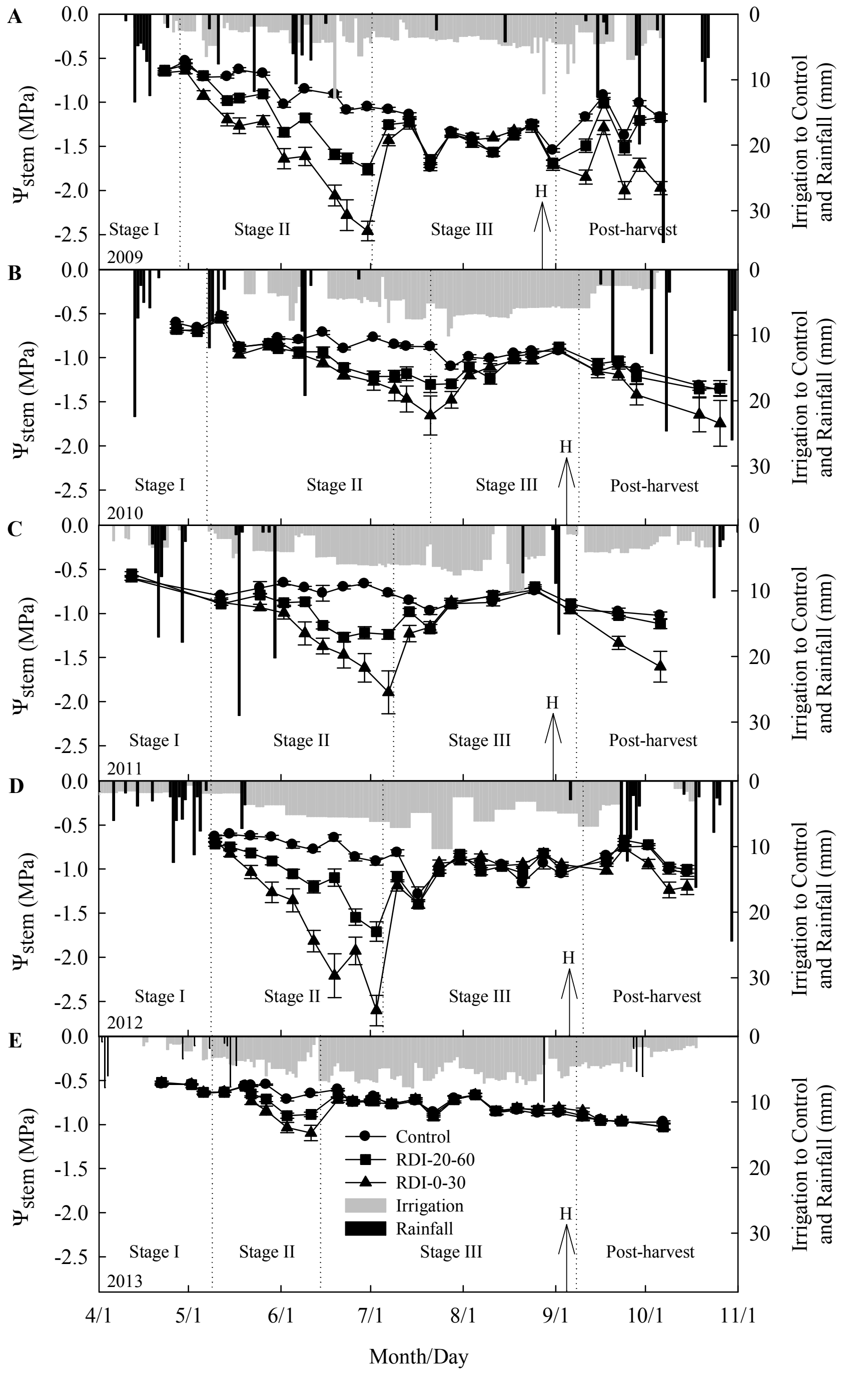

Fig. 2.2 Seasonal variations in midday stem water potential (Ψ_{stem}) of Angeleno plum trees subjected to different irrigation treatments during the 2009 (A), 2010 (B), 2011 (C), 2012 (D), and 2013 (E). Fruit growth stages (I, II, and III) and post-harvest are shown and the arrow H indicates harvest date. Each value is the mean of 8 trees ± standard error. Verticals bars indicate daily rainfall and daily irrigation for Control trees.

2.3.3. Fruit and vegetative growth

Table 2.2 shows the development stages of plum trees during the five experimental years (2009-2013). Irrigation did not affect flower phenology in any year (data not shown). As an average, fruit set was established between 42 and 74 days after bud-break and commercial harvest ranged from 27 August to 6 September (Table 2.2).

Table 2.2 Mean onset of phenological stages, total growing period and the accumulation of degree-days (base 6 ºC) from bud-break to leaf fall during the five experimental years.

Year	Bud-break	Full bloom	Onset Stage I	Onset Stage II	Onset Stage III	Harvest	Leaf fall	Growing period (days)	Degree-day accumulation
2009	2/4[1]	3/2	4/4	4/28	7/1	8/27	11/30	300	3618
2010	2/11	3/5	4/11	5/6	7/24	9/6	11/20	283	3404
2011	1/31	3/1	3/24	5/7	7/9	8/30	11/23	297	3627
2012	2/20	3/12	4/2	5/7	7/4	9/6	11/19	274	3339
2013	1/31	3/7	4/15	5/7	6/11	9/4	11/21	295	3341
Average	2/7	3/6	4/5	5/11	7/5	9/2	11/23	290	3466

[1]Indicates date (month/day)

Fruit growth in the cv. Angeleno was continuous from fruit set until harvest, resulting in a period of approximately 140-160 days (Table 2.2 and Fig. 2.3). Therefore, it was difficult to identify when stage II began and finished. There were no significant differences in fruit size between all the treatments at the beginning of stage II in any experimental year (Fig. 2.3). RDI imposed on trees in stage II reduced fruit diameter from the second half of stage II, except in 2013 (Fig. 2.3D), but the differences between the lowest two irrigation levels were not significant, except in 2012, where fruits on RDI-0-30 trees were significantly smaller than those on the RDI-20-60 trees at the end of this stage (Fig. 2.3C). Fruit growth in RDI treatments did not recover to Control´s fruit size when irrigation was increased to 100% ET_c during the subsequent stage.

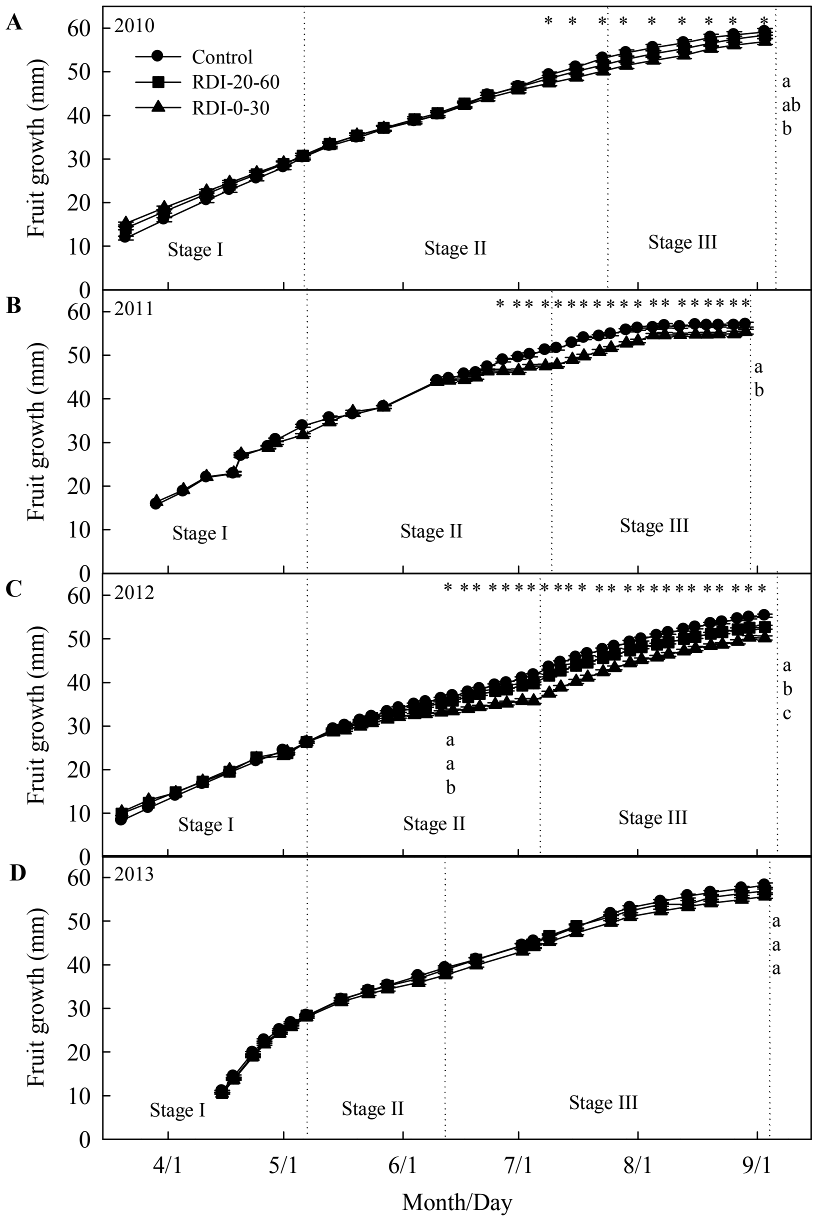

Fig. 2.3 Seasonal variations in fruit growth in response to different irrigation treatments during the 2010 (A), 2011 (B), 2012 (C), and 2013 (D). Each value is the mean of 64 fruits ± standard error in 2010, 2012 and 2013 and 30 fruits ± standard error in 2011. Asterisk in the top represent the date when significant differences between treatments appeared.

Intercepted PAR was significantly reduced in 2010 and 2012 in the RDI treatments, but the higher or lower level of stress produced no differences in intercepted PAR between RDI strategies (Fig. 2.4A). During 2011 and 2013, intercepted PAR was relatively similar in all treatments (Fig. 2.4A). The highest values of intercepted PAR were reached on August 17, 2010 where intercepted PAR for Control increased from

20% at bud-break to about 80% on that date, indicating that the trees were completely developed during the second year of this study. The corresponding values for RDI treatments on August 17, 2010 were 74% for intercepted PAR. In the following years, especially in 2011, intercepted PAR was lower than in 2010 and 2013, because summer pruning was more severe than in previous years (Fig. 2.4A).

Trunk growth was clearly reduced in those treatments that underwent water stress (Fig. 2.4B). Trees of RDI treatments had significantly smaller trunks than Control from the first year of deficit irrigation, continuing until the end of the experimental period, with no significant differences between RDI treatments (Fig. 2.4B). Total TCSA was reduced by 27.2% and 29.6% with respect to the Control treatment in RDI-20-60 and RDI-0-30 treatments, respectively (Table 2.3).

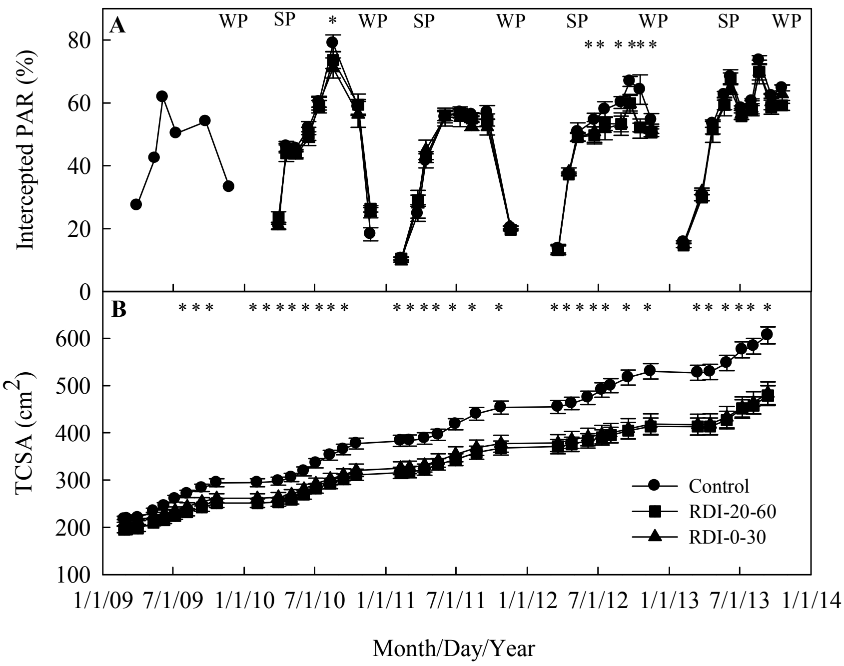

Fig. 2.4 Seasonal variations in intercepted PAR (A) and trunk cross sectional area (TCSA) (B) of 'Angeleno' plum trees in response to different irrigation treatments during the years 2009-2013. Each value is the mean of 16 trees ± standard error. Asterisk in the top represent the date when significant differences between treatments appeared. SP, WP and H indicate summer pruning, winter pruning and harvest, respectively.

RDI treatments had lower amount of new and old wood than Control treatment, with no differences between RDI treatments. Of the total wood pruning 61% corresponded to new wood, 25% to old wood, and the rest to summer pruning (Table 2.3). The results include pruning weight of 2013 because we can assume that the reduction in RDI treatments is due to water deficit during phase II. Therefore, averages reductions (2009-2013) in accumulated pruning of new and old wood for RDI-20-60, compared to Control were 30% and 26%, respectively. The corresponding reductions for RDI-0-30 were 31% and 34%, respectively (Table 2.3). In general, pruning weights in the Control treatment were significantly higher than in those of RDI-20-60 (26.6% reduction) and RDI-0-30 treatment (30% reduction), with no significant differences between RDI treatments (Table 2.3). In total pruning per TCSA the results were similar than in total pruning, with significant differences among Control treatment and RDI treatments (Table 2.3).

Table 2.3 Effects of irrigation on annual and accumulated increase in TCSA, winter pruning of new wood, winter pruning of old wood, total pruning and total pruning per TCSA during the years 2009-2013.

Parameters	Treatments	2009		2010		2011		2012		2013		Accum.	
Increase in TCSA (cm^2)	Control	77	a	83	a	76	a	77	a	76	a	389	a
	RDI-20-60	56	b	60	b	57	b	46	b	65	b	284	b
	RDI-0-30	52	b	59	b	57	b	41	b	65	b	274	b
	ANOVA	***		***		**		**		**		***	
Winter pruning of new wood (kg $tree^{-1}$)	Control	13.8	a	19.0	a	11.0	a	7.5	a	10.2	a	62	a
	RDI-20-60	8.1	b	13.3	b	7.2	b	5.5	b	9.2	a	43	b
	RDI-0-30	7.5	b	13.7	b	7.0	b	5.1	b	8.8	a	42	b
	ANOVA	***		***		**		*		n.s.		***	
Winter pruning of old wood (kg $tree^{-1}$)	Control	9.6	a	7.8	a	3.1	a	2.8	a	2.1	a	25	a
	RDI-20-60	5.0	b	6.2	b	3.6	a	2.1	a	1.9	a	19	b
	RDI-0-30	5.3	b	5.8	b	2.5	a	1.8	a	1.5	a	17	b
	ANOVA	***		**		n.s.		n.s.		n.s.		***	
Total pruning (kg $tree^{-1}$)	Control	23.4	a	27.3	a	16.1	a	14.3	a	20.3	a	101	a
	RDI-20-60	13.1	b	19.9	b	12.6	b	11.1	b	17.7	b	74	b
	RDI-0-30	12.8	b	20.0	b	11.8	b	10.4	b	16.0	b	71	b
	ANOVA	***		***		*		*		*		***	
Total pruning per TCSA (g cm^{-2})	Control	79.6	a	72.3	a	35.5	a	27.0	a	33.5	a	248	a
	RDI-20-60	52.3	b	64.0	a	34.3	a	26.7	a	37.0	a	214	b
	RDI-0-30	48.8	b	62.5	b	31.3	a	24.7	a	33.2	a	201	b
	ANOVA	***		***		n.s.		n.s.		n.s.		***	

Total pruning is the sum of summer pruning and winter pruning (new + old wood). Values within columns followed by different letters are significantly different according to Duncan´s Multiple Range test (P=0.05). *, **, ***, n.s., Significant at P = 0.05, 0.01, 0.001, or non-significant, respectively. Each value is the mean of 16 trees.

There was a linearly correlation between canopy volumes before winter pruning (Fig. 2.5A) and annual increase in TCSA (Fig. 2.5B) versus total pruning. But while the first was adjusted to a polynomial relationship, the second was adjusted to a linear relationship.

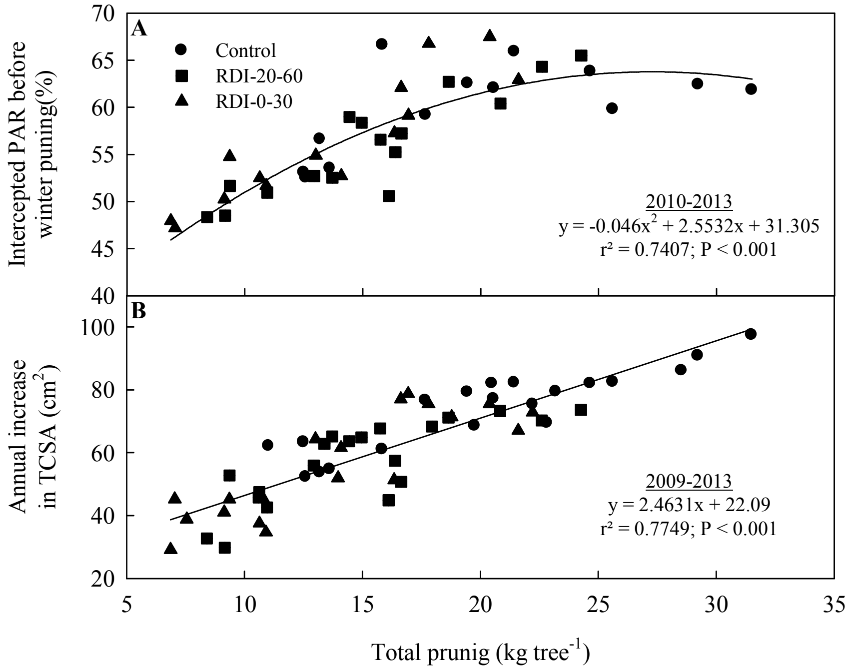

Fig. 2.5 Relationship between intercepted PAR before winter pruning (A) and annual increase in TCSA (B) and the total pruning during the years 2009-2013. Each data point is the average value per each experimental plot.

2.3.4. Yield determinations

The average yield and fruit number per tree were significantly higher for RDI treatments (Fig. 2.6A and B), instead water stress applied during stage II significantly reduced average fruit fresh weight (Fig. 2.6C). The average yield increase due to RDI was 19% for RDI-20-60 and 14% for RDI-0-30 respect to Control. The corresponding values for fruit number per tree were 30 and 35%, respectively. Average fruit fresh weight was reduced in an 8% and 15% for RDI-20-60 and RDI-0-30, respectively. There were some trends in individual years; the mean yield obtained in the orchard in 2009 was much lower than in other years (Fig. 2.6A). No significant differences in yield parameters were found in 2009 and 2013, except in fruit fresh weight in 2009, where RDI treatments had lower fruit fresh than Control. RDI treatments induced a higher yield compared to Control treatment in 2010, 2011 and 2012, because fruit number per tree in these treatments were higher than Control treatment (Fig. 2.6A and B). Fruit fresh weight was also the lower for these treatments in these years (Fig. 2.6C). Due to the important reduced in vegetative growth in RDI treatments which led to a consistent increase in yield per canopy volume at harvest, fruit number per canopy volume at harvest and yield per total pruning, with significant differences between RDI treatments and Control treatment (Fig. 2.6D, E and F).

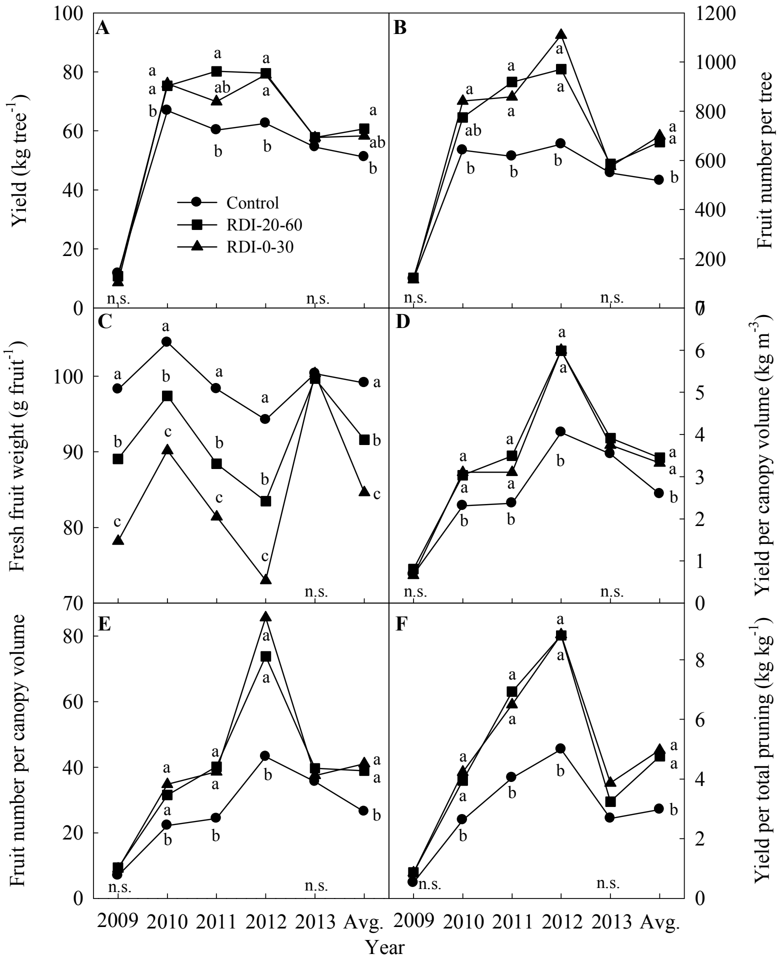

Fig. 2.6 Effects of irrigation on annual and average yield (A), fruit number per tree (B), fruit fresh weight (C), water use efficiency (WUE) (D), fruit number per canopy volume at harvest (E) and yield per total pruning weight (F) during the years 2009-2013. Each value is the mean of 16 trees. For each irrigation treatment, different letters are significantly different at $P < 0.05$ according to Duncan´s test.

Fruit size distribution shifted towards larger fruits with increasing irrigation level, with higher percentage of fruits >59 mm in Control than in RDI strategies (Fig. 2.7). Usually, the most common fruit size distribution in the three irrigation treatments was

56-59 mm. For commercial category of 59-61 mm, Control treatment had higher percentages than deficit irrigation treatments in 2011 and 2012, and for commercial category of > 61 mm, Control treatment was clearly above those deficit irrigation treatments (Fig. 2.7). The average proportion of fruit <53 mm increased from 16% for Control treatment to 28% and 43% for RDI-20-60 and RDI-0-30, respectively, with significant difference between irrigation treatments (Fig. 2.7F). The corresponding proportion for fruits of >61 mm were 19%, 9% and 6% for Control, RDI-20-60 and RDI-0-30, respectively, with significant differences between Control treatment and RDI treatments.

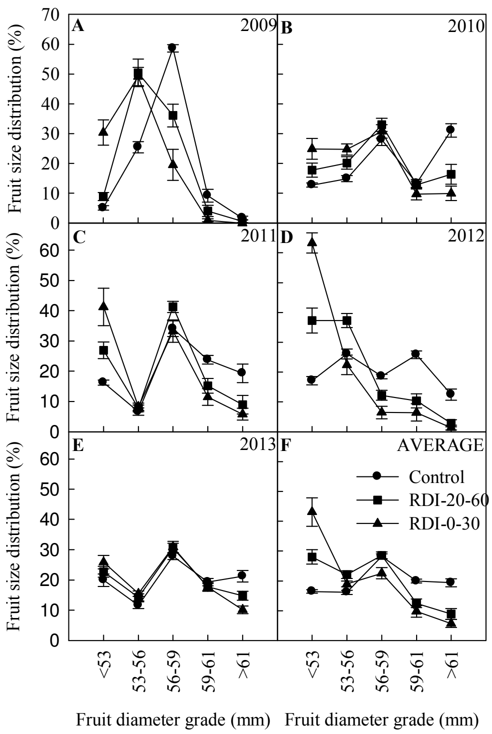

Fig. 2.7 Fruit size distribution in response to different irrigation treatments during the 2009 (A), 2010 (B), 2011 (C), 2012 (D), and 2013 (E). Each value is the mean of 16 trees ± standard error.

There was a linear regression between fresh fruit weight and the minimum Ψ_{stem} measured at the end of stage II of fruit growth (Fig. 2.8). Fruit fresh weight decreased with decreasing Ψ_{stem}, from 100 g fruit^{-1} with a Ψ_{stem} of -1.0 MPa to 65 g fruit^{-1} with a Ψ_{stem} of -2.9 MPa.

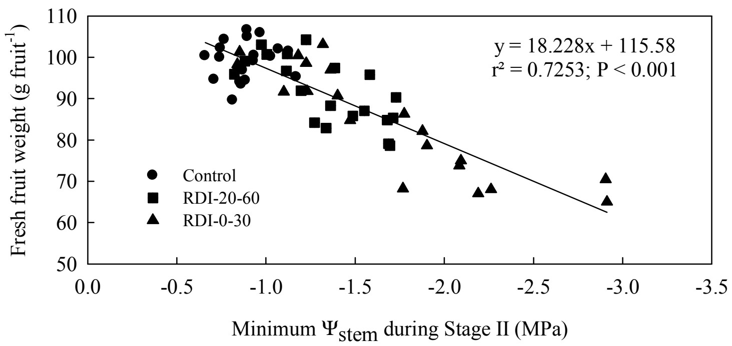

Fig. 2.8 Relationships between midday stem water potential (Ψ_{stem}) and fruit fresh weight for 'Angeleno' plum during the years 2009-2013. The values for Ψ_{stem} correspond to the most stressed day during phase II (last day of the period). Each data point is the average value per each experimental plot.

Figure 2.9 shows the relationship between fruit number per tree with yield and fruit fresh weight. These relationships fitted a quadratic equation, and showed a good correlation. The increase of fruit number per tree increased yield (Fig. 2.9A) and decreased fruit fresh weight (Fig. 2.9B), ranging from 41 kg tree^{-1} and 100 g fruit^{-1} with 400 fruit tree^{-1} to 85 kg tree^{-1} and 72 g fruit^{-1} with 1200 fruit tree^{-1}.

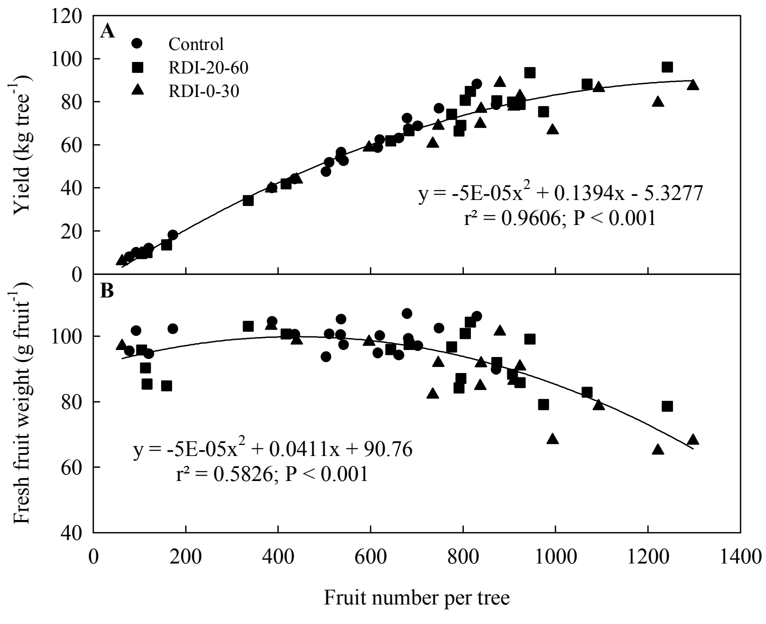

Fig. 2.9 Relationship between yield (A) and fresh fruit weight (B) and the fruit number per tree during the years 2009-2013. Each data point is the average value per each experimental plot.

2.3.5. Economic assessment and water use efficiency

Table 2.4 shows the rates of economic evaluation and the indices of irrigation water efficiency. GI and PC were not significant differences, except in 2009 where Control treatment had higher GI and PC than RDI treatments (Table 2.4). Reducing the water supply during stage II and post-harvest led to a 46% and 16% higher average GM in RDI-20-60 and RDI-0-30 respectively, compared to Control treatment (Table 2.4). These results indicate that there was great difference between RDI-20-60 and Control treatments with RDI-0-30 treatment. The profit margin was higher in RDI-20-60 with 0.14 € $kg^{-1}$and similar in Control and RDI-0-30 with 0.12 € kg^{-1} (Table 2.4). Bearing in mind the 26% and 34% water saving obtained in RDI-20-60 and RDI-0-30 (Table 2.1), respectively, plus the fact that plum yield increased compared to Control (Table 2.4), the WUE increased notably in these treatments: 4.4 and 4.6 kg of plums were produced per cubic meter of water provided in RDI-20-60 and RDI-0-30, respectively, compared to only 2.8 kg in Control (Fig. 2.6). This was reflected in the greater WEE in the RDI treatments with significant differences between RDI-20-60 and Control (Table 2.4). IAUP was lower in RDI treatments than in Control: RDI-20-60 and RDI-0-30 needed 34 and 30 liters of irrigation for obtain one fruit, respectively, compared to 55 liters in Control (Table 2.4).

Table 2.4 Effects of irrigation on gross income (GI), production cost (PC), gross margin (GM), water use efficiency (WUE), water economic efficiency (WEE) and irrigation applied to produce one fruit (WAF).

Parameters	Treatments	2009		2010		2011		2012		2013		Avg.	
GI ($€ ha^{-1}$)	Control	1904	a	12,965	a	8981	b	14,094	a	12,519	a	10,093	a
	RDI-20-60	1798	ab	13,771	a	10,857	a	16,061	a	12,942	a	11,086	a
	RDI-0-30	1334	b	13,212	a	8752	b	14,757	a	12,683	a	10,148	a
	ANOVA	*		n.s.		*		n.s.		n.s.		n.s.	
PC ($€ ha^{-1}$)	Control	6016	a	8756	a	8060	a	7686	a	7489	a	7602	a
	RDI-20-60	5161	b	8406	a	8489	a	7937	a	7266	a	7452	a
	RDI-0-30	5003	b	8332	a	7954	a	7823	a	7162	a	7255	a
	ANOVA	***		n.s.		n.s.		n.s.		n.s.		n.s.	
GM ($€ ha^{-1}$)	Control	-4112	b	4209	b	921	b	6408	b	5030	a	2491	b
	RDI-20-60	-3363	a	5365	a	2368	a	8124	a	5675	a	3634	a
	RDI-0-30	-3669	ab	4880	b	799	b	6935	b	5521	a	2893	b
	ANOVA	*		*		*		*		n.s.		*	
WUE ($kg\ m^{-3}$)	Control	0.7	a	4.1	b	3.1	b	3.1	b	2.9	a	2.8	b
	RDI-20-60	0.9	a	6.3	a	5.8	a	5.4	a	3.5	a	4.4	a
	RDI-0-30	0.9	a	6.9	a	6.1	a	5.6	a	3.6	a	4.6	a
	ANOVA	n.s.		***		***		***		n.s.		***	
WEE ($€ m^{-3}$)	Control	-0.70	a	0.65	b	0.13	b	0.83	b	0.66	a	0.31	b
	RDI-20-60	-0.87	b	1.17	a	0.49	a	1.48	a	0.84	a	0.62	a
	RDI-0-30	-1.16	c	1.17	a	0.21	ab	1.32	a	0.83	a	0.47	ab
	ANOVA	***		*		*		***		n.s.		*	
IAUP ($l\ fruit^{-1}$)	Control	148.2	a	27.0	a	28.0	a	30.1	a	39.72	a	54.60	a
	RDI-20-60	93.8	b	14.4	b	13.2	b	14.4	b	36.38	a	34.42	b
	RDI-0-30	81.2	b	12.7	b	11.4	b	12.0	b	32.87	a	30.04	b
	ANOVA	**		***		***		***		n.s.		***	

Values within columns followed by different letters are significantly different according to Duncan´s Multiple Range test (P=0.05). *, **, ***, n.s., Significant at P = 0.05, 0.01, 0.001, or non-significant, respectively. Each value is the mean of 16 trees.

2.4. Discussion

2.4.1. Effect of irrigation on plant water status

Applied water to Control treatment was calculated by multiplying reference evapotranspiration (ET_o) by the crop coefficient (K_c) (Allen et al., 1998). However, the determination of ET_c through soil water balance method has led to deviations between actual needs and estimated according to the FAO method (Ayars et al., 2003; Martín-vertedor, 2010; Samperio et al., submitted to Agricultural and Forest Meteorology).

Moreover, RDI strategies were established by applying a certain percentage of reduction over the considered optima applied water. Nevertheless, soil and climatic conditions as well as crop management such as fruit load or time and intensity of summer pruning interact with the irrigation reduction for determining plant water status. It is therefore necessary a reliable plant water status assessment in order to help in scheduling irrigation during the irrigation period. The range in Ψ_{stem} for Control between -0.6 to -0.7 MPa during stage I, -0.6 to -0.8 MPa during stage II, -0.7 to -1.1 MPa during stage III and -0.9 to -1.1 MPa during post-harvest (Fig. 2.2) agree quite well with published values for peach (Garnier and Berger, 1985), European plum (McCutchan and Shackel, 1992) and Japanese plum (Johnson et al., 1994; Intrigliolo and Castel, 2010). These values might be used as threshold values for irrigation scheduling in late maturing Japanese plum under well-watered conditions. In RDI treatments, Ψ_{stem} values decreased after water restriction started, during stage II reached up -1.75 MPa in RDI-20-60 (Fig. 2.2A, D) and -2.60 MPa in RDI-0-30 (Fig. 2.2D) with a maximum decrease of 0.019 MPa day^{-1} and 0.036 MPa day^{-1}, respectively. The minimum average Ψ_{stem} value obtained in RDI-20-60 and RDI-0-30 are at the same level as that obtained by Girona et al. (2004) in peach (-1.7 MPa) and that obtained in plum trees grown in a deep soil with a high clay profile (Naor et al., 2004) (-2.2 MPa). Tree water status was recovered when irrigation was returned to full irrigation during stage III in all years (Fig. 2.2), where different Ψ_{stem} was reached, different crop load was obtained and different summer pruning intensities were done. In other experiment (Intrigliolo and Castel, 2010), when deficit irrigation was applied for extended period during stage II and then returned to full irrigation during rapid fruit growth, the Ψ_{stem} of the RDI treatments remained significantly lower than in Control treatments. This was probably because the phase II was longer than usual and therefore, the phase II was so short that not allow the recovery of trees water status to Control level. It is important, after a severe or extended period of plant water stress, that trees are able to return to their optimum plant water status before harvest (Intrigliolo and Castel, 2010). The time that a tree takes to return to the Control status after a deficit irrigation treatment is also an important factor because phase III is a critical period for the application of deficit irrigation (Torrecillas et al., 2000; Girona et al., 2004; Intrigliolo and Castel, 2005). Post-harvest Ψ_{stem} in RDI-20-60 and RDI-0-30 treatments reached about -1.35 to -2.0 MPa, respectively at the end of the season in 2010 and 2009, respectively (Fig. 2.2A and B) and no reduction of yield resulted in 2011 and 2010, respectively (Fig. 2.6A and B). At this moment begins leaf senescence and water stress does not affect the accumulation of reserves or floral differentiation (Johnson et al., 1992, 1994; Intrigliolo and Castel, 2004, 2005, 2010), indicating the possibility of important water savings during post-harvest period. Therefore, these thresholds may also provide a tool to assist in the irrigation scheduling in late maturing Japanese plum orchard under RDI conditions.

2.4.2. Effect of irrigation on fruit growth and vegetative growth

Fruit growth in stage II was reduced in RDI treatments during 2010-2012 (Fig. 2.3A-C), because tree water stress was extended for a period of time longer than two months, however, in 2013, RDI was extended for a period of one months and tree water status was better than in other years and therefore, fruit growth in RDI treatments was not reduced compared with Control trees (Fig. 2.3D). Reapplying water at Control levels (100% ET_c) at the beginning of the stage III did not promote compensatory growth of the fruit in the year when this was reduced (Fig. 2.3A-C). Fruit growth was stimulated due to an accelerated rate of growth when irrigation was increased to 100% ET_c during the subsequent stage in pear (Caspari et al., 1994), apple (Ebel et al., 1995), apricot (Torrecillas et al., 2000) and peach (Girona et al., 2003), although no such observation has been found in peach (Girona et al., 2005b) and apricot (Pérez-Pastor et al., 2014) when full irrigation was applied beyond the end of stage II.

Intercepted PAR in RDI treatments was only reduced in two experimental years. In the last year of experiment there were not significantly differences between treatments (Fig. 2.4A), provides an evidence that no negative effects in the long-term due to carry-over effects from one year to the next was inflicted by the RDI treatments in tree size, because intercepted PAR along the seasons was similar for all three treatments (Fig. 2.4A). Moreover, summer pruning weight was not affected by the previous year's deficit irrigation, which is other evidence that deficit irrigation in post-harvest period did not affect pre-harvest vegetative growth in the next year. Summer pruning is a common practice in our area to promote the inner zone lighting tree to enhance flower buds quality, but it reduces the effect of water deficit on vegetative growth. Therefore, summer pruning decreases intercepted PAR (Fig. 2.4A), which may reduces the water requirements of the trees and delay de appearance of leaf wilting symptoms. In contrast, Johnson et al. (1992) found a lower shaded area in deficit irrigated peach trees during the post-harvest. However, the more precise vegetative growth parameters (TCSA and total pruning), seems to be a more reliable parameter for detecting differences between irrigation treatments. A decrease in vegetative growth (both shoot elongation and trunk growth) due to reduced irrigation water is one of the most sensitive processes to water stress in most deciduous fruit trees (Hsiao, 1990; Moriana and Fereres, 2002; Nortes et al., 2005; Marsal et al., 2008). In this experiment, TCSA and total pruning weight were seen to be very sensitive to water deficit (Fig. 2.4B and Table 2.3), which led to reductions in tree size, but with similar intercepted PAR. These result are in agreement with reported in almond (Girona et al., 2005a), peach (Girona et al., 2005b), plum (Intrigliolo and Castel, 2005) and apricot (Pérez-Pastor et al., 2009). However, in these previous researches a reduction in vegetative growth was associated with yield loss, because of an reduced on bloom or fruit set the next season and consequently fruit number per tree (Goldhamer and Viveros, 2000; Torrecillas et al., 2000; Girona et al., 2003; Naor et al., 2006). Despite promoting a slight water deficit, the reduction of irrigation water amount to 20% ET_c in the RDI-20-60 treatment during the stage II, slowed vegetative growth, which was not compensated when the irrigation water was raised to 100% ET_c at the onset of stage III. The fact that stage III of fruit growth in stone fruits coincides with the second shoot growth period suggest that any competition for photo-assimilates is resolved in favor of the first (Forshey and Elfving, 1989). The RDI-0-30 treatment had higher water savings than RDI-20-60 (Table 2.1), although intercepted PAR, TCSA and total pruning weight were not significant different (Fig. 2.4 and Table 2.3). This may be because even slight water stress can causes a halt to vegetative growth as cell expansion is the physiological process which is most sensitive to water stress (Hsiao, 1973).

A very good and highly significant correlation was observed between total pruning weight and intercepted PAR before winter pruning (Fig. 2.5A) and increase in TCSA at each year (Fig. 2.5B), indicating that total pruning can be reduced with reducing intercepted PAR and trunk growth in accordance with the rate of accumulated water stress (Girona et al., 2003). These reductions in vegetative growth in RDI treatments can lead to smaller trees and therefore better orchard managements to farmers, saving costs of pruning, thinning, harvesting and other cultural practices (Pérez-Pérez et al., 2010). The patterns of vegetative growth, were similar between years, indicated that fruit number per tree did not reduce tree vigor. These result are similar than obtained by

Intrigliolo et al. (2013) in a mid-season maturing plum. However, in an experiment with peach trees (Girona et al., 2003) shown that the patterns of vegetative growth were different in a year with high crop load as a result of the differences in fruit sink strength between treatments, which highlighted the importance of fruit load as a vegetative growth regulator.

2.4.3. Effect of irrigation on yield parameters

RDI during stage II reduced fruit fresh weight (Fig. 2.6C) except in 2013, while RDI did not negatively affect fruit number per tree and yield in 2010, 2011, 2012 and 2013 (Fig. 2.6A and B). Probably because in late-maturing cultivars, such as ‘Angeleno’, flower initiation occurs in early to mid July, because in years where water stress on early July was not very severe (less than -2.0 MPa as in 2010 and 2011) a linear correlation between minimum Ψ_{stem} reached at this stage and fruit number per tree in following year was found (data not shown). However, when severe water stress was reached on early July (between -2.0 and -3.0 MPa as in 2012), fruit number per tree in the next year was reduced. In 2009, this effect was not observed, probably because when flower initiation occurred, tree water status of RDI treatments had yet recovery. This could disagree with that proposed by Faust (1998) in an early-maturing cultivar, which suggested that the flower initiation occurs just after harvest in late July to early August. Therefore, future research in Japanese plum should be aim to determine the time when flower initiation and bud differentiation occur, and the stress level that can be supported during this time, in order to carry out a more comprehensive tree physiological behavior. In early maturing plum, Johnson et al. (1994) observed less flowering, since the water deficit occurred during bud differentiation. The severity of the water deficit during bud differentiation can influence the impact on flowering and on fruit set, with drought reducing flowering in some cases (Girona et al., 2003) and increasing it in others (Johnson et al., 1992). In mid-season Japanese plum Intrigliolo and Castel, (2005) indicated that combined RDI after three year did not affect yield, but, in the last year of that experiment there was a reduction in yield compared with Control trees, as a consequence of the cumulative effects of water deficit on flowering, fruit set and tree growth. The most probable reason for this was that tree size (as considered trunk perimeter and shaded area) in the experiment of intrigliolo and Castel, (2005) was lower than in our experiment, and thus an additional reduction in tree size could reduce fruit number per tree.

Fruit size distribution was shifted towards smaller fruits at the lower irrigation level (Fig. 2.7). The years in which higher water stress was reached during stage II in RDI-0-30, higher proportion of fruits <53 mm were obtained, indicating that the demand for assimilates is below the maximum assimilate production rate under conditions of minimum water stress and therefore potential fruit size is not reached (Naor et al., 2008). Similarly, fruit fresh weight increased with the improvement of plant water status (Fig. 2.8). This suggest that Ψ_{stem} may be used as a good predictor of fruit size, over a wide range of Ψ_{stem} (-0.65 to -2.9 MPa) as reported for pear (Ramos et al., 1994; Naor et al., 2000), apple (Naor et al., 2008), peach (Berman and DeJong, 1996) and Japanese plum (Naor, 2004). However, the increase of fruit number per tree increased yield (Fig. 2.9A), and as a result of the higher fruit number per tree in RDI treatments, fruit fresh weight was reduced for these treatments (Fig. 2.9B), which indicate a significant limitation of assimilates at high crop loads (more than 1000 fruits tree^{-1}) under RDI (DeJong and Grossman, 1995). The decrease in fruit fresh weight with increasing fruit number per tree is in agreement with reports on peach (Berman and DeJong, 1996), nectarine (Naor et al., 1999; 2001) and Japanese plum (Naor et al., 2004). For 'Angeleno' plums, and depending on market prices, the total number of fruit per tree that are left after thinning should be chosen to optimize profits by obtaining a maximum yield with a maximum fresh fruit weight. At a low fruit number per tree (less than 1000 fruits per tree), there was not difference between the Control and RDI treatments, suggesting that at low fruit number per tree, the yield and fruit fresh weight is similar for both the Control treatment and those submitted to RDI.

2.4.4. Effect of irrigation on economic assessment

Fruit size is an important component for obtaining high economic return in fresh-market 'Angeleno' plum, but a higher fruit number per tree, which will produce smaller fruits, may be offset by an increase in yield, long as the yield is within commercial sizes. RDI has been shown as an effective technique in stone fruit to reduce applied water. In our growing conditions, Control trees required between 591-776 mm of irrigation water between 2009 and 2013 (Table 2.2). RDI during stage II and post-harvest saved up to a 28-30% in RDI-20-60 and up to a 32-47% in RDI-0-30 during 2009-2012. Reducing the water applied during stage II and post-harvest led to a higher GM in RDI treatments compared to Control (Table 2.4). The increase in GM was due to higher GI and lower PC, mainly due to an increase in yield and a reduction in annual pruning costs (28%) and applied water and electricity consumption (26%) in RDI treatments compared to Control (Table 2.4). The GM would have been greater if we had suppressed summer pruning, as RDI techniques produce an effective vigor control, especially in adult orchards where vegetative growth is less intense. The ratio GM/PC was higher for RDI treatments than Control with 49% and 40% greater for RDI-20-60 and RDI-0-30, respectively (Table 2.4). These results are equal to those obtained in early-maturing peach and apricot (García-García, 2007) and higher to obtained in almond (García-Garcia et al., 2004), plum (García-García, 2007) and early maturing peach (García-García and García, 2012). WUE ranged from 4.4 to 4.6 kg m^{-3} for RDI treatments (Table 2.4). These ranges were not very different to those obtained in peach (Goldhamer et al., 2002; Dichio et al., 2007), where WUE were around 4.1-4.7 kg m^{-3}. This is reflected in the greater WEE in RDI treatments than Control, and therefore, the reduction in fruit size is compensate for the increase in yield and reduction in irrigation cost (pruning, water and electricity). These results are in disagreement with those found in Japanese plum (Intrigliolo and Castel, 2010), where similar values of WEE in RDI and fully irrigated trees were obtained. The IAUP was lower under RDI; each fruit were produced with 22 and 25 liters less than in the Control treatment.

2.5. Conclusions

Moderate regulated deficit irrigation applied during stage II and post-harvest in a late maturing plum, in the long-term, save water, produces an effective control of tree vigor, and increased fruit number per tree, yield and the grower's final return respect to well irrigated trees. A severe and extended water deficit during fruit growth led to fruit size reductions. However, the reduction of water deficit period during fruit growth and lower stress intensity had no detrimental effects on fruit growth and fruit size distribution. Therefore, if a farmer wants to apply RDI during stage II of fruit growth, it is necessary determined very accurately the end of this stage to apply the total water needs and not affect fruit growth. Further research should focus on determine the end of stage II and the effect of deficit irrigation on flower initiation as well as in fruit quality at harvest, with the intent of developing a drought management strategy that will reduce water use while preserving marketable yield and quality.

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Chapter 3: Effect of crop load and combined deficit irrigation during phase II and post-harvest in Japanese plum trees cv. Angeleno

Abstract

The combined effect of irrigation and crop load on tree water status, vegetative growth, yield, fruit quality and income in Japanese plum (*Prunus salicina* cv. Angeleno) was evaluated during two years. Two regulated deficit irrigation applied during phase II of fruit growth and post-harvest were compared with a Control watered according to crop water needs. Three thinning treatments were imposed within each irrigation treatment. Deficit irrigation reduced midday stem water potential (Ψ_{stem}) and stomatal conductance (g_l) during phase II in both experimental years and during post-harvest in 2011. The deficit irrigation treatments were suitable for controlling tree vigor without decreasing fruit yield. Deficit irrigation had a negative effect on fruit fresh weight and soluble solid concentration/titratable acidity ratio were higher in deficit irrigation treatments. In the year when crop load was higher, fruit thinning increased fruit fresh weight, firmness and titratable acidity. No interaction was found between irrigation and crop load. In these growing conditions is recommended to maintain Ψ_{stem} and g_l during phase II above -1.5 MPa and 110 mmol (H_2O) m^{-2} s^{-1} respectively. A crop load lower than 1100 fruits per tree reduces yield and adds an extra application cost which reduces the grower's final return.

Key words: stem water potential, stomatal conductance, vigor control, fruit yield, fruit quality, profit

3.1. Introduction

Agricultural production has been frequently associated with high water consumption. The competition for water among agricultural, industrial and population areas, the rising costs associated with irrigation practices (electricity, water, labor, etc) and the increasingly limited availability of this resource exacerbated by climate change, require a rational use of water in agriculture. This is particularly important in Mediterranean production areas where the hot and dry summers make summer crops totally dependent on irrigation. In this context, Regulated Deficit Irrigation (RDI) could be useful to reduce water use in agriculture and to optimize grower's return.

In several fruit tree species it has been demonstrated that RDI can be applied during certain phenological periods of crop development without detrimental effects to yield (Behboudian and Mills, 1997; Naor, 2006; Fereres y Soriano, 2007). In peach, a water reduction below crop water needs could be a reliable RDI strategy during pit hardening phase (phase II of fruit growth). During this period, fruit growth is slow and its sensitivity to water stress is lower than in other fruit growth periods (Girona et al., 2004; Naor, 2006). Saving water is the most direct benefit of this strategy, but other benefits could be attained like vigor control and better fruit quality (Behboudian et al., 2011). Post-harvest water stress is another option: it offers the opportunity of saving water without interference with fruit growth. However, it must be applied with caution as severe water stress during post-harvest could have a detrimental effect on floral bud quality, tree reserves and, consequently, in the next season yield in peach (Girona et al., 2003; Naor et al., 2005), apple (Ebel et al., 2001) and almond (Goldhamer and Viveros, 2000; Marsal et al., 2008). To attain the maximum benefits of such strategies, RDI has been combined during phase II and post-harvest in peach (Gelly et al., 2003, 2004) and apricot (Perez-Pastor et al., 2009). There is little information on the application of this technique to Japanese plum trees, despite the importance of this crop.

In the last years, the most important fruit producing areas of Spain such as Extremadura have changed pear and apple crop surface area for Japanese plum orchard. Japanese plum ranks second behind cherry (excluding the vine and the olive), with 25% of its area and 38% of national production mainly concentrated in the province of Badajoz. About 3,848 ha of Japanese plum are equipped with irrigation systems (MAGRAMA, 2012). Nonetheless, in fruit trees maximum profit does not coincide with maximum yield, since a high fruit number per tree gives smaller fruit sizes. In this sense, fruit thinning has been used as a useful technique in improving fruit size when deficit irrigation is applied during a sensitive phase of fruit growth (Lopez et al., 2006: Marsal et al., 2008). Lower crop load should improve tree water status by improving fruit size, yield and quality under deficit irrigation (Girona et al., 2004; Naor et al., 2004; Intrigliolo and Castel, 2010; Marsal et al., 2010). With the above in mind, we conducted field experiments over two growing seasons to understand the limitations and possibilities of using RDI and crop load interactions in Japanese plum, taking into account physiological responses (water relationships and leaf conductance), tree growth, yield, fruit quality and several indicators of grower’s return. This will make it possible to determine the most suitable RDI + fruit thinning strategy in Japanese plum orchards under the agronomical conditions of the experiment.

3.2. Material and methods

3.2.1. Experimental plot and climatic conditions

The experiment was performed over two years (2010-2011) in a 1.0 ha orchard of a late-maturing Japanese plum (*Prunus salicina* Lindl. cv. Angeleno), located on “Finca

La Orden-Valdesequera" experimental farm, Badajoz (38°51'N, 6º40'W, elevation 184 m), Spain. Plum trees were planted in spring 2005 at a spacing of 6 x 4 m, in an east-west row orientation (5º towards north). Trees were grafted on *Mariana* 2624 rootstock and were trained to an open vase system with four main scaffold branches per tree. *Prunus salicina* cv. Larry Ann and cv. Fortune were planted in guard rows in a sufficient number as pollinizers. Bee hives were used at flowering to ensure optimal pollination. The climate of the area is Mediterranean with mild Atlantic influence, dry and hot summers, with high daily irradiance and evaporative demand. The average annual temperature was 16.2 °C (1992-2012) and average annual rainfall and reference evapotranspiration (ET_o) were 438 mm and 1297 mm, respectively. The soil was in the order Alfisol, suborder Xeral and in the major Haploxeralf group, with mainly acid pH, low organic matter content and high bulk density, light colors, moderate to weak structure, with normal and even very high content of P_2O_5, low content of Na^+ and K^+ and low cation exchange capacity. The texture was loam, with low stone content and depth greater than 2.5 m. The plot was managed according to commercial practices in the area, except for irrigation and fruit thinning during the experimental period.

3.2.2. Irrigation management

The trees were irrigated on a daily basis by a drip irrigation system with four pressure-compensated emitters per tree (4 l h^{-1} for each dripper). There was a single pipeline per tree row, which was located close to the trunk. Trees fully irrigated received full replacement crop evapotranspiration (ET_c) minus effective rainfall. ET_c was calculated by multiplying reference evapotranspiration (ET_o) by the crop coefficient (K_c) (Allen et al., 1998). The Penman-Monteith method was used to determine ET_o. In 2010, K_c was calculated weekly by the soil gravimetric method described by Fereres and Goldhamer (1990). In 2011, K_c was obtained from Allen et al. (1998). Weather data were obtained from an automated weather station located 600 m from the plum orchard.

3.2.3. Irrigation and fruit thinning treatments

In 2010, irrigation began on May 24 and ended on October 5. In 2011 the irrigation season was longer than in 2010 (from April 8 to October 23). The end of the irrigation season coincided with the onset of autumn rains.

The irrigation treatments were applied during phase II and post-harvest (Fig. 3.1). They were: (Control) irrigated at 100% ET_c during all the season to completely cover crop water requirements; (DI-20-60) applying 100% ET_c in phase I and phase III, 20% ET_c during phase II and 60% ET_c during post-harvest; (DI-0-30) applying 100% ET_c in phase I and phase III, no irrigation during phase II and 30% ET_c during post-harvest. Each irrigation treatment was combined with three levels of crop load by applying three fruit thinning intensities 62 and 57 days after full bloom in 2010 and 2011, respectively. Fruit thinning levels were: no thinning (NT); commercial thinning (CT) leaving 75% of the crop load; and intense thinning (IT) leaving 50% of the crop load.

3.2.4. Experimental design

A randomized split-plot design was used with four block replicates. The whole-plot factor was irrigation and the sub-plot factor was fruit thinning. Each main plot consisted of four adjacent rows of four trees. Each sub-plot consisted of three trees in the first, third and fourth rows. The criterion for choosing crop load levels was based on fruit number per tree at the thinning time. Trees with highest and lowest fruit number per tree within the sub-plot were chosen as no thinning and intense thinning, respectively. Commercial thinning was applied to the remaining trees in the sub-plot. An adjacent guard row existed between the main plots. A total of 36 experimental trees were monitored.

3.2.5. Applied water and plant water status

The irrigation volumes were recorded daily by digital water meters (CZ2000-3M, Contazara, Zaragoza, Spain) installed on each replicate. Midday stem water potential (Ψ_{stem}) was measured with a pressure chamber (Model 3005; Soil Moisture Equipment, Santa Barbara, CA, USA.) following the recommendations of Shackel et al. (1997). Measurements were taken at solar noon from leaves situated near the base of the trunk of each experimental tree (two leaves per tree). Measurements were carried out every 15 days during phase I and post-harvest, and once a week during phase II and phase III. Stomatal conductance (g_l) was measured with a steady-state, continuous flow porometer (PP Systems PMR-5, Hitchin, Hertfordshire, UK) between 10:00 and 11:00 h solar time from two leaves for each experimental tree. We selected mature, well-exposed sunlit leaves located in the middle of current growth year shoots. g_l and Ψ_{stem} were measured the same day.

3.2.6. Phenology, reproductive and vegetative growth of cv. Angeleno

The growth stages were determined weekly from bud-break to leaf fall using the Baggiolini scale (Baggiolini, 1952). Trunk cross sectional area (TCSA) was determined by measuring the trunk perimeter with a tape measure, about 15 cm above ground level, as $(Ø/(2 \times \Pi))^2 \times \Pi)$, where Ø is the trunk perimeter. Canopy volume was calculated assuming a conical shape from telescopic pole measures with two diameters at right angles and the height of the canopy, as $(\Pi \times r^2 \times h)/3$ where r is the mean canopy diameter (average of S-N diameter and E-W diameter) and h the canopy height. Summer pruning was carried out in the first half of May, but the weight of wood removed by pruning was monitored only in 2011. Winter pruning was carried out in December and the vegetation removed by pruning was weighed in both years. A sample of known fresh weight was dried at 65ºC in a forced air oven (DryBig 250, Borel Swiss S.A, Neuchâtel, Switzerland) and the dry weight was then recorded. The dry/fresh ratio was calculated for the sample and this ratio was then applied to the total fresh weight of pruning to determine the total dry weight.

3.2.7. Yield and fruit quality determinations

Fruits were harvested in a single picking, according to commercial criteria of fruit color, firmness between 3.0-4.0 kg cm^{-2} and soluble solid concentration (SSC) above 12 ºBrix. Average fruit mass and fruit number per tree were determined using a commercial grading machine (Greefa Machinebouw B.V., Tricht, Holland), separating fruit into four categories (<53; 53-56; 56-59; >59 mm). A sample of 30 fruits of known fresh weight per tree was taken and dried at 65ºC in a forced air oven and the dry weight recorded. This weight was applied to the total fresh weight of harvest to determine the total dry weight. Mean fresh and dry fruit weight at harvest was estimated by dividing the total fresh and dry mass of the harvested fruits per tree by the number of fruits. Several harvest indices were determined from harvest data: water use efficiency (WUE, kg m^{-3}) calculated as yield divided by irrigation applied plus effective rainfall until harvest (Oweis et al., 1999; Zhang et al., 1999), crop production efficiency (CPE, kg cm^{-2}) calculated as yield divided by TCSA, yield divided by pruning weight and fruit number per canopy volume.

To assess fruit quality, thirty representative fruits per experimental tree were sampled at harvest. Fruit samples were taken to a laboratory for automatic control of fruit quality

(Pimprenelle, Setop Giraud Technologie, Cavaillon, France). The parameters measured for individual fruit were: soluble solid concentration (SSC, ºBrix) and firmness (FR, kg cm^{-2}). A set quantity of each fruit's juice was taken to determine the sample's global titratable acidity (TA, g malic acid l^{-1}). The juice of all the fruit was gathered, weighed and compared to the cumulative weight of all the fruit, determining juiciness (JI, %). TA was determined by titrating with 0.1 N NaOH to an end-point of pH 8.1. The SSC/TA ratio was calculated from SSC and TA data.

3.2.8. Economic indices

Crop accounting was established for a cultivated area of 1 ha in which all the normal agricultural practices of the study area are carried out. This is a comparative analysis of income and costs for different irrigation and fruit thinning treatments during 2010 and 2011. We used cost-benefit analysis (Ballesteros, 2000) to calculate the economic indices which allow the treatments to be compared and any differences to be identified from an economic point of view: gross margin, water economic efficiency, break-even point and irrigation applied per unit of plum. Gross margin (GM, € $tree^{-1}$) was calculated as the difference between gross income and production costs. Water economic efficiency (WEE, € m^{-3}) was calculated as GM per irrigation applied to each treatment. Break-even point (BP) indicates the price per kilo of plum above which the business begins to generate profit. Irrigation applied per unit of plum (IAUP, l $fruit^{-1}$) indicates the ratio between irrigation applied to each treatment and fruit number per tree. Gross income (GI, € $tree^{-1}$) was calculated for each treatment bearing in mind the prices received by farmers per kilogram of fruit of each commercial category and discounting costs for loading and unloading of the goods (0.009 € kg^{-1}), cold storage (0.018 € kg^{-1}) and marketing (0.1862 € kg^{-1}). Final prices in € kg^{-1} were 0.22, 0.41, 0.45

and 0.49 for 2010 and 0.19, 0.35, 0.37 and 0.41 for 2011 for commercial category <53, 53-56, 56-59 and >59 mm, respectively. Production costs (PC, € $tree^{-1}$) were calculated considering those costs that *a priori* are considered differential between treatments, namely electricity (0.057 € m^{-3}), irrigation (0.022 € m^{-3}), annual pruning (0.099 € kg^{-1}), thinning (0.004 € $fruit^{-1}$) and harvest (0.094 € kg^{-1}). The following costs were considered common to all treatments because they were commonly applied: plant protection products (502 € ha^{-1}), herbicides (72 € ha^{-1}), fertilizers (418 € ha^{-1}), crop insurance (500 € ha^{-1}), and fixed personnel (2100 € ha^{-1}). Similarly, the fixed assets and overheads associated with the regular workforce of the orchard are common to the treatments and therefore not included. We use data from the experiment and other data referring to irrigated plum production in the orchard in the Vegas Bajas del Guadiana.

3.2.9. Statistical analyses

The effects of irrigation treatments on all the parameters were compared for each fruit thinning treatment. The effects of fruit thinning were also analyzed separately for each irrigation treatment. The significance of the irrigation and crop load interaction was also explored. Data were analyzed by analysis of variance (ANOVA) and regression analysis. Statistical significance was established for $P<0.05$. Least Significant Difference (LSD) test was applied to separate means that differed significantly. Statistical analyses were performed using version 2.10.1 of the R statistical package (R Development Core Team, 2009) aided by the version 1.5-4 of R Commander package (Fox et al., 2009).

3.3. Results

3.3.1. Phenology, climatic conditions and applied irrigation

Figure 3.1 shows the date for each phenological stage of the orchard trees for each experimental year. All phenological events took place earlier in 2011 compared to 2010. Bud break was advanced 10 days, flowering 5 days, fruit set 18 days, onset phase I 18 days, phase II 29 days, phase III 15 days and harvest 7 days.

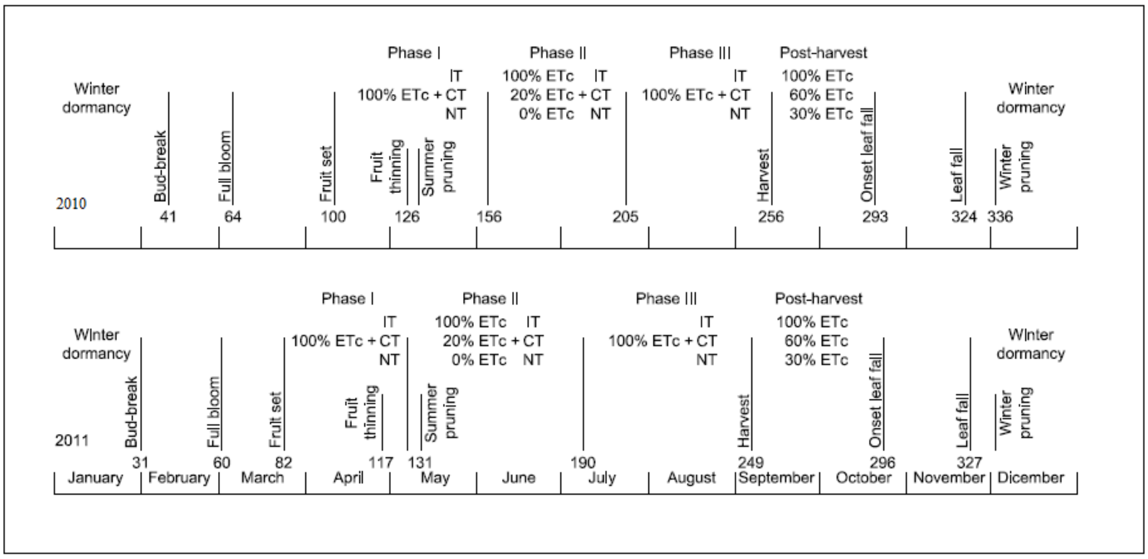


Fig. 3.1 Phenological stages, crop managements, applied treatments and measurements during 2010-2011. The numbers below the lines indicate the day of the year.

Weather conditions varied between years (Table 3.1). During fruit growth, average air temperature was higher and relative humidity lower in 2010 than in 2011. The opposite conditions were observed during post-harvest. Annual precipitation in 2010 was twice that in 2011, with 740 and 378 mm, respectively. During the crop growing season precipitation was similar between years, 163 mm and 147 mm in 2010 and 2011, respectively. ET_c was higher in phase I in 2010 due to the longer duration of the phase and a greater water demand, and for the same reasons was higher in 2011 in phases II, III and post-harvest (Table 3.1). The total annual amounts of water applied (mm) in phase II in 2010 were, respectively, 211, 45 and 3 for Control, DI-20-60, and DI-0-30 (Table 3.1). The respective values during post-harvest were 52, 32, and 17. In 2011, irrigation applied (mm) in phase II was 231, 59 and 4 for Control, DI-20-60, and DI-0-30, and during post-harvest 135, 83 and 43 (Table 3.1), respectively. Total irrigation water savings compared with Control in 2010 were 28% for DI-20-60 and 35% for DI-0-30. Savings in 2011 were 30% and 45%, respectively (Table 3.1).

Table 3.1 Average air temperature (T^a avg), average relative humidity (H^a avg), reference evapotranspiration (ET_o), rainfall (R), crop evapotranspiration (ET_c) and applied water for each irrigation treatment and for the two experimental years in different phases of fruit growth development.

Parameter	Year	Phase I	Phase II	Phase III	Post-harvest	Bud-break – Onset leaf fall
T^a avg	2010	18	23	26	18	19
(ºC)	2011	17	22	24	20	19
H^a avg	2010	63	56	49	66	62
(%)	2011	67	58	56	54	62
ET_o	2010	268	316	317	111	1,164
(mm period^{-1})	2011	173	378	358	178	1,193
R	2010	73	32	0	57	370
(mm period^{-1})	2011	61	54	33	0	240
ET_c	2010	200	271	281	96	941
(mm period^{-1})	2011	122	312	322	150	970
Irrigation (mm period^{-1})	2010					
Control		41	211	338	52	642
DI-20-60		35	45	348	32	460
DI-0-30		44	3	354	17	418
Irrigation (mm period^{-1})	2011					
Control		30	231	299	135	695
DI-20-60		31	59	315	83	488
DI-0-30		31	4	303	43	381

3.3.2. Effect of irrigation and fruit thinning on tree water status

Control trees had higher Ψ_{stem} and g_l values than deficit irrigation trees during phase II in both experimental years and during post-harvest in 2011 (Figs. 3.2-3.3). Significant differences in Ψ_{stem} between Control and deficit irrigation trees were observed 12 and 19 days after the onset of phase II in 2010 and 2011, respectively. At that time, there were no significant differences between DI-20-60 and DI-0-30 trees. Differences in Ψ_{stem} between deficit irrigation treatment trees were significant 23 and 24 days after the onset of phase II in 2010 and 2011, respectively (Fig. 3.2A and 2B).

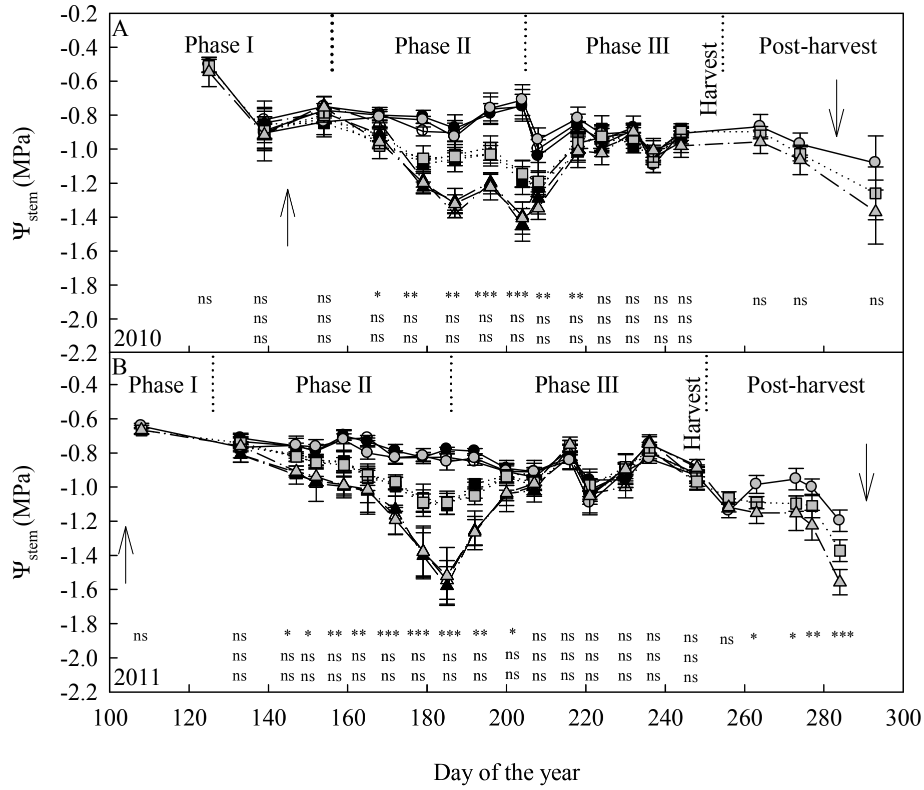


Fig. 3.2 Seasonal variations in midday stem water potential (Ψ_{stem}) during 2010 (A) and 2011 (B). On each measurement day, the asterisks indicate significant effects of irrigation (upper), crop level (middle) and interaction (lower) factors. ***, **, * and n.s. denote significant differences at $P < 0.001$, 0.01, 0.05 and non-significant differences, respectively, between factors effect from ANOVA at $P < 0.05$. Each value is the mean of 12 trees ± standard error. ↑, ↓ indicate the start and the end of irrigation seasons respectively. Symbols represent: (●) Control_IT; (■) DI-20-60_IT; (▲) DI-0-30_IT; (○) Control_AC; (□) DI-20-60_AC; (△) DI-0-30_AC; (●) Control_NT; (■) DI-20-60_NT; (▲) DI-0-30_NT.

With respect to g_l, differences between Control and deficit irrigation treatments appeared in the middle of phase II in 2010. It was not until 10 days before the end of phase II when differences were established between deficit irrigation treatments (Fig. 3.3A). In 2011, differences in g_l between Control and deficit irrigation treatments appeared at 33 days after the onset of phase II and between deficit irrigation treatments at 39 days. In both seasons, the maximum differences between treatments appeared at the end of phase II (Fig. 3.3B). When water was returned to full irrigation during phase III differences in deficit irrigation treatments in Ψ_{stem} and g_l disappeared, reaching Control values in about 3 weeks, so at harvest all trees had the same water status (Figs. 3.2-3.3). After harvest, there was a general decrease of Ψ_{stem} and g_l in 2010 and no significant differences between irrigation treatments were observed in this period (Fig. 3.2A and Fig. 3.3A). In 2011, Ψ_{stem} and g_l in deficit irrigation trees had significantly lower values than Control trees and the values were significantly different between deficit irrigation treatments (Fig. 3.2B and Fig. 3.3B). No significant differences in Ψ_{stem} and g_l were observed between crop load levels in either season (Figs. 3.2-3.3), and no significant interaction between irrigation and crop load was observed in either season during phase II (Tables 3.2-3.3).

Table 3.2 Effect on P-Value of irrigation treatments (I), crop load levels (C) and irrigation by crop load interaction (I x C) on midday stem water potential (Ψ_{stem}) during phase II of fruit growth.

		P-Value							
Source	df	168	179	187	196	204			
2010									
Block	3	0.2858	0.7749	0.0347	0.0334	0.0123			
Irrigation (I)	2	0.0182	0.0075	0.0018	0.0001	0.0001			
Crop Load (C)	2	0.1569	0.7724	0.7231	0.2588	0.2624			
I x C	4	0.8357	0.6190	0.6325	0.3852	0.8257			
		133	147	152	159	165	172	179	185
2011									
Block	3	0.2602	0.1457	0.5547	0.6767	0.0579	0.0348	0.077	0.0485
Irrigation (I)	2	0.2830	0.0125	0.0447	0.0085	0.0053	0.0001	0.0001	0.0001
Crop Load (C)	2	0.9409	0.9918	0.7688	0.9166	0.9032	0.7546	0.8722	0.9997
I x C	4	0.5946	0.9819	0.9755	0.9979	0.9191	0.8529	0.9889	0.6885

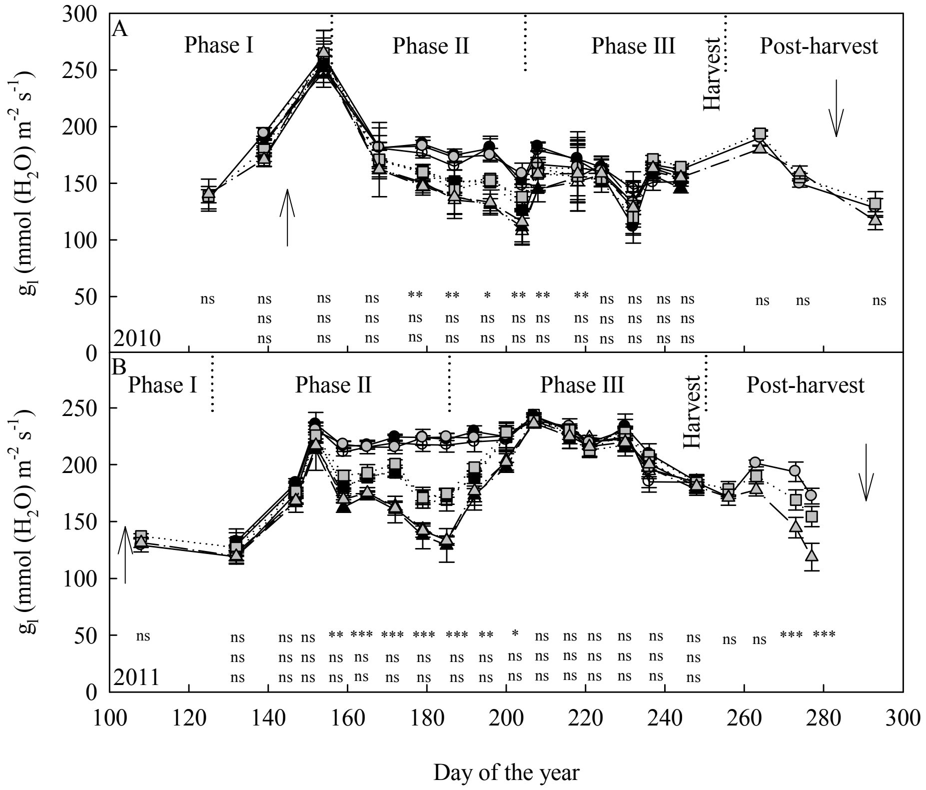


Fig. 3.3 Seasonal variations in leaf conductance (g_l) during 2010 (A) and 2011(B). On each measurement day, the asterisks indicate significant effects of irrigation (upper), crop level (middle) and interaction (lower) factors. ***, **, * and n.s. denote significant differences at P < 0.001, 0.01, 0.05 and non-significant differences, respectively, between factors effect from ANOVA at P < 0.05. Each value is the mean of 12 trees ± standard error. ↑, ↓ indicate the start and the end of irrigation seasons respectively. Symbols represent: (●) Control_IT; (■) DI-20-60_IT; (▲) DI-0-30_IT; (○) Control_AC; (□) DI-20-60_AC; (△) DI-0-30_AC; (●) Control_NT; (■) DI-20-60_NT; (▲) DI-0-30_NT.

Table 3.3 Effect on P-Value of irrigation treatments (I), crop load levels (C) and irrigation by crop load interaction (I x C) on stomatal conductance (g_l) during phase II of fruit growth.

		P-Value							
Source	df	168	179	187	196	204			
2010									
Block	3	0.0127	0.0688	0.0134	0.0635	0.0101			
Irrigation (I)	2	0.4303	0.0018	0.0056	0.0441	0.0017			
Crop Load (C)	2	0.2641	0.2380	0.3415	0.8476	0.2688			
I x C	4	0.9681	0.6140	0.9470	0.7465	0.9250			
		133	147	152	159	165	172	179	185
2011									
Block	3	0.5583	0.6855	0.2689	0.2854	0.0321	0.0804	0.0509	0.0465
Irrigation (I)	2	0.1324	0.2432	0.2639	0.0015	0.0001	0.0001	0.0001	0.0001
Crop Load (C)	2	0.5844	0.6457	0.7480	0.1695	0.8890	0.9739	0.8506	0.7131
I x C	4	0.816	0.7547	0.5975	0.1780	0.9720	0.7866	0.8914	0.9445

3.3.3. Effect of irrigation and fruit thinning on the vegetative growth

Deficit irrigation reduced tree canopy volume and trunk growth in both years, but no differences between deficit irrigation treatments were observed (Fig. 3.4 and Table 3.4). The reduction in canopy volume due to deficit irrigation compared with the Control trees was 13.3% in 2010 and 11.5% in 2011 (Fig. 3.4). With respect to trunk growth, the reduction compared with the Control trees was 29% in 2010 and 16% in 2011 (Table 3.4). Water stress did not affect the amount of vegetation removed by summer pruning in 2011 (Table 3.4). In winter pruning and total pruning, however, less wood was removed by pruning in deficit irrigation trees compared to Control trees (Table 3.4). No differences in total pruning between deficit irrigation treatments were observed (Table 3.4). Reductions in total pruning in deficit irrigation treatments compared with the Control were about 20% in 2010 and 17% in 2011. Fruit thinning had a lower impact on vegetative growth than did irrigation (Table 3.4). No significant interaction between irrigation and crop load was observed for winter pruning, total pruning and annual increase in trunk cross sectional area (Table 3.4).

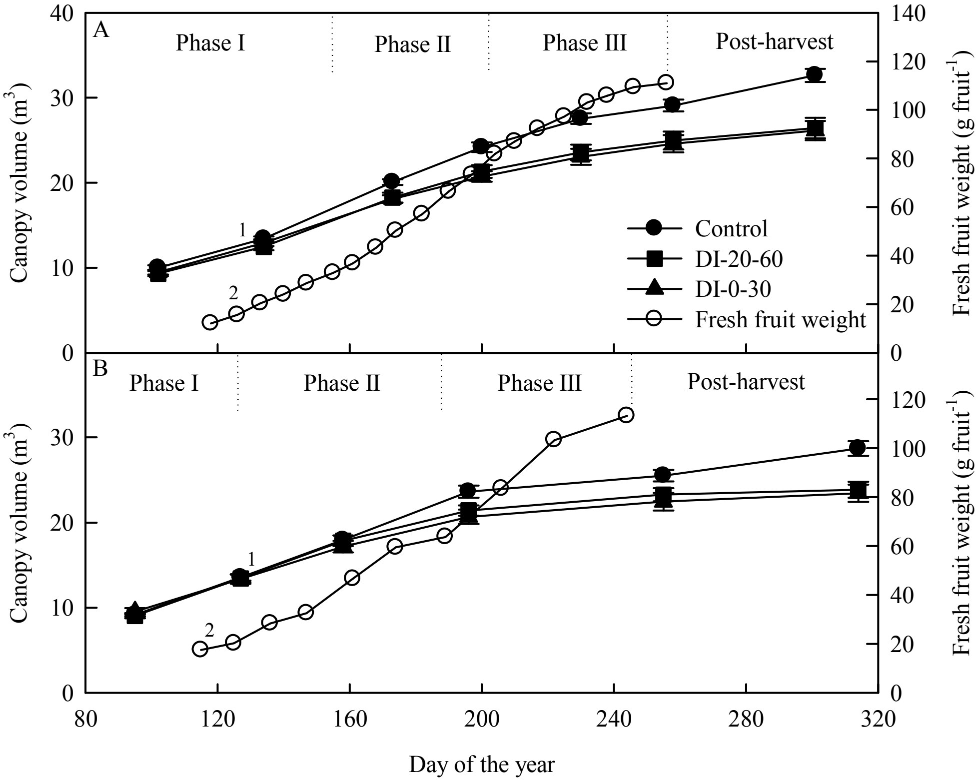


Fig. 3.4 Seasonal variations in canopy volume and fruit fresh weight in response to irrigation during 2010 (A) and 2011 (B). Each value is the mean of 12 trees and 16 fruit ± standard error for canopy volume and fruit fresh weight, respectively. Numbers represents: (1) summer pruning; (2) fruit thinning.

Table 3.4 Effects of irrigation on total pruning (summer + winter) and annual increase in trunk cross sectional area for 'Angeleno' plum in 2010 and 2011 at different crop load levels.

Year	Treatments									P-value		
	Intense thinning			Commercial thinning			No thinning			I	C	I x C
	Control	DI-20-60	DI-0-30	Control	DI-20-60	DI-0-30	Control	DI-20-60	DI-0-30			
Winter pruning (kg tree^{-1})												
2010	25.5 a	19.0 b	19.8 b	27.9 a	25.7 a	21.4 b	26.5 a	20.0 b	22.3 b	0.0035	0.0919	0.4336
2011	16.3 a	13.2 b	14.0 b	11.5 a	12.2 a	13.0 a	10.9 a	10.6 a	13.0 a	0.0053	0.3369	0.2517
Total pruning (kg tree^{-1})												
2010	25.5 a	19.0 b	19.8 b	27.9 a	25.7 a	21.4 b	26.5 a	20.0 b	22.3 b	0.0035	0.0919	0.4336
2011	19.4 a	13.9 b	13.9 b	15.9 a	14.6 a	13.2 a	17.2 a	16.0 a	15.5 a	0.0054	0.2682	0.3554
Annual increase on trunk cross sectional area (cm^2)												
2010	91.4 a	54.2 b	61.6 b	79.7 a	65.2 b	65.3 b	79.2 a	57.2 b	52.6 b	0.0001	0.4474	0.5650
2011	62.7 a	49.0 b	55.2 ab	67.2 a	53.3 b	55.0 b	59.5 a	54.8 a	52.9 a	0.0046	0.7731	0.8777

Total pruning is the sum of summer pruning and winter pruning. For each crop load treatment, means along the row followed by different letters are significantly different at 5% according to LSD test. Each value is the mean of 12 trees. (I) irrigation; (C) crop load; (I x C) irrigation by crop load interaction

3.3.4. Effect of irrigation and fruit thinning on yield and fruit quality parameters

Fruit number per tree varied between years. In 2011, trees had on average about 200 fruits more than in 2010 at all three crop load levels. This could explain the smaller fruit weight and higher yield in 2011 compared to 2010 (Table 3.5). Deficit irrigation did not affect yield at any crop load level (Table 3.5). In both years, deficit irrigation reduced fruit fresh weight, with significant differences between Control and DI-0-30 in 2010 and between Control and both deficit irrigation treatments in 2011 (Table 3.5). Fruit fresh weight was correlated with the minimum Ψ_{stem} values observed during phase II in both years (Fig. 3.5). Fruit weight decreased with decreasing Ψ_{stem}. Larger fruit weights were attained with similar Ψ_{stem} values in 2010 than in 2011, with similar slopes in both years (Fig. 3.5). Irrigation treatment did not affect dry fruit weight in either year (Table 3.5).

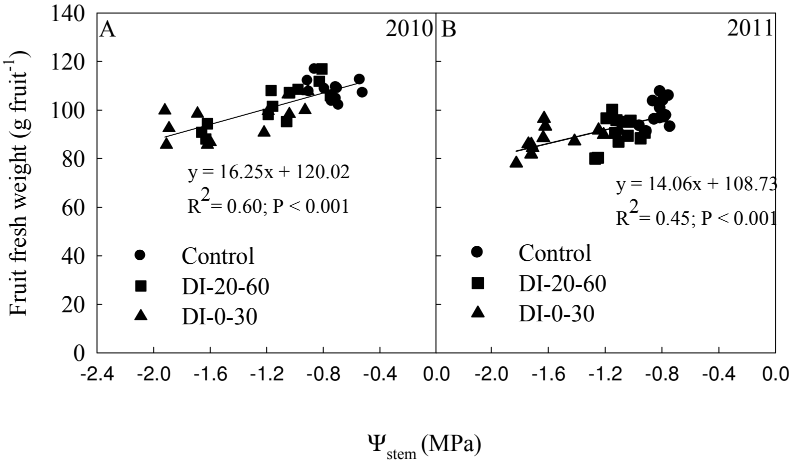


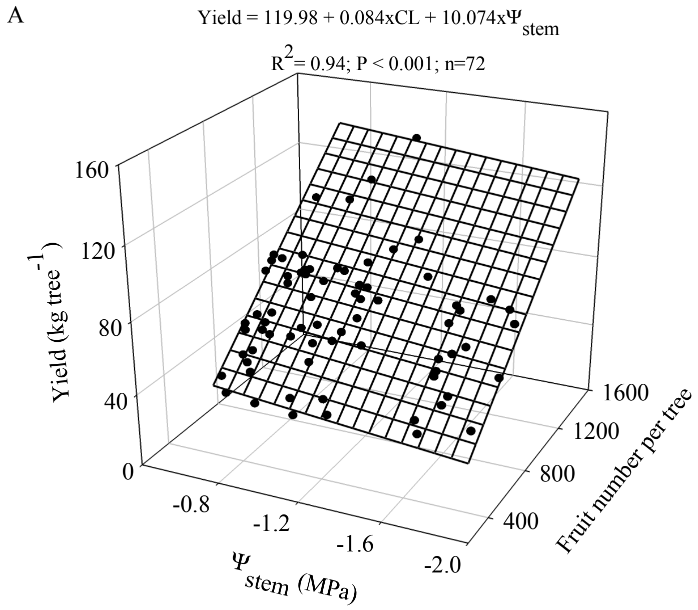
Fig. 3.5 Relationships between midday stem water potential (Ψ_{stem}) and fruit fresh weight for 'Angeleno' plum in 2010 (A) and 2011 (B). The values for Ψ_{stem} correspond to the most stressed day during phase II (last day of the period). Each point represents an individual tree measure.

Table 3.5 Effects of irrigation on fruit number per tree, yield, fruit fresh weight, fruit dry weight, water use efficiency (WUE), crop production efficiency (CPE), yield per total pruning and number of fruit per canopy volume for 'Angeleno' plum in 2010 and 2011 at different crop load levels.

Year	Treatment									P-Value		
	Intense thinning			Commercial thinning			No thinning					
	Control	DI-20-60	DI-0-30	Control	DI-20-60	DI-0-30	Control	DI-20-60	DI-0-30	I	C	I x C
Fruit number per tree												
2010	405 a	422 a	430 a	605 a	626 a	643 a	814 a	839 a	821 a	0.2962	0.0001	0.6194
2011	616 a	648 a	641 a	803 a	813 a	842 a	1044 a	1107 a	1102 a	0.8735	0.0001	0.9889
Yield (kg tree^{-1})												
2010	43.8 a	40.4 a	40.1 a	64.8 a	64.3 a	61.5 a	88.3 a	86.8 a	81.0 a	0.1579	0.0001	0.7211
2011	62.7 a	60.1 a	57.6 a	80.3 a	74.5 a	74.6 a	97.8 a	96.5 a	95.5 a	0.8138	0.0001	0.9935
Fruit fresh weight (g)												
2010	108.0 a	95.5 b	93.4 b	107.3 a	102.9 a	95.8 b	108.5 a	103.5 a	98.7 b	0.0462	0.2531	0.7503
2011	101.9 a	92.7 b	89.8 b	100.5 a	91.9 b	88.9 b	93.8 a	87.7 b	86.0 b	0.0251	0.0374	0.7763
Fruit dry weight (g)												
2010	22.7 a	20.0 a	19.9 a	18.2 a	18.5 a	17.7 a	18.5 a	21.5 a	20.7 a	0.6900	0.0380	0.2221
2011	15.6 a	15.1 a	14.5 a	15.5 a	14.4 a	14.4 a	14.4 a	13.8 a	13.2 a	0.1228	0.0018	0.7773
WUE (kg m^{-3})												
2010	2.80 b	3.45 a	3.62 a	4.15 b	5.48 a	5.55 a	5.66 b	7.40 a	7.31 a	0.0001	0.0001	0.0716
2011	4.10 b	5.19 ab	5.75 a	5.26 c	6.43 b	7.44 a	6.40 c	8.33 b	9.53 a	0.0075	0.0001	0.3521
CPE (kg cm^{-2})												
2010	0.12 b	0.14 b	0.14 b	0.19 b	0.21 a	0.20 ab	0.26 b	0.31 a	0.28 b	0.0284	0.0001	0.5343
2011	0.15 a	0.17 a	0.15 a	0.17 a	0.19 a	0.19 a	0.23 a	0.27 a	0.26 a	0.5926	0.0001	0.9238
Yield/Total pruning (kg kg^{-1})												
2010	1.77 b	2.14 a	2.05 a	2.36 b	2.52 b	2.91 a	3.36 b	4.60 a	3.68 b	0.0208	0.0001	0.2033
2011	3.82 b	5.65 a	5.30 a	6.14 b	6.16 b	7.21 a	7.06 a	7.68 a	7.62 a	0.0317	0.0001	0.5705
Fruit number per canopy volume (fruit m^{-3})												
2010	14.2 b	18.0 a	18.4 a	22.2 b	26.5 a	28.1 a	28.5 b	34.6 a	34.1 a	0.0725	0.0001	0.9566
2011	25.6 a	27.4 a	29.9 a	31.8 b	39.1 a	39.7 a	40.7 b	46.1 a	47.1 a	0.0241	0.0001	0.9053

For each crop load treatment, means along the row followed by different letters are significantly different at 5% according to LSD test. Each value is the mean of 12 trees. (I) irrigation; (C) crop load; (I x C) irrigation by crop load interaction.

Yield was highly correlated with tree water status (based on minimum values during phase II of Ψ_{stem} and g_l) and fruit number per tree in a multiple regression (Fig. 3.6), where all the parameters were highly significant ($P < 0.001$).



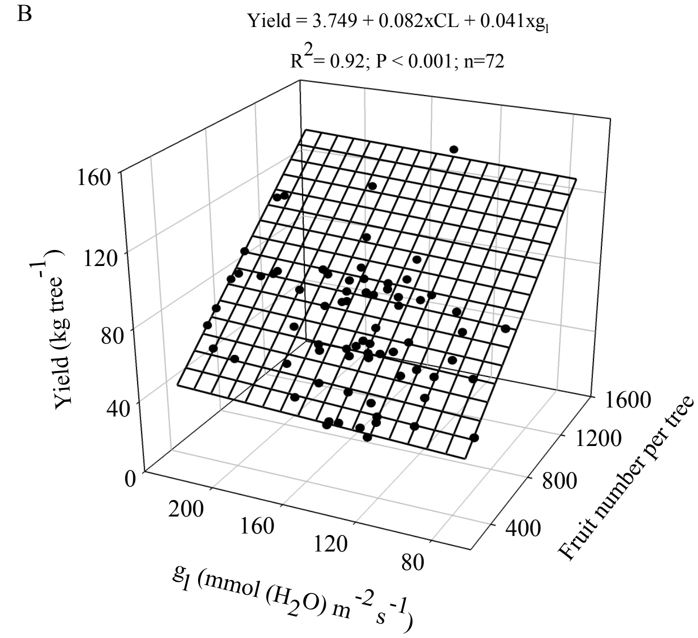


Fig. 3.6 Yield as a function of midday stem water potential (Ψ_{stem}) and fruti number per tree (A) and stomatal conductance (g_l) and fruit number per tree (B) for 'Angeleno' plum during 2010-2011. The values for Ψ_{stem} and g_l correspond to the most stressed day during phase II (last day of the period). Each point represents an individual tree measure.

There was a highly significant correlation for each treatment between fruit number per canopy projection area and fruit number per tree or total yield (Fig. 3.7). The rise in fruit number per canopy projection area increased fruit number per tree and yield, from

400 fruit tree^{-1} and 20 kg tree^{-1} with 20 fruit m^{-2} to 1100 fruit tree^{-1} and 97 kg tree^{-1} with 59 fruit m^{-2}.

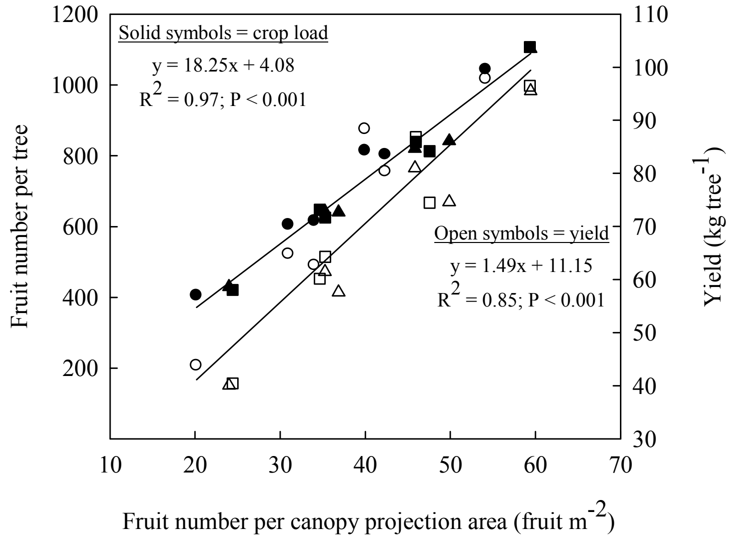


Fig. 3.7 Relationships between fruit number per tree (A) and yield (B) and the fruit number per canopy projection area for 'Angeleno' plum during 2010-2011. Each point represents the mean of four replicates. Solid symbols represent crop load: (●) Control; (■) DI-20-60; (▲) DI-0-30. Open symbols represent yield: (○) Control; (□) DI-20-60; (△) DI-0-30.

Due to a similar yield in the three irrigation treatments, deficit irrigation led to an increase in WUE proportional to the reduction of water applied, with values between 3.5 and 7.3 kg m^{-3} in 2010 and between 5.2 and 9.5 kg m^{-3} in 2011 (Table 3.5). Also, as a result of reduced vegetative vigor of trees in 2010 (Table 3.4 and Fig. 3.4), CPE, yield per total pruning weight and fruit number per canopy volume increased in deficit irrigation treatments (Table 3.5). Fruit fresh weight was only affected by crop load at harvest in 2011 with higher fruit weight at lower crop loads. Fruit size distribution shifted towards larger fruits with increasing irrigation level during phase II in both years and in 2011 fruit diameter was higher in lower crop loads (data not shown).

There were significant differences in fruit quality parameters between years: JI and SSC/TA ratio were higher in 2010 than in 2011 and SSC, FR and TA were lower (Table 3.6). Water stress significantly increased SSC, with values above 14.8 ºBrix in deficit irrigation treatments, whereas Control treatment was below these values, with differences of more than 1 ºBrix between extreme treatments. JI in 2010 and FR and TA in 2011 tended to be higher in Control than in deficit irrigation treatments, with significant differences (Table 3.6). The SSC/TA ratio was significantly different between deficit irrigation treatments and Control (Table 3.6). SSC, TA, JI and SSC/TA ratio were significantly correlated with Ψ_{stem} in 2010 and 2011, except for the JI in 2011 (Fig. 3.8). The slopes of the relationships between Ψ_{stem} and the quality parameters were not significantly different between the years, except for the JI (results from ANCOVA analysis not shown).

Fruit thinning had a lower impact on fruit quality than did irrigation (Table 3.6). FR in both years, TA in 2011 and JI in 2010 were significantly higher in IT and CT than in NT (Table 3.6). No significant interaction between irrigation and crop load was observed in yield and fruit quality parameters (Tables 3.5-3.6).

Table 3.6 Effects of irrigation on soluble solids concentration (SSC), firmness (FR), titratable acidity (TA), juice index (JI) and SSC/TA ratio for 'Angeleno' plum in 2010 and 2011 at different crop load levels.

Year	Treatment									P-Value		
	Intense thinning			Commercial thinning			No thinning					
	Control	DI-20-60	DI-0-30	Control	DI-20-60	DI-0-30	Control	DI-20-60	DI-0-30	I	C	I x C
SSC (ºBrix)												
2010	13.8 c	14.9 b	15.8 a	14.6 b	14.8 b	15.2 a	14.1 c	14.9 b	15.6 a	0.0011	0.9970	0.3622
2011	15.1 b	16.2 a	16.7 a	15.1 c	15.7 b	16.6 a	15.2 a	15.7 a	15.6 a	0.0277	0.2942	0.4749
FR (kg cm^{-2})												
2010	3.1 a	3.3 a	3.5 a	3.2 a	3.1 a	3.3 a	3.0 a	3.0 a	3.1 a	0.3974	0.0737	0.7835
2011	3.8 a	3.6 b	3.5 b	3.7 a	3.4 b	3.4 b	3.4 a	3.3 ab	3.3 b	0.0214	0.0083	0.8147
TA (g malic acid l^{-1})												
2010	5.9 a	4.6 a	4.9 a	5.5 a	5.6 a	4.9 a	4.8 a	4.9 a	5.4 a	0.3434	0.4929	0.2665
2011	6.3 a	5.4 b	5.7 b	6.4 a	5.4 b	4.8 c	5.6 a	5.0 b	5.1 b	0.0072	0.0128	0.1206
JI (%)												
2010	17.3 a	16.5 b	15.5 c	16.4 a	16.6 a	15.9 b	16.2 a	15.5 b	15.1 b	0.0269	0.0442	0.4689
2011	15.8 a	15.2 a	15.3 a	15.9 a	15.6 a	15.2 a	15.4 a	15.0 a	15.1 a	0.1971	0.5321	0.9623
SSC/TA (%/g malic acid l^{-1})												
2010	2.3 b	3.3 a	3.3 a	2.7 b	2.7 b	3.2 a	3.0 a	3.1 a	3.1 a	0.0123	0.4816	0.6916
2011	2.4 b	3.1 a	2.9 a	2.4 c	2.9 b	3.5 a	2.7 b	3.2 a	3.1 a	0.0086	0.1717	0.1579

For each crop load treatment, means along the row followed by different letters are significantly different at 5% according to LSD test. Each value is the mean of 12 trees. (I) irrigation; (C) crop load; (I x C) irrigation by crop load interaction.

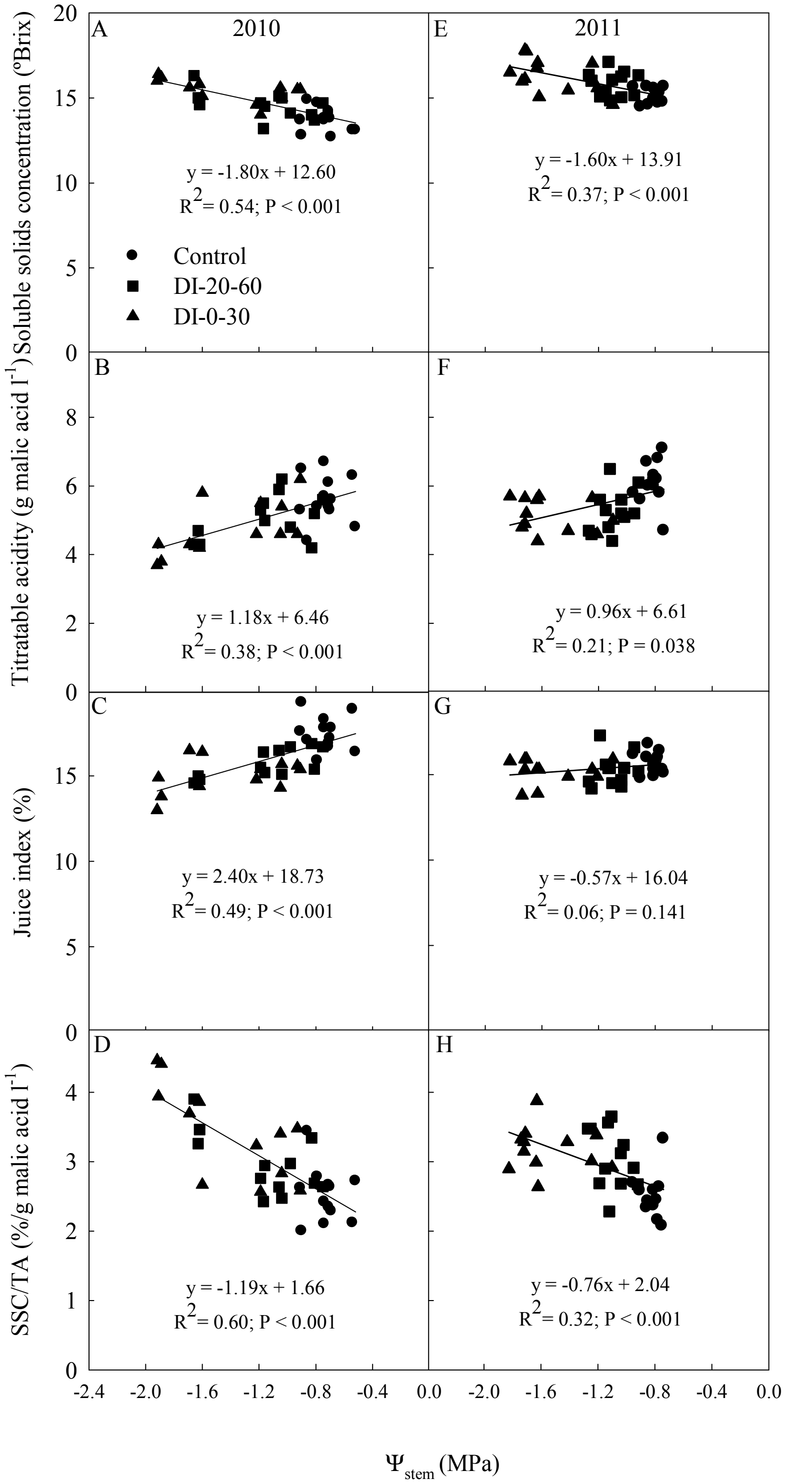


Fig. 3.8 Relationships between midday stem water potential (Ψ_{stem}) and fruit quality parameters for 'Angeleno' plum in 2010 (A-D) and 2011 (E-H). The values for Ψ_{stem} corresponds to the most stressed day during phase II (last day of the period). Each point represents an individual tree measure.

3.3.5. Effect of irrigation and fruit thinning on economic indices

Differences in size distribution between irrigation treatments were not reflected in GI (Table 3.7). PC and IAUP in both years and BP in 2010 were significantly lower in deficit irrigation treatments than in Control (Table 3.7). These results were consistent within each fruit thinning treatment (Table 3.7). In both years, GM and WEE were significantly higher in deficit irrigation treatments than in Control, except for the trees under intense thinning (Table 3.7). There was a clear effect of crop load, with fruit thinning reducing GI, PC, GM, WEE and BP, except for the PC and BP in 2011 (Table 3.7).

Table 3.7 Effects of irrigation on gross income (GI), production cost (PC), gross margin (GM), water economic efficiency (WEE), break-even point (BP) and Irrigation applied per unit of plum (IAUP) for 'Angeleno' plum in 2010 and 2011 at different crop load levels.

Year	Treatment									P-Value		
	Intense thinning			Commercial thinning			No thinning					
	Control	DI-20-60	DI-0-30	Control	DI-20-60	DI-0-30	Control	DI-20-60	DI-0-30	I	C	I x C
GI (€ tree^{-1})												
2010	19.6 a	22.8 a	19.9 a	26.6 a	30.3 a	27.0 a	35.1 a	35.7 a	35.9 a	0.6749	0.0001	0.9470
2011	23.2 a	21.8 a	19.8 a	25.2 a	27.3 a	24.0 a	35.9 a	31.2 a	29.7 a	0.6686	0.0001	0.6583
PC (€ tree^{-1})												
2010	21.0 a	20.0 b	19.2 c	22.6 a	21.8 b	20.5 b	23.2 a	21.7 b	21.4 b	0.0061	0.0001	0.7873
2011	22.0 a	21.6 b	19.9 c	22.4 a	20.4 b	20.0 b	21.7 a	21.3 b	20.8 b	0.0031	0.8034	0.4639
GM (€ tree^{-1})												
2010	-1.4 a	2.8 a	0.7 ab	4.0 b	8.6 a	6.5 ab	11.9 b	14.0 a	14.5 a	0.0429	0.0001	0.9756
2011	1.2 a	0.2 b	-0.1 b	2.8 b	6.9 a	4.0 ab	14.2 a	9.9 b	8.9 b	0.0808	0.0001	0.3048
WEE (€ m^{-3})												
2010	1.4 b	2.2 a	2.1 a	1.9 b	3.0 a	2.8 a	2.5 b	3.5 a	3.8 a	0.0175	0.0001	0.7578
2011	1.7 b	2.3 a	2.5 a	1.9 b	2.8 a	3.0 a	2.7 b	3.2 a	3.7 a	0.0554	0.0001	0.8218
BP (kg tree^{-1})												
2010	46.9 a	36.0 b	39.8 b	55.7 a	47.5 b	48.8 b	60.6 a	53.8 b	50.4 b	0.0089	0.0001	0.9082
2011	59.3 a	60.0 a	57.9 a	72.8 a	55.8 a	63.9 a	59.0 a	66.2 a	71.8 a	0.5848	0.1944	0.0754
IAUP (l fruit^{-1})												
2010	35.2 a	24.2 b	22.3 b	23.3 a	16.3 b	14.9 b	17.3 a	12.2 b	11.6 b	0.0132	0.0001	0.1547
2011	22.2 a	14.9 b	13.0 b	16.8 a	11.9 b	9.9 b	13.0 a	8.9 b	7.6 b	0.0001	0.0001	0.2907

For each crop load treatment, means along the row followed by different letters are significantly different at 5% according to LSD test. Each value is the mean of 12 trees. (I) irrigation; (C) crop load; (I x C) irrigation by crop load interaction.

3.4. Discussion

Stone fruit productivity depends largely on the appropriate choice of irrigation and crop load among other factors. Studying the interaction between deficit irrigation strategies and crop load is relevant in water limited areas. This could allow the optimization of tree and fruit size, yield and quality by selecting an adequate combination of water stress and crop load (Naor et al., 2004; Marsal et al., 2006, 2008, 2010; Intrigliolo and Castel, 2010; Lopez et al., 2010). In this experiment, we evaluated combined regulated deficit irrigation during phase II and post-harvest as a tool to save water and reduce excessive vegetative growth in Japanese plum trees. Several crop load levels were explored in combination with deficit irrigation to find the optimum combination in terms of yield, fruit quality and economic indices. In the following discussion, the combined effect of irrigation and crop load on tree water status, vegetative growth, yield, fruit quality and economic return are discussed in different sections to facilitate the presentation.

3.4.1. Effect of irrigation and fruit thinning on tree water status

During fruit growth g_l variability was higher than Ψ_{stem} measurements between years (Figs. 3.2-3.3). The higher g_l variability was probably due to the effect on leaf transpiration of climatic conditions (Hsiao, 1973) and crop load (Marsal et al., 2005). Since Ψ_{stem} determinations were taken with bagged leaves, the effect on leaf transpiration of climatic conditions was blocked (Shackel et al., 1997). The higher fruit number per tree in 2011 can also explain this g_l variability between years. The range in Ψ_{stem} for Control between -0.5 MPa at the beginning of the season, -0.8 MPa during most of fruit growth and -1.1 MPa at the end of the season (Fig. 3.2) agrees quite well with published values for peach (Garnier and Berger, 1985), European plum (McCutchan and Shackel, 1992) and Japanese plum (Johnson et al., 1994; Intrigliolo and Castel, 2010). Deficit irrigation during phase II significantly reduced Ψ_{stem} and g_l (Figs. 3.2-3.3), suggesting that plum trees can respond sensitively to water availability in the soil to optimize water use efficiency (Cheng et al., 1996). The minimum average

Ψ_{stem} value obtained in DI-0-30 during phase II (-1.5 MPa) is at the same level as that obtained by Johnson et al. (1994) in plum (-1.0 to -1.5 MPa), Berman and DeJong (1996) in peach (-1.35 MPa) and Girona et al. (2004) in peach (-1.7 MPa), and less negative than that obtained in plum trees grown in a deep soil with a high clay profile (Naor et al., 2004) (-2.2 MPa). Tree water status (based on Ψ_{stem} and g_l) recovered when irrigation was returned to full irrigation during phase III (Figs. 3.2-3.3). It is important, after a severe or extended period of plant water stress, that trees are able to return to their optimum plant water status before harvest (Intrigliolo and Castel, 2010). The time that a tree takes to return to the Control status after a deficit irrigation treatment is also an important factor because phase III is a critical period for the application of deficit irrigation (Torrecillas et al., 2000; Girona et al., 2004; Intrigliolo and Castel, 2005).

Ψ_{stem} and g_l were independent of crop load and no significant interaction between irrigation and crop load was observed (Tables 3.2-3.3). This could be due to several reasons. Firstly, in trees under water stress the effect of crop load on tree water status is more pronounced during phase III (DeJong, 1986b). This phase is a phenological period highly sensitive to water deficits (Torrecillas et al., 2000; Girona et al., 2004; Intrigliolo and Castel, 2005), explaining the behavior observed in Ψ_{stem} and g_l during phase II between trees of different crop load in our experiment. Another factor concerns soil properties which may include a lower soil resistance to the absorption of water, leading to less negative values of Ψ_{stem} and the fruit being an effective sink. Similar results have been found in peach (DeJong, 1986b; McFayden et al., 1996) and pear (Naor, 2001). Contrastingly, high crop loaded trees had higher Ψ_{stem}, g_l and assimilation rates than low crop loaded trees under deficit irrigation in peach (Chalmers et al., 1983; DeJong, 1986a; Lopez et al., 2010), European plum (Gucci et al., 1991) pear (Marsal et al., 2010) and olive (Martín-Vertedor et al., 2011). These contradictions in the results can be attributed to changes in responses during the growing season, changes in the response after fruit thinning, different response of stomata in the morning and in the afternoon or the existence of other sinks, mainly shoot growth in girth (Gucci et al., 1991).

Reductions in applied water in post-harvest period caused sharp reductions in Ψ_{stem}, g_l, trunk growth and total pruning (Figs. 3.2-3.3 and Table 3.4), but no reduction of yield resulted in the following season (Table 3.5). In this experiment, the minimum values in Ψ_{stem} and g_l were obtained at the end of the season. At this moment, leaf senescence begins and water stress does not affect the accumulation of reserves or floral differentiation (Johnson et al., 1992, 1994; Intrigliolo and Castel, 2004, 2005, 2010). In late-maturing plum (as the cultivar studied in this experiment), flower differentiation occurs before harvest in late August, offering the possibility of important water savings during the post-harvest period. In other species, post-harvest deficit irrigation had a negative impact on yield in the following season because of reduced levels of bloom in almond (Goldhamer and Viveros, 2000) or fruit set in apricot (Torrecillas et al., 2000). The occurrence of double fruits and deep suture was not observed, as similarly occurred with Red Beaut, Ambra, Durado, Black Amber or Black-Gold cultivars (Johnson et al., 1994; Naor et al., 2004; Intrigliolo and Castel, 2005). This suggests that plum cultivars are less sensitive to these disorders as reported for peaches and nectarine (Johnson et al., 1992; Handley and Johnson, 2000; Naor et al., 2005).

3.4.2. Effect of irrigation and fruit thinning on vegetative growth

Vegetative growth, and more specifically canopy volume, trunk growth and total pruning weight were clearly reduced in both years in deficit irrigation treatments compared to Control (Fig. 3.4 and Table 3.4), which led to reductions in tree size and smaller canopies. A decrease in vegetative growth (both shoot elongation and trunk growth) in response to water deficit is recognized as being the most sensitive process to water stress (Moriana and Fereres, 2002; Nortes et al., 2005; Marsal et al., 2008). This favors fruit growth due to a shift in the carbon allocation (Chalmers et al., 1981; Mahhou et al., 2006; Intrigliolo and Castel, 2010). No differences in vegetative growth were observed between deficit irrigation treatments in either year. This may be because even slight water stress can causes a halt to vegetative growth as cell expansion is the physiological process which is most sensitive to water stress (Hsiao, 1973).

The patterns of vegetative growth were modified from 2010 to 2011 as a result of the differences in fruit sink strength between years; 2010 experienced the highest growth rates and 2011 the lowest (Fig. 3.4 and Table 3.4). This response in 2011 reflects the importance of fruit load as a vegetative growth regulator, which in this research appeared to be stronger under non-stressed trees than under deficit irrigation trees. Plum cultivars appear to have a sink-limited stage occurring during phase II of fruit growth (Basile et al., 2002). The bases of sink demand are maintenance respiration and the maximum organ growth potential (which is defined as the genetically determined growth attained when an organ is grown under optimal environmental conditions). Under such conditions, vegetative growth could be limited by applying deficit irrigation treatment during phase II without affecting fruit yield at harvest.

3.4.3. Effect of irrigation and fruit thinning on yield and fruit quality parameters

Fruit fresh weight was reduced by deficit irrigation (Table 3.5), indicating a decrease in fruit turgor (Naor et al., 2001) caused by water stress. Also, the excessive length of the deficit irrigation period (about two months) along with the difficult to identify the end of phase II (Fig. 3.4), as well as the three weeks it took after the deficit irrigation period to return to Control tree water status when full irrigation was resumed during phase III (Figs. 3.2-3.3), may explain this reduction in fruit fresh weight. Fruit fresh weight in both years was related to minimum Ψ_{stem} values during phase II (Fig. 3.5). These results agree with those obtained in apple (Naor et al., 1995), peach (Naor et al., 2001), almond (Shackel et al., 1997) and plum (Naor, 2004; Intrigliolo and Castel, 2006). In our study, the reduction of fruit fresh weight with decreasing Ψ_{stem} was 16.5 g MPa^{-1} and 14.0 g MPa^{-1} in 2010 and 2011, respectively (Fig. 3.5). Therefore, our results agree more with Naor (2004), where the reduction was 18.8 g MPa^{-1}, than with Intrigliolo and Castel (2006) where the reduction was 45.3 g MPa^{-1}. This important difference suggests that the relations obtained between fruit weight and Ψ_{stem} cannot easily be extrapolated from one location to another and from one cultivar to another.

The combined data of yield, tree water status (based on minimum values during phase II of Ψ_{stem} and g_l) and fruit number per tree in a multiple regression show that yield decreased with lower values of Ψ_{stem} and g_l (Fig. 3.6). However, this relationship shows that higher fruit numbers per tree had no effect on Ψ_{stem} and g_l, and explain why Ψ_{stem} and g_l were found not to be sensitive to fruit number per tree (Figs. 3.2-3.3). For a same fruit number per tree, the decrease in Ψ_{stem} from -0.8 MPa (value for Control) to -1.6 MPa (value for DI-0-30) produced a reduction in yield of 8.1 kg $tree^{-1}$. However, the decrease in g_l from 220 mmol (H_2O) $m^{-2}s^{-1}$ (value for Control) to 110 mmol (H_2O) $m^{-2}s^{-1}$ (value for DI-0-30) produced a reduction in yield of 4.5 kg $tree^{-1}$. This could be due to the higher g_l variability as a result of the effect of different climatic conditions between years (Table 3.1). These differences between different measuring methods of plant water status indicate that further research should be done in the future to explore the possible generalization of the relationships between plant water status indicators and fruit weight and yield among orchards with different characteristics (Intrigliolo and Castel, 2006; Marsal et al., 2010).

In 2011, fruit thinning increased fruit fresh weight when fruit number per tree was higher than in 2010 (Table 3.5). However, it seems that the crop loads obtained in 2010 were within the optimal range and the trees were not source-limited, maintaining their capacity for partitioning dry matter into fruit (DeJong and Grossman, 1995). So, all fruit grew to their maximum fruit fresh weight potential which seems to be about 100 g fruit^{-1}. In 2011 however, crop load levels in the NT treatments were severe enough to limit fruit growth under conditions of water stress and therefore potential fruit size was not reached even at high irrigation rates (Table 3.5). However, the decrease in yield observed under low crop levels and the cost of hand-thinning do not compensate for the increase in fruit fresh weight, reducing the gross margin (Table 3.7). The relationship between total yield and fruit number per canopy projection area was linear (Fig. 3.7), indicating that crop load levels were not severe enough to limit yield. Therefore, thinning cannot be recommended for these levels. This appears to be a characteristic for late maturing cultivars; however, in midseason-maturing cultivars normally trees can support ≤ 600 fruits per tree in a good year (Naor, 2004; Intrigliolo and Castel, 2010). This explains why fruit thinning is often the ultimate step to take in commercial late-maturing cultivars, even in years of high crop load and low water resources. So, fruit thinning will have even greater relevance for midseason-maturing cultivars that cannot support high crop loads.

The fruits were harvested according to criteria established by market cooperatives, with the advances in fruit maturity in deficit irrigation treatments confirmed by SSC, FR and TA which have been considered good indicators of fruit maturity (Crisosto, 1994; Walsh et al., 2007; Iglesias and Echeverria, 2009). Significant relationships were found between SSC, TA, SSC/TA ratio and minimum Ψ_{stem} values for both years and for JI in 2010 (Fig. 3.8). Water stress had a positive effect on SSC (Table 3.6 and Fig. 3.8). Fruits with high SSC generally have a higher retail value (Parker et al., 1991) and greater consumer acceptance (Crisosto and Crisosto, 2005). This is consistent with previous studies in peach (Gelly et al., 2004; Mahhou et al., 2006; Mercier et al., 2009) and Japanese plum (Intrigliolo and Castel, 2010). The higher fruit SSC values reported in deficit irrigation treatments might be attributable to several reasons: (i) a dilution effect because fruit from deficit irrigation trees were smaller (Intrigliolo and Castel, 2010) and had similar dry weight (Table 3.5); (ii) a passive concentration of sugars after partial fruit dehydration (Lopez et al., 2010), (iii) the degree of water stress may play a significant role in fruit maturity, while moderate water stress appears to advance fruit maturity, severe water stress appears to delay this process (Lopez et al., 2010).

FR of fruits under water stress was lower than Control fruit in the second year (Table 3.6 and Fig. 3.8). Since flesh softening can be considered as an improvement for fresh consumption, softer plums collected in deficit irrigated trees may have greater consumer acceptance, with this being a signal often related to better maturity. However, these results do not concur with those obtained in other pear, apple and peach studies where water stress increased FR possibly due to a reduction in fruit size (Leib et al., 2006; Lopez et al., 2010; 2011), though Mpelasoka et al. (2000) in apple indicated that an increase in FR under water stress is irrespective of fruit size.

TA was not affected by irrigation levels in the first year of the experiment, as in peach (Crisosto et al., 1994), apple (Mpelasoka and Behboudian, 2002) and Japanese plum (Naor et al., 2004; Intrigliolo and Castel 2010). The second year saw a reduction in TA in deficit irrigation treatments, as in apple (Mills et al., 1996) and peach (Gelly et al., 2004). Fruit acidity can also influence consumer acceptance, with acceptance being greater for fruit with lower acidity values (Scandella et al., 1997). Water stress had a significant effect on the SSC/TA ratio (Table 3.6 and Fig. 3.8). This ratio is the fruit quality parameter that is ultimately most closely related with consumer acceptance (Crisosto et al., 1997, 2006; Gelly et al., 2004; Vallverdu et al., 2012). Because of their higher SSC/TA ratio (above 3.0), customers would probably prefer the fruits from the deficit irrigation treatments over those from the Control treatment.

Crop load had no significant effect on SSC (Table 3.6). Our results are contrary to findings in peach (Crisosto et al., 1997; Walsh et al., 2007) and apple (Johnson, D.S., 1995), whose values increased with reduction in crop load as a consequence of the increased fruit demand for assimilates (Chapman et al., 1991). A significant crop load effect was observed on FR in both years, on TA in 2011 and JI in 2010 (Table 3.6) whose values decreased with increased crop load. These results are in disagreement with those obtained in pear by Lopez et al. (2011), who reported that fruit thinning did not affect FR, TA, and SSC at harvest. Factors such as the timing of fruit thinning may explain the lack of significant responses in the study by these authors. However, early season fruit thinning did increase FR, SSC and TA in apple (Wunsche and Ferguson, 2005) and SSC in peach (Crisosto et al., 1994).

3.4.4. Effect of irrigation and fruit thinning on economic indices

Gross margin under the commercial prices for the present experiment was higher in deficit irrigation treatments (Table 3.7). The increase in GM was due to lower PC, mainly due to a reduction in annual pruning costs, applied water and electricity consumption compared to Control (Table 3.7). The results were the same as those obtained in early-maturing peach and apricot (García-García, 2007) and higher than obtained in almond (García-Garcia et al., 2004), plum (García-García, 2007) and early maturing peach (García-García and García, 2012). Crop loads lower than those tested here for the Control treatment would therefore not be advisable since they would not result in an increase in GM (Table 3.7). The reduction in GM due to deficit irrigation at NT level was more important than the decrease in yield alone. It is important to note that, despite the deficit irrigation treatments having lower GMs than Control at NT level, higher GMs were obtained in the deficit irrigation treatments with NT level compared with the deficit irrigation treatment with CT level (Table 3.7). However, higher values of WEE were obtained in deficit irrigation treatments than in Control treatment (Table 3.7). These results are in disagreement with those found in Japanese plum (Intrigliolo and Castel, 2010), where similar values of WEE in the deficit and fully irrigated trees were obtained. BP confirms that the IT level in Control treatment in 2010 and in DI-0-30 in 2011 was below the minimum yield required to generate income (Table 3.7).

3.5. Conclusions

The combination of deficit irrigation and different levels of crop load in 'Angeleno' plum helped to identify the higher impact of water stress compared to fruit thinning on tree water status, vegetative growth, fruit yield and quality. In this study however, intense fruit thinning was disadvantageous in terms of yield in 'Angeleno' plum. As for water stress, it seems that maintaining Ψ_{stem} and g_l above -1.5 MPa and 110 mmol (H_2O) m^{-2} s^{-1}, respectively, during phase II in plum will have no negative effects on yield. Therefore, below these levels of water stress the application of additional fruit thinning is unnecessary as it does not improve tree water status, lowers yield and entails an additional application cost which reduces final grower's return. Intense fruit thinning may only be required if the levels of water stress are much higher than those observed in our experiment. Besides maintenance of yield under deficit irrigation conditions, water stress applied during phase II and post-harvest reduced excessive vegetative growth and increased water use efficiency with average water savings of 29% for DI-20-60 and 40% for DI-0-30 in comparison with the Control. All these benefits together with a clear potential to increase fruit quality, which we expect will be taken into account by market cooperatives in coming years, make deficit irrigation a suitable technique in Japanese plum trees. We think our study provides useful information to manage plum trees in terms of thinning and irrigation in areas where water is limited.

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Chapter 4: Use of CropSyst as a tool to predict water use and crop coefficient in Japanese plum trees in two different maturing cultivars

Abstract

The development of a method to estimate the seasonal crop coefficient (K_c) would be of great benefit to irrigated agriculture. We examined the simulation capacities of CropSyst for determining crop water use of Japanese plum under varying growing conditions. These conditions involved weather changes occurring during a period of three years (2010-2012), different pruning intensities, and the use of two cultivars having different vigor and maturity time (*Prunus salicina* Lindl. 'Angeleno' and 'Red Beaut'). Crop evapotranspiration (ET_c) was determined using the soil water balance method. Midday stem water potential (Ψ_{stem}) was determined using a pressure chamber. Two parameters of the CropSyst crop model: crop coefficient at full canopy ($K_{c,fc}$) and maximum plant hydraulic conductance (C_{max}) were parameterized in 2010 season to predict K_c, while 2011 and 2012 were used for validation. In 2011 and 2012, 'Angeleno' trees were subjected to severe summer pruning so that tree size would be smaller than in 2010. The influence of the high vigor and early harvest of 'Red Beaut' was tested in 2011. The results of 2010 parameterization revealed that $K_{c,fc}$ and C_{max} had a distinctive seasonal pattern. This parameterization was adequate to simulate K_c and Ψ_{stem} for 'Angeleno' in other seasons and smaller trees than in 2010. The parameters adjusted in 2010 were not adequate to simulate the behavior of the more vigorous cultivar of 'Red Beaut'. In 'Red Beaut', the factor that best explained the need to adapt CropSyst parameters was the difference in vigor but not the time of the removal of fruit sinks. To accurately simulate K_c and Ψ_{stem} in 'Red Beaut' it was required to use slightly higher values of $K_{c,fc}$ and C_{max} during a specific midsummer period.

Key words: Irrigation; Soil water balance; Fraction of intercepted solar radiation; Stem water potential.

4.1. Introduction

Irrigation in commercial fruit orchards can be scheduled by using the water balance method for estimating crop evapotranspiration (ET_c) (Allen et al., 1998), the product of reference evapotranspiration (ET_o) and crop coefficient (K_c). However, there is no infallible technique for accurate determination of ET_c as K_c is dependent upon crop phenological stage, canopy height, cover and architecture (Allen et al., 1998). In annual crops, averaged values that are found in the literature could be used to estimate mean ET_c values. In fruit trees, the dependency of K_c on crop characteristics and management practices such as crop load adds uncertainty to its use wherever these factors are widely variable. Lower crop load levels typically reduce stomatal conductance and photosynthetic rate in peach, apple and pear (Chalmers et al., 1975; Crews et al., 1975; DeJong and Goudriaan, 1989; Reyes et al., 2006; Marsal et al., 2008) and therefore reduce transpiration rate and water uptake due to the decrease in demand of assimilates (Chalmers et al., 1983) or by restricted root growth (Williamson and Coston, 1989). In addition, it should be considered that K_c assessment can be improved when two separate coefficients are considered as (K_{cb} + K_e), where K_{cb} is the basal crop coefficient which represents the transpiration of the crop and K_e is the soil water evaporation coefficient which considers evaporation from the soil surface (Allen et al., 1998).

The development of a simple method to estimate the seasonal K_{cb} for different crops, including woody, perennial horticultural crops would be of great benefit to the agricultural industry (Williams and Ayars, 2005). The most direct method for estimating

ET_c is through lysimeters, although these are expensive and are not generally available to growers. In the case of Japanese plum trees there is no information available on crop ET with the precision offered by lysimeters. Other alternatives such as the water balance method have been proposed to estimate irrigation needs. The soil water balance method uses the law of mass conservation (Faures et al., 1995; Moreno et al., 1996; Sanchez-Cohen et al., 1997) as $\Delta S = P + I - D - R - ET_c$, where ΔS is the change in soil water storage between two consecutive dates, P is effective rainfall, I is irrigation, D is drainage, R is runoff and ET_c is crop evapotranspiration. Although this method can be employed to estimate ET for longer time periods than a day (e.g., week-long or ten-day periods), it has also been widely used to quantify seasonal ET_c of different crops such as almonds (Fereres et al., 1981a; 1981b; Andreu et al., 1997), olive (Moreno et al., 1988), apricot (Abrisqueta et al., 2001) or citrus (Castel et al., 1987; García-Petillo and Castel, 2007).

In the last few years, the development of crop models has received renewed attention because of their value when analyzing the behavior of agricultural systems under a variety of climatic and geographical conditions. CropSyst is a general crop growth model (Stöckle et al., 2003) that can have many applications. The development of CropSyst started in the early 1990s to simulate crop productivity, development, soil water budget, soil-plant nitrogen budget and management strategies for both arable and horticultural crops. Presently, CropSyst is being supplemented with developments for tree crop applications. Although its application to specific species requires the calibration of certain specific parameters, it has been successful at simulating plant water stress in pear trees during short periods of time (Marsal and Stöckle, 2012) and at predicting crop coefficient for apple (Marsal et al., 2013).

CropSyst considers daily changes in tree size to calculate canopy light interception and ground cover (Oyarzun et al., 2007). Tree transpiration is related to the amount of radiation intercepted by the canopy and soil evaporation is separated from the transpiration by using the fraction of intercepted radiation as a multiplier coefficient of maximum evapotranspiration ($ET_{c,\ max}$) (Stöckle et al., 2003). This $ET_{c,\ max}$ is calculated as ET_o x $K_{c,fc}$, where $K_{c,fc}$ is a model parameter which corresponds to K_c for a canopy that is fully covering the ground. It has been reported that this parameter for deciduous fruit trees is variable depending on the species and the time of the year (Marsal et al., 2014). In the case of plum, there is no information on seasonal patterns of $K_{c,fc}$. In addition, whole season validations of CropSyst simulations to other years and cultivar within the same species have not yet been published. Our objective was to carry out a model parameterization for 'Angeleno' plum during 2010 and validate these CropSyst parameters for the seasons 2011 and 2012. Another aim was to validate 'Angeleno-2010' parameters adjusted to another cultivar with notable differences in vigor and maturity time. The purpose of the work was to provide useful parameter values so that CropSyst could be used as a tool for irrigation scheduling in Japanese plum orchards.

4.2. Materials and methods

4.2.1. Model description

CropSyst is a multi-year, multi-crop, daily time-step cropping system simulation model developed to serve as an analytical tool to study the effects of climate, soil and management on cropping system productivity and the environment (Stöckle et al., 2003) and can be found at http://www.bsyse.wsu.edu/CS_Suite/CropSyst/register.htm. Simulation scenarios are divided into separate input data files: Simulation Options, Climate, Soil, Crop and Management files, providing daily or annual results of soil and crop. Details on the use, parameterization and execution of the model are given in the user's manual (Stöckle and Nelson, 2000) and definitions, usage, and range of variation of all parameters required by CropSyst can be found in the Help facility of the model interface.

The model uses the following protocol: the simulation of crop phenology and daily updates in tree size are based on thermal time. A light interception component of the model is used to calculate solar radiation interception and ground cover according to Oyarzun et al. (2007). Plant water potential and tree transpiration are related and calculated at the same time using an Ohm's law analogy. ET at full canopy (ET_{fc}) is determined by multiplying ET_o by crop coefficient for total canopy cover ($K_{c,fc}$).

The other target parameter of this study, maximum plant hydraulic conductance (C_{max}) is determined from a definition of maximum water uptake of the crop (U_{max}) as:

$$C_{max} = U_{max} / (\Psi_{fc} - \Psi_{l,sc}) \quad [1]$$

where Ψ_{fc} is soil water potential at field capacity, and $\Psi_{l,sc}$ is the parameter that indicates the lowest plant water potential that does not limit transpiration. Values for Ψ_{fc} are those simulated from the soil module of the model. Values for $\Psi_{l,sc}$ change throughout the season and for this study we adopted those suggested by Fereres et al. (2012) for fruit trees. U_{max} is the maximum water uptake for a fully developed green crop, completely covering the ground, unstressed and fully watered, with unrestricted root growth, and under environmental conditions providing large atmospheric evaporative demand (Stöckle and Nelson, 2000).

For the simulations in this study we have used version 4.18.04. This version allows the use of multiple $K_{c\ fc}$ and C_{max} parameterization throughout the season.

4.2.2. Approach

CropSyst was used following an inverse modeling approach. Information for parameterization was gathered from a field orchard in trees which were fully irrigated during 2010. Soil water content was measured by the gravimetric method and crop water use was calculated using the law of mass conservation. Complementary data on tree intercepted radiation, soil evaporation determined by microlysimeters, and midday stem water potential were used for that purpose.

Since data of soil evaporation (E_m) were measured at the same intervals as ET, CropSyst was not used to predict soil evaporation and, therefore, outputs in CropSyst ET at any stage of canopy development were determined as predicted transpiration plus measured soil evaporation by using the fraction of intercepted solar radiation (F_{IPAR}) as a multiplier coefficient of ET_o:

$$ET = T + E = F_{IPAR} \cdot K_{c,fc} \cdot ET_o + E_m \qquad [2]$$

The parameterization of $K_{c,fc}$ and C_{max} was done in periods from 10 to 30 days which coincided with periods with available information on measured ET_c. On a seasonal basis, this corresponds to an average of 10 periods for each season. The parameterization was adjusted in two steps: firstly, adjusting $K_{c,fc}$ so that the differences between CropSyst predictions and measured ET_c were minimized, and secondly, adjusting C_{max} by minimizing the error of CropSyst predictions in midday stem water potential.

Model parameterization was carried out using 2010 measurements for ‘Angeleno’ and validations were performed by using measured data from other years (2011 and 2012) and another cultivar (‘Red Beaut’) and compared with CropSyst simulations.

4.2.3. Location

The experiment was performed in a Japanese plum orchard located on “Finca La Orden-Valdesequera” experimental farm, Badajoz (38°51'N, 6º40'W, elevation 184 m), Spain. The climate of the area is Mediterranean with mild Atlantic influence, dry and hot summers, with high daily irradiance and evaporative demand and an average of 4 dry months per year from June to September. The average annual temperature (T^{a}_{avg}) was 16.2 °C (1992-2012), with a minimum of -5 °C recorded from December to February and a maximum above 35 °C from June to August. The T^{a}_{avg} was 16.5 ºC in 2010; 16.7 ºC in 2011 and 15.5 ºC in 2012. The average annual rainfall was 438 mm (1992-2012), beginning in October and extending through May. The annual rainfall was 739 mm, 376 mm, and 352 mm in 2010, 2011, and 2012, respectively. Reference evapotranspiration (ET_o) calculated according to the Penman-Monteith method (Allen et al., 1998) was 1317 mm in 2010, 1529 mm in 2011 and 1325 mm in 2012. Daily ET_o usually reached demands greater than 6.5 mm day^{-1} from June to August, with a peak of about 7.5-8.0 mm day^{-1} around mid-July. The daily average relative humidity and mean wind speed (1992-2012) were 66.6% and 2.1 m s^{-1}, respectively.

The soil falls into the Alfisol order, of suborder Xeralf and part of the larger Haploxeralf group, with mainly acid pH, low organic matter content and high bulk density (ρ_b = 1.412 g cm^{-3}), light colors, moderate to weak structure, with normal and even very high content of P_2O_5, low content of Na^+ and K^+ and low cation exchange capacity. The texture is loam, with low stone content and depth greater than 2.5 m (Table 4.1).

Table 4.1 Summary of soil physical properties in the experimental plum orchard. Values from 0-2.0 m of the soil profile.

Depth (cm)	Sand (%)	Clay (%)	Silt (%)	Bulk density (g cm^{-3})	Field capacity (m^3 m^{-3})	Wilting point (m^3 m^{-3})	Organic matter (%)
0-20	48.35	38.15	13.50	1.48	0.24	0.10	1.00
20-40	47.20	38.70	14.10	1.48	0.24	0.10	0.90
40-60	47.60	37.40	15.00	1.48	0.24	0.10	0.90
60-80	39.20	39.10	21.70	1.42	0.26	0.12	0.70
80-100	38.90	36.08	25.02	1.41	0.26	0.13	0.50
100-120	38.00	38.60	23.40	1.41	0.26	0.12	0.40
120-140	38.40	39.80	21.80	1.39	0.27	0.14	0.30
140-160	38.45	46.08	15.47	1.41	0.27	0.12	0.30
160-180	33.85	43.38	22.77	1.38	0.28	0.14	0.30
180-200	34.10	44.50	21.40	1.38	0.28	0.14	0.30

4.2.4. Experimental plot

The experiment was performed over a three year period (2010-2012) in a 1.0 ha experimental orchard of late maturing Japanese plum (*Prunus salicina* Lindl. 'Angeleno') grafted onto *Mariana* 2624 rootstock. Plum trees were planted in the spring of 2005 at a spacing of 6 x 4 m, in an east-west row orientation (5º towards north) and were trained to an open vase system with four main branches from 0.25 to 0.40 m above ground. *Prunus salicina* 'Larry Ann' and 'Fortune' were planted in guard rows in a sufficient number as pollinizers. Bee hives were placed at flowering to ensure pollination. Trees were irrigated on a daily basis controlled by a commercial irrigation controller (Agrónic 2000, Sistemes Electrònics Progrès, Bellpuig, Spain) and electro-hydraulic valves that were reprogrammed once a week. The drip irrigation system consisted of a single lateral line per tree row, with four pressure compensated on-line drip emitters with 4 l h^{-1} discharge rates, located close to the tree trunk, spaced 0.5 and 1.5 m from each tree trunk. Weather data were collected from an automated weather station equipped with all necessary sensors and placed over a grass reference surface in the experimental farm and located ~ 600 m away from the plum orchard. ET_o were calculated using the FAO-56 Penman-Monteith method (Allen et al., 1998).

4.2.5. Measurements in 2010

Tree sizes were measured at bud-break and before leaf fall. Respectively, initial and final tree widths across the row were 4.2 and 5.7 m, tree widths along the row were 3.9 and 4.9 m, and tree heights were 2.5 and 4.6 m. The growth stages were determined weekly from bud-break to fruit set using the Baggiolini scale (Baggiolini, 1952). Soil water content was measured by the gravimetric method once a week in the morning. A total of six auger holes were made in the southwest quarter of the area occupied by each tree, according to the criteria specified in Fig. 4.1. Soil core samples were taken every 20 cm down to a depth of 2 and 3 m with a manual auger (Edelman type, model GM081, Eijkelkamp, Giesbeek, The Netherlands). Water content (θ_i) was estimated as the average measurement of two trees and was calculated as the difference between fresh and dry mass of the sample divided by dry mass of the sample. Once θ_i was determined, soil profile water content (SWC, mm) was determined as:

$$SWC = \sum \theta_i \text{ x } Z_i \text{ x } \rho_b \qquad [3]$$

where Z_i is the depth of each layer (mm) and ρ_b is the bulk density (g m^{-3}). The SWC for the whole tree was calculated as the average of the six holes of each tree. The ρ_b was measured by taking samples of soil with a known volume and drying at 105 °C to constant weight in the oven.

Crop water use (ET_c) was calculated using the law of mass conservation as:

$$ET_c = P + I - D - R - \Delta S \qquad [4]$$

where P is effective rainfall, I is irrigation, D is drainage, R is runoff and ΔS is the change in soil water storage between two consecutive dates. All terms are expressed in mm for a given period. The R was insignificant because the orchard was on level ground and no R was observed. D was considered to occur if ΔS was positive from maximum root depth. After calculating crop evapotranspiration (ET_c), the crop coefficients (K_c) were estimated as the ratio between ET_c and ET_o.

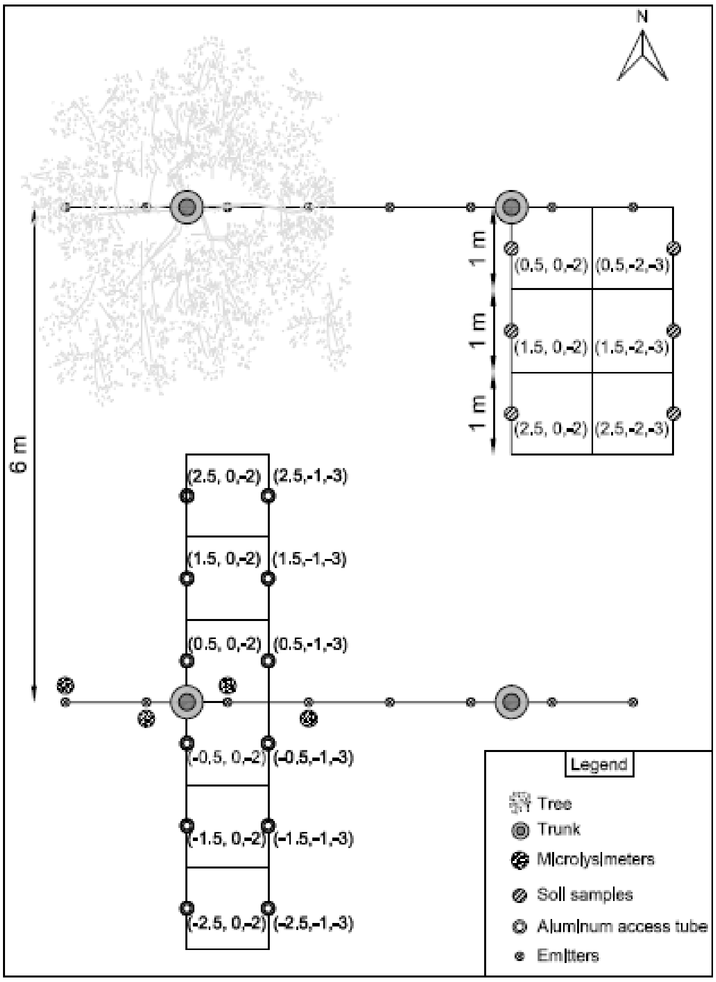

Fig. 4.1 Diagram of experimental trees, microlysimeters, soil samples distribution, access tubes for neutron probe and emitters. Cartesians coordinates.

Rooting depth was estimated from soil water uptake patterns (Green and Clothier, 1999). Root water uptake profile was inferred by subtraction between soil water content values measured immediately before withholding irrigation and after 3 weeks without irrigation and rainfall during early September 2011. PAR intercepted by tree canopy was evaluated every 2 hours for 16 specific days by using a portable ceptometer of 80 cm probe length (Accupar Linear PAR, Decagon Devices, Inc., Pullman, WA, USA).

PAR was used to determine the daily fraction of intercepted radiation (F_{IPARd}) by the trees and was done according to the protocol followed by Auzmendi et al. (2011).

Direct evaporation (E_s) from bare soil was measured with microlysimeters installed on both sides of the tree along the row in the fully irrigated field trees based on the model of Bonachela et al. (2001). Bonachela's model was site calibrated for the growing conditions of 2008 by Martin-Vertedor (2010).

Ψ_{stem} was measured with a Scholander pressure chamber (Model 3005; Soil Moisture Equipment, Santa Barbara, CA, USA.) at 1200 GMT once a week using covered shaded leaves located close to the trunk base. Selected leaves were bagged with aluminum foil for 2 h before measurement (Shackel et al., 1997). Since CropSyst simulates daily leaf water potential (Ψ_{leaf}), an empirical relationship was also developed to convert simulated Ψ_{leaf} into midday simulated Ψ_{stem} values. During pit hardening and for four different days in 2010 and two different days in 2011, daily courses of Ψ_{stem} were obtained by measuring Ψ_{stem} every 2 hours and integrating the diurnal course to obtain daily averages. The empirical polynomial relationship used to relate Ψ_{stem} and Ψ_{leaf} was:

$$\Psi_{stem} = 0.1122\ \Psi_{leaf}^2 + 1.3665\ \Psi_{leaf} + 0.0076\ (R^2 = 0.98;\ P < 0.001) \qquad [5]$$

Fruit were harvested in a single picking on 6 September (DOY 249). Summer pruning was carried out on 29 April (DOY 119).

4.2.6. CropSyst inputs and parameters

Daily rainfall, maximum and minimum temperature and relative humidity, wind speed and net solar radiation data from meteorological stations were used as input for model simulations. Water infiltration in the soil was simulated with the hourly cascade module. The simulation of crop phenology was based on thermal time, which required daily accumulation of average air temperature above a base temperature and below a cut-off temperature to reach given growth stages. The base and cut-off temperature used for parameterization were 6 and 25 ºC, respectively (Tabuenca and Herrero, 1966) and the counting of thermal time to bud-break started on January 1. The model of Oyarzun et al. (2007) used to calculate canopy light interception and ground cover requires information on geographical coordinates of the orchard, canopy size and extinction coefficient for solar radiation. Tree height and width across the row, and tree width along the row at bud-break and before onset of leaf fall were used for initial and final values of canopy size simulation. The porosity coefficient for solar radiation was determined by finding the best match between the crop radiation interception simulations provided with CropSyst after trees reached maximum size for the year and actual measured values. The rest of the input crop parameters were used as default values as provided by the application software. Soil hydraulic properties required to run CropSyst (volumetric soil water content at water potentials of -33 and -1,500 kPa) were estimated using regression equations from soil measurements on soil texture (Saxton et al., 1986).

4.2.7. Validation of 'Angeleno-2010' to 2011 and 2012

Validation of optimized CropSyst $K_{c,fc}$ and C_{max} parameters in 2010 for other years was carried out with data collected during 2011 and 2012 in the same orchard. In this case, soil water content was measured with a neutron probe (CPN 503DR Hydroprobe, CPN International, Inc., Port Chicago Highway, CA, USA), but using an identical sampling layout as in 2010 with the gravimetric method. Briefly, 6 aluminum access tubes with a length of 2.0 m and 6 tubes of 3.0 m were installed vertically on either side of the measurement tree (Fig. 4.1). The first sets (tubes of length 2.0 m) were installed perpendicular to the measuring tree row and the second sets (tubes of length 3.0 m) were installed 1.0 m apart from the first set. In both cases, the distance between two consecutive tubes was 1 m. In each tube measurements were made from 0.30 to 1.80 and from 0.30 to 2.70 m, respectively, in 0.3 m increments. The neutron probe readings were calibrated for the experimental soil in situ with undisturbed soil samples, according to the experimental equation:

$$\theta_i = 0.0015 \times N/SC - 0.488 \ (R^2 = 0.97; P<0.001) \qquad [6]$$

where N is the neutron probe count reading, θ_i is the volumetric soil water content (m^3 m^{-3}) and SC is the standard count reading. In 2011, measurements started on 28 June. In 2012, due to a failure of the neutron probe, it was only possible to measure until 21 August. ET_c was calculated using the law of mass conservation.

PAR intercepted was measured at solar noon (F_{IPARm}) and this was used to estimate F_{IPARd} by the experimental linear relationship obtained in 2010:

$$F_{IPARd} = 0.9427\ F_{IPARm} + 0.0562 \ (R^2 = 0.99; P<0.0001) \qquad [7]$$

Initial and final tree widths across the row were 3.9 and 5.7 m in 2011 and 4.3 and 5.1 m in 2012, tree widths along the row were 3.4 and 4.6 m in 2011 and 3.6 and 4.2 m in 2012, and tree heights were 2.8 and 4.1 m in 2010 and 2.4 and 2.9 m in 2012. Evaluation of phenological traits, soil evaporation and Ψ_{stem} was carried out as described in section 2.5. Fruit were harvested in a single picking on 30 August in 2011 (DOY 242) and on 6 September in 2012 (DOY 249). Summer pruning was carried out on 10 May in 2011 (DOY 130) and 24 May in 2012 (DOY 145). In 2011, and particularly in 2012, trees were subjected to severe summer pruning so that CropSyst could be tested for different conditions in the fraction of canopy intercepted radiation.

4.2.8. Validation of 'Angeleno-2010' to 'Red Beaut' in 2011

Validation of optimized CropSyst $K_{c,fc}$ and C_{max} parameters to another cultivar was performed with data collected for 2011 during post-harvest in an adjacent orchard growing a Japanese plum early maturing cultivar (*Prunus salicina* Lindl. 'Red Beaut'). The experimental orchard and trees had the same characteristics as the 'Angeleno'. All measurements were taken as indicated in sections 2.5 and 2.7. Initial and final tree widths across the row were 4.1 and 6.0 m, tree widths along the row were 3.8 and 5.0 m, and tree heights were 2.8 and 5.3 m. The experimental relationship (eq. [7]) obtained in 2010 for 'Angeleno' was also valid for 'Red Beaut'. Fruit were harvested on 23 and 30 May (DOY 143 and 150). Summer pruning was carried out on 4 May (DOY 124).

4.2.9. Simulations and data analysis

Yearly simulations started on 1 January and finished on 31 December. Model simulation results were compared to the mean value calculated from experimental data replicates (average of two tree replicates). Soil water content was assumed to be always at field capacity. Model performance was evaluated qualitatively using scatter plots of predicted vs. actual values around 1:1 line (regression parameters are close to 0 and 1 for intercept and slope, respectively).

4.3. Results

The results of model parameterization of $K_{c\ fc}$ and C_{max} for 'Angeleno' plum during 2010 and the validations are organized into different sections to facilitate their presentation.

4.3.1. Soil water balance and climatic conditions

The drying cycle carried out to reveal the soil depletion pattern revealed a maximum depletion zone at the top layer of the soil profile and at 180 cm depth (Fig. 4.2A). However, much of the soil moisture was mainly drawn from the layers between a soil depth of 0.3 and 1.8 m. Depletion in the top layer is expected since it can be more related to soil evaporation than root uptake. The maximum extraction observed at a depth of 1.8 m may be more related to root activity and, therefore, we considered an effective rooting depth of 2.1 m (Fig. 4.2B).

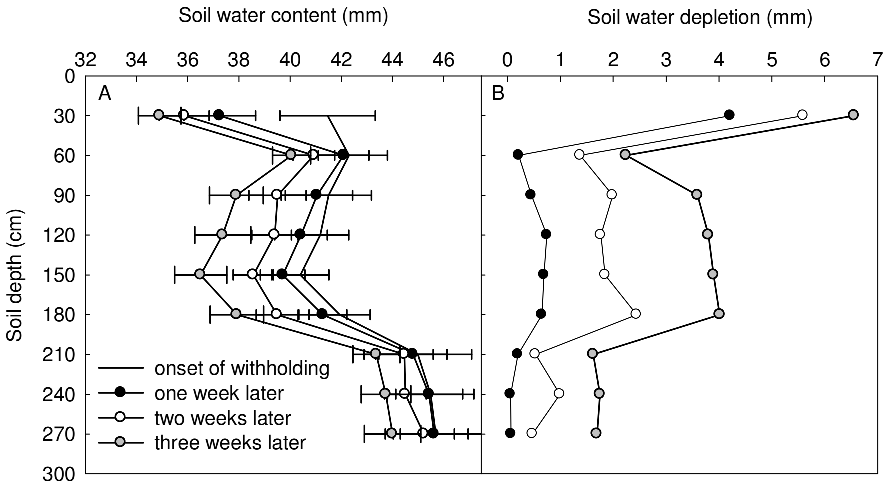

Fig. 4.2 Variation in soil water content (A) and soil water depletion (B) within the soil profile during a period of three weeks without irrigation and rainfall. Each value represents the average of 12 measurements for the depth 30-180 cm and of 6 measurements for the depth 180-270 cm. Bars represents the standard error of the mean. The considered period includes four measurement days.

Soil evaporation from late May until harvest remained at values between 0.4 to 0.8 mm day^{-1}, and rarely above this value. After harvest and until the end of the irrigation period (DOY 249-279), evaporation decreased progressively to values close to 0.2 mm day^{-1} (Fig. 4.3A). Water storage fell steadily from 1 May to 23 July (DOY 121-204), after which the variations were less marked, with total soil water depletion being 46% during the irrigation period (Fig. 4.3A). After the end of the rainy season (DOY 159 and 160), soil water storage throughout the soil profile was maintained. Both measured ET_c

and calculated ET_o displayed similar trends across the seasons, increasing from mid-May (DOY 138) to reach a peak in mid-July (DOY 195), then remaining relatively stable until the end of August (DOY 240) and finally falling until the end of the irrigation period (DOY 273) (Fig 3B). Seasonal patterns of ET_o and ET_c showed two periods: the first during spring, where ET_o values were higher than those of ET_c and, the second during summer, where ET_c values were higher than those of ET_o due to greater canopy development. ET_o and ET_c remained at high values, around 7.5 and 7.0 mm day^{-1} on average, respectively, with occasional peak values of ET_c around 7.7 mm day^{-1} in early August (DOY 215). Afterwards, ET_c fell steadily to 4.0 and 3.4 mm day^{-1} in autumn (DOY 273) (Fig 3B). Rainfall during the water balance periods was scarce and mainly occurred in May and early autumn. It should be noted that from June to September, there was no rainfall (Fig 3B). The drainage component in spring was mainly caused by rainfall when coinciding with irrigation rates of 3-5 mm day^{-1}. During summer, drainage coincided with irrigation rates higher than 7-10 mm day^{-1}. Total drainage accounted for 12.5% of the growing season rainfall and irrigation (Fig 3B).

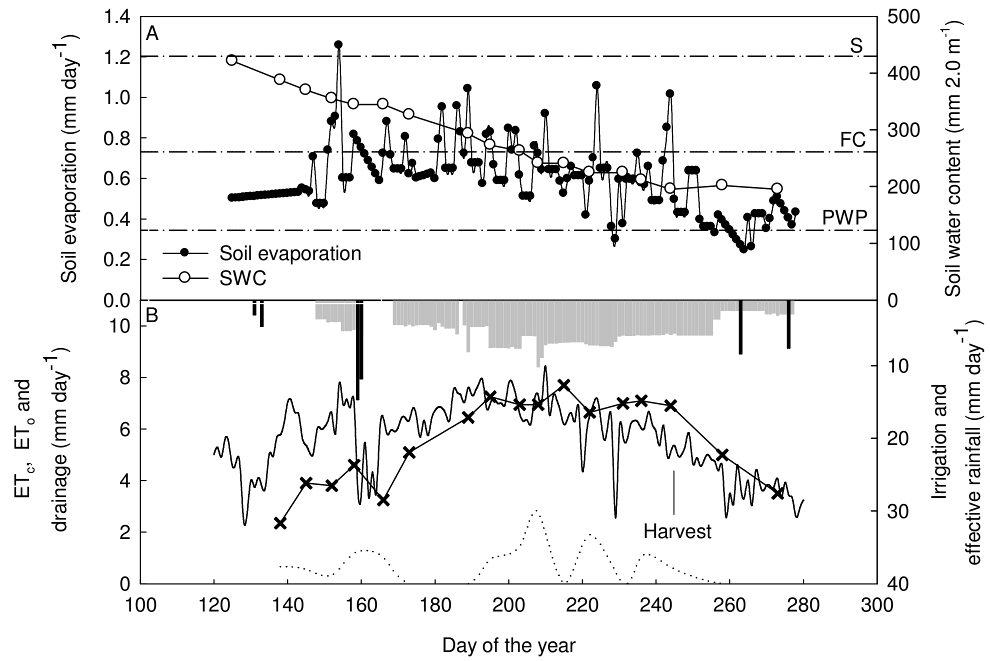

Fig. 4.3 Seasonal evolution of soil evaporation (E_s) and soil water content (SWC) (A), crop evapotranspiration (ET_c), reference evapotranspiration (ET_o), drainage (D), irrigation (I) and effective rainfall (R) (B) during season 2010. Dot-dashed lines in the upper panel represent saturation (S), field capacity (FC) and permanent wilting point (PWP).

Symbols represent: ● E_s; ○ SWC; **x** ET_c; — ET_o; ··· D; ▌I; ▌R

Seasonal evolutions of vapor pressure deficit and daily incident solar radiation were similar between years, but maximum values were reached in 2010 (Fig. 4.4). A pattern was observed of an increase from early May (DOY 120) reaching a maximum level in mid-August (DOY 226) and then decreasing until the onset of leaf fall (DOY 295). Incident solar radiation decreased sooner than vapor pressure deficit. The peak for solar radiation occurred from 10 to 14 days earlier than vapor pressure deficit, depending on the year (Fig. 4.4).

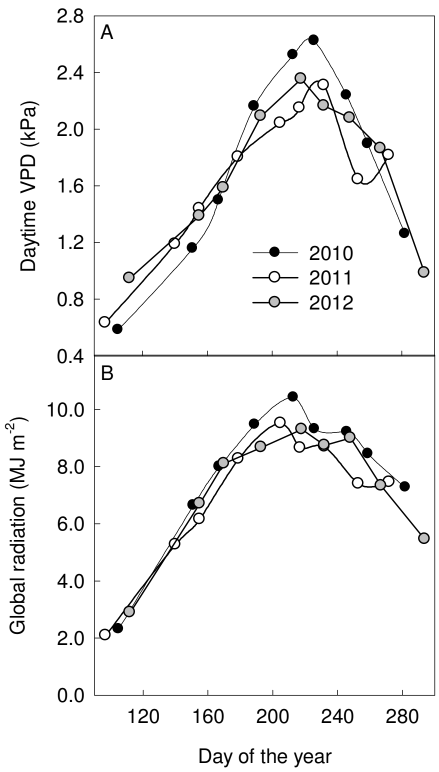

Fig. 4.4 Seasonal evolution of daytime vapor pressure deficit (VPD) (A) and daily incident global solar radiation (B).

4.3.2. Parameterization of 'Angeleno' to 2010

The seasonal pattern of $K_{c,fc}$ adjusted after minimizing the error between observed ET_c and CropSyst predicted ET_c remained stable during spring until early June (DOY 155). It subsequently rose before reaching a peak in mid-August of about 1.7 (DOY 226), coinciding with maximum VPD, and then decreasing to 1.0 before the onset of leaf fall (DOY 295) (Fig. 4.5A). The seasonal patterns of C_{max} indicated an evolution in three phases: an increase of 8.9 mm MPa^{-1} during spring (DOY 105-189), followed by a period of relative stability until harvest (DOY 249), and finally decreasing from harvest until the onset of leaf fall (DOY 295) (Fig. 4.5B).

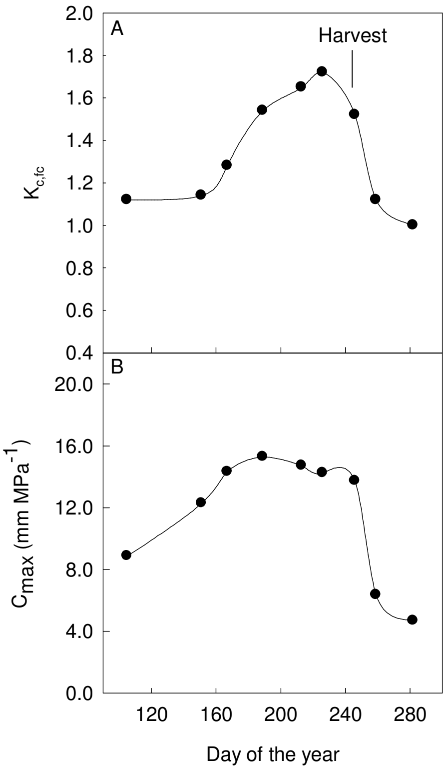

Fig. 4.5 Seasonal evolution of CropSyst parameter crop coefficient at full canopy ($K_{c,fc}$) (A) and maximum plant hydraulic conductance (C_{max}) (B) during 2010 in 'Angeleno', after parameterization.

After $K_{c,fc}$ and C_{max} parameterization, simulations of F_{IPARd}, ET_c, K_c and Ψ_{stem} simulations produced with CropSyst were in agreement as expected with the seasonal patterns observed in the field (Fig. 4.6). F_{IPARd} increased during spring from 0.57 to 0.89 at the end of the irrigation period in October (Fig. 4.6A). ET_c annual patterns point to an asymmetry, similar to that observed for C_{max} (Fig. 4.5), and also a turning point in ET_c, which occurred right after harvest. ET_c increased from 2.35 mm day^{-1} during spring, reaching a peak of 7.7 mm day^{-1} and tended to remain constant during summer and then decreased to 3.5 mm day^{-1} at the end of the irrigation season (Fig. 4.6B). The seasonal patterns of daily K_c followed a similar trend to those of ET_c (Fig. 4.6C). Initial K_c values were about 0.56 and then increased with time until reaching maximum values of about 1.2 at shortly before harvest. After harvest, K_c decreased until the end of the irrigation season to a minimum value of 0.9 (Fig. 4.6C). Ψ_{stem} decreased during the fruit growth period, from -0.65 to -0.98 MPa (Fig. 4.6D). The minimum Ψ_{stem} of -1.08 MPa was reached at the end of the post-harvest period.

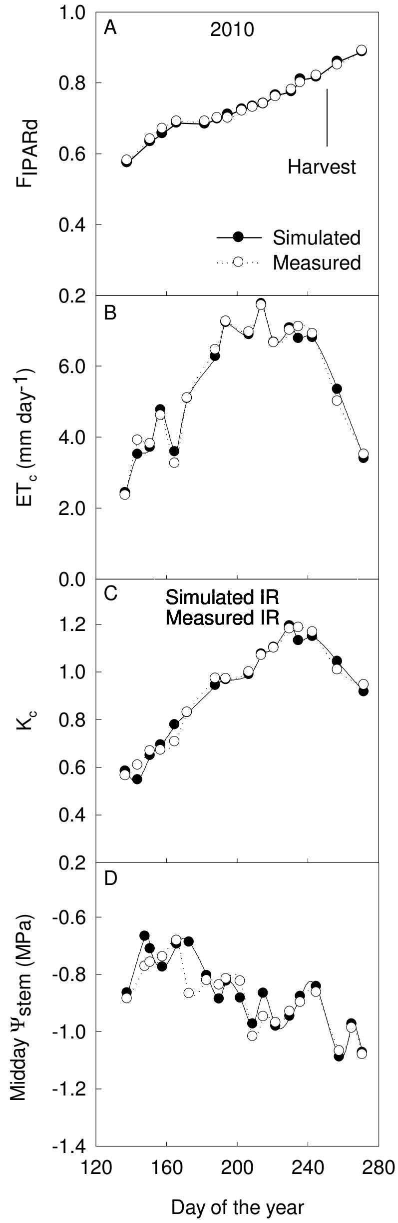

Fig. 4.6 Seasonal evolution of fraction intercepted radiation (F_{IPARd}) (A), crop evapotranspiration (ET_c) (B), crop coefficients (K_c) (C) and midday stem water potential (Ψ_{stem}) (D) predicted by CropSyst after parameters of the model had been adjusted and measured in the field during season 2010 in 'Angeleno'.

4.3.3. Validation of 'Angeleno' to the seasons of 2011 and 2012

Tree sizes in 2011 and particularly in 2012 were slightly smaller than in 2010, due to severe summer pruning and, therefore, trees had a lower F_{IPARd} (results not shown). The physiological crop parameters such as ET_c, K_c and Ψ_{stem} measured in the field and simulated with CropSyst displayed reasonable agreement (Fig. 4.7). Maximum values of ET_c were about 6.8 and 7.3 mm day^{-1} in 2011 and 2012, respectively (Fig. 4.7A and B). The corresponding values for K_c were 1.05 and 1.2 (Fig. 4.7C and D). In 2011, Ψ_{stem} decreased during the fruit growth period, from -0.65 to -0.95 MPa (Fig. 4.7E). Conversely, in 2012 after harvest Ψ_{stem} increased progressively until the end of the irrigation period.

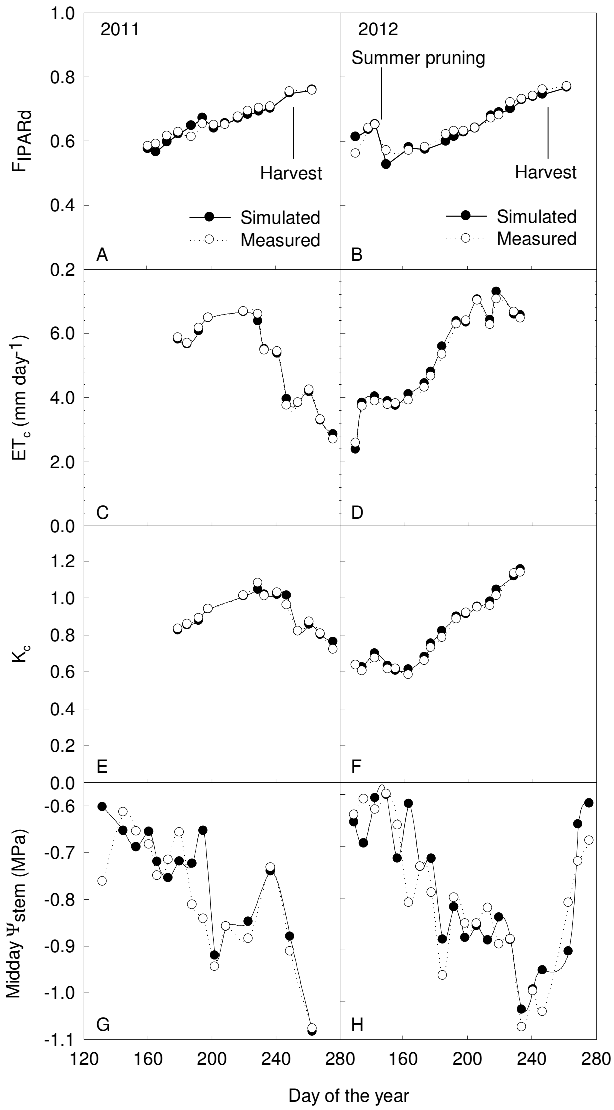

Fig. 4.7 Validation of 'Angeleno-2010' CropSyst parameters for seasons 2011 and 2012. Seasonal evolution crop evapotranspiration (ET_c) (A, B), crop coefficients (K_c) (C, D) and midday stem water potential (Ψ_{stem}) (E, F) simulated by CropSyst after parameters of the model had been adjusted and field observation during season 2011 (A, C, E) and 2012 (B, D, F).

The agreement between data measured in the field and simulated with CropSyst of K_c and Ψ_{stem} was very consistent for both seasons and the vast majority of the data. Relationships between observed and simulated data were linear and narrowly distributed along the 1:1 line, producing slopes of 1.0006 and 0.955, respectively (Fig. 4.8A and B).

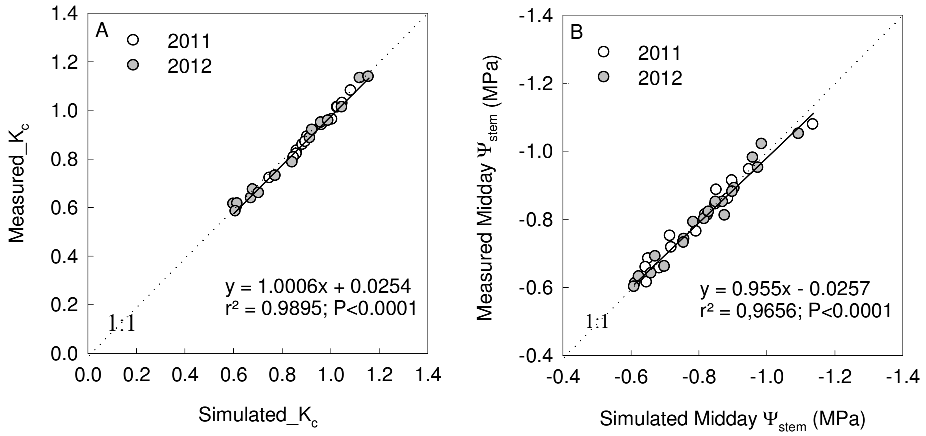

Fig. 4.8 Comparison between values of crop coefficients (K_c) (A) and midday stem water potential (Ψ_{stem}) (B) simulated by using CropSyst parameters optimized for 'Angeleno-2010' and field observations during seasons 2011 and 2012.

4.3.4. Validation of 'Angeleno' to 'Red Beaut' in 2011

Within the same year, 'Red Beaut' trees were taller higher than 'Angeleno' trees. Therefore, measured K_c had higher values than when simulated by CropSyst, except at end of season when measured K_c had lower values (Fig. 4.9B). However, the opposite happened with Ψ_{stem}, with less negative values at early season for observed Ψ_{stem} than CropSyst predicted Ψ_{stem}, with the process being reversed after DOY 195 (Fig. 4.9C). The threshold level of -0.85 MPa in Ψ_{stem} was never surpassed in CropSyst simulations, while measured Ψ_{stem} ranged from -0.82 to -0.97 MPa. Though the relationship between simulated and measured K_c was in good agreement, the accuracy of simulated Ψ_{stem} as a predictor of measured Ψ_{stem} was not as high as desirable (Fig. 4.10).

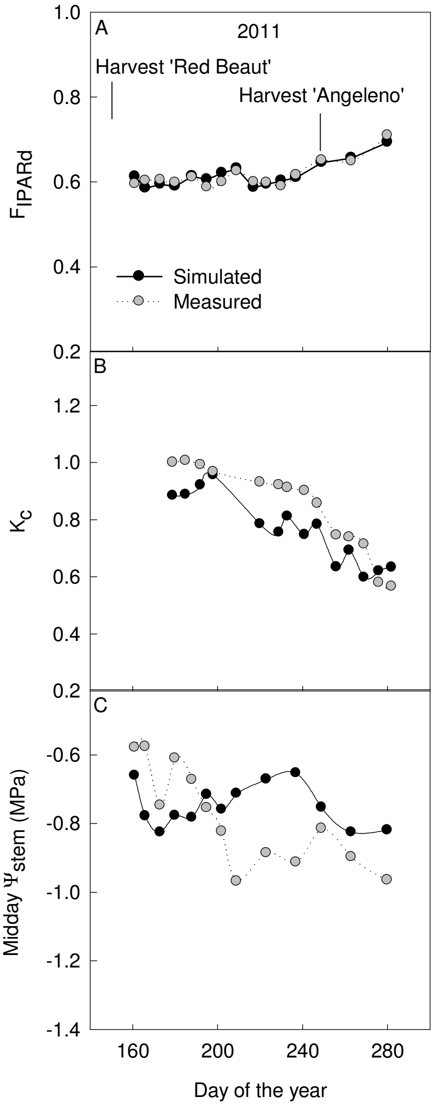

Fig. 4.9 Validation of 'Angeleno-2010' CropSyst parameters for 'Red Beaut'. Seasonal evolution of fraction intercepted radiation (F_{IPARd}) (A), crop coefficients (K_c) (B) and midday stem water potential (Ψ_{stem}) (C) simulated by CropSyst and after field observations in 'Red Beaut' during season 2011.

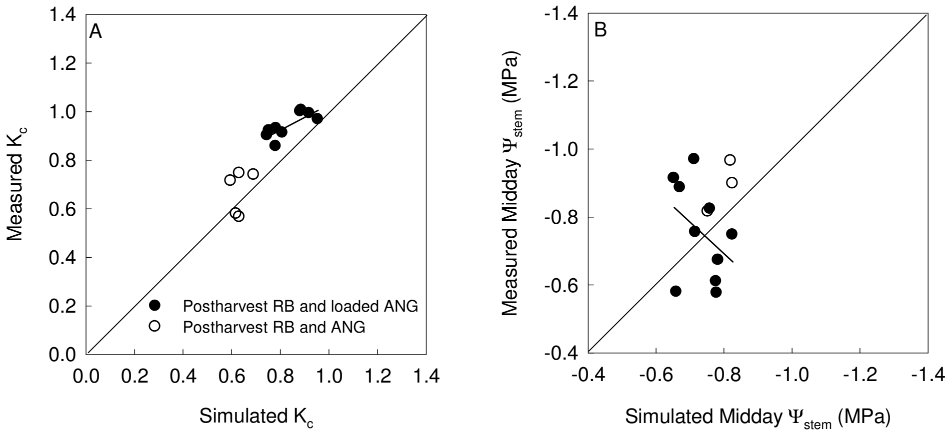

Fig. 4.10 Comparison between values of crop coefficients (K_c) (A) and midday stem water potential (Ψ_{stem}) (B) simulated by using CropSyst parameters optimized for 'Angeleno-2010' and after field observations to 'Red Beaut' during season 2011.

4.4. Discussion

The main input parameter for this study is the K_c and thus accurate estimations of ET_c are desirable. The results of the water balance method seemed to provide reasonable estimations of K_c in the context of fruit trees. Maximum K_c during summer of 2010 was 1.2 (Fig. 4.3), which falls within the expected range for an orchard having a large groundcover of 85% at the end of the summer (Allen et al., 1998). Accurate estimations of soil water content depend on sample size to compensate for induced heterogeneities in soil humidity by the irrigation system. A soil water content estimation per day was derived from 75 direct soil water content measurements in 2010, and in 2011 and 2012 from 90 measurements. This sampling size seems sufficient to provide a consistent seasonal pattern in soil water content (Fig. 4.3). The estimates of soil water content indicate that at the beginning of the 2010 season the soil was water saturated (Fig. 4.3A). As the season progressed, soil water content tended to decline because the soil areas not wetted by the irrigation system started to dry out (data not shown). By midsummer, average soil water content values were indicative of being drier than field capacity, but one should bear in mind that this estimation was the result of averaging dry with wet parts of the soil. Drainage occurred at maximum rates close to 2 mm during summer and this implied that irrigation rates were superior to actual ET_c and thus it can be inferred that no deficit irrigation applied (Fig. 4.3A).

Measured seasonal E_s from bare soil using the microlysimeter technique produced annual values for the area wetted by emitters under drip irrigation of 300 mm. This is in line with previous studies using the same method and same orchard (Matrín-Vertedor, 2010). Considering that 60% of total tree spacing was un-wetted by the irrigation system, E_s represented 12.5% of estimated annual plum ET_c. These results are similar to those measured in a pistachio orchard (Iniesta et al., 2008) and an olive orchard (Bonachela et al., 1999; Orgaz and Fereres, 2007).

4.4.1. CropSyst parameterization for 'Angeleno' 2010

There are two relevant parameters that are crucial for the determinations of K_c in view of the CropSyst conceptual framework for the prediction of crop water use: the crop coefficient at full canopy ($K_{c,fc}$) and maximum crop hydraulic conductance (C_{max}). The two parameters, after being adjusted, gave values that were not seasonally stable and fluctuated according to a distinctive pattern. $K_{c,fc}$ increased during spring, reaching a peak in mid-August and subsequently decreasing until leaf fall (Fig. 4.4A). C_{max} seemingly increased during spring, remained relatively stable from early July to harvest and decreased from harvest until the onset of leaf fall (Fig. 4.4B). These two patterns are reminiscent of those found by Marsal et al. (2014) for pear and to a lesser extent for peach. This confirms that in fruit tree orchards there is no direct relationship between crop light interception and K_c that is valid throughout the season. A practical implication of this finding is that protocols for irrigation of fruit tree orchards should consider such seasonal patterns for better accuracy.

There are several reasons that can explain the seasonal fluctuations in $K_{c,fc}$, and why they differ between species. Marsal et al. (2014) attributed these seasonal effects to leaf ageing which has an effect on the capacity for transpiration, less capacity at juvenility and senescence (Kramer and Kozlowski, 1979; Kennedy and Johnson, 1981; Schaffer et al., 1991). Therefore in deciduous trees, canopies are made by leaf populations that differ in average age as the season progresses, and this average age may be reduced if the tree is vigorous and keeps producing new leaves after midseason. Phenology is another factor to consider and the occurrence of phenological events that can be shifted in time depends on the characteristic of each species and the respective cultivars. This shift in time can change the source-sink relationships and this can strongly affect photosynthesis and stomata conductance and thus transpiration throughout the season (DeJong et al., 1987; Ayars et al., 2003; Reyes et al., 2006; Marsal et al., 2008). In our study, the response of Japanese plum was interpreted by the marked vigor of Japanese plum until harvest: ‘Angeleno’ grafted onto ‘Mariana’ rootstock did not produce more leaves after harvest and thus had no leaf replacement, thereby reducing the average leaf in the canopy. This could explain the progressive decrease in $K_{c,fc}$ after midseason. This is not contradictory with the steady increase in F_{IPARd} after midseason which was related to the combination of tree row orientation (east-west) and zenithal sun angle inclination rather than any true increase in tree volume (data not shown) (Fig 6A). ‘Angeleno’ plums are considered as vigorous as peaches and this would account for the marked increases in $K_{c,fc}$ during spring and its maximum values of 1.7 slightly above the 1.65 reported for other species by Marsal et al. (2014).

The seasonal patterns of Japanese plum in C_{max} were similar to those reported for $K_{c,fc}$, and are also reminiscent of those for pear reported by Marsal et al. (2014). Interpretation of C_{max} seasonal fluctuation may be not straightforward since there are a number of factors that can justify this pattern. C_{max} may be affected by (I) vigor conditions, with higher C_{max} expected for higher vigor (Solari et al., 2006); (II) influence of temperature on water viscosity, with lower C_{max} values expected early in spring and later after the summer season (Tyree and Zimmerman, 2002); (III) loss of functionality of stem vessels at the end of the season (Tyree and Zimmerman, 2002); (IV) progressive suberization of ageing absorbing roots as the season progresses limiting root water absorption (Kramer and Boyer, 1995). A factor that has not been mentioned and that should be carefully considered is that the rootstock used in our study is a complex hybrid ('Mariana 2624') whose parents are all of a different *Prunus* species than Japanese plum. This case is similar to that of 'Conference' pear growing on quince rootstock (Marsal et al., 2014). In both cases, maximum values for C_{max} during the season were similar (15 mm MPa^{-1} for plum and 16 mm MPa^{-1} for pear) and noticeably lower than for peach (24 mm MPa^{-1}) (Marsal et al., 2014).

4.4.2. Validation of 'Angeleno-2010' parameters to 2011 and 2012 seasons

In this experiment, canopy during 2011 and 2012 was subjected to increased pruning intensities so that CropSyst could be tested for different conditions in the fraction of canopy intercepted radiation. While in 2010, maximum F_{IPARd} was 0.88, in 2011 and 2012 the maximum values fell to 0.76. Besides variation in tree size (as defined by the F_{IPARd}), CropSyst can predict K_c considering different weather conditions (Stockle et al., 2003), with 2011 and 2012 being milder seasons compared to the warmest season of 2010. The results of the validation indicated that CropSyst could successfully account for the differences in weather and F_{IPARd} between seasons, meaning that adjusted parameters in 2010 were stable for the conditions evaluated (Fig. 4.7). In this case, when comparing seasons K_c increased proportionally with canopy size and the relationship between simulated *vs* observed data fitted an equation with a high coefficient of determination and slope of 1, irrespective of the years (Fig. 4.8). Therefore, the use of different $K_{c,fc}$ values throughout the season allowed CropSyst to produce realistic information on tree water consumption. Our results are in agreement with those found by Marsal et al. (2013) using CropSyst to predict K_c for apple trees with canopies subjected to different pruning intensities and tree dimensions.

Although the effect of training systems has not been validated in this study, CropSyst offers the possibility to account for different systems by defining specific tree shapes in the input parameters. In fact, CropSyst has been successfully used for different training systems such as vase in plum or peach and central leader for pear and apple (Marsal et al., 2014). In addition, because CropSyst deals with daily, instead of noon light interception, and uses different values of $K_{c,fc}$ throughout the season, it avoids the non-linearity problem observed by Girona et al. (2011) between midday canopy light interception and K_c.

4.4.3. Validation of 'Angeleno-2010' parameters to 'Red Beaut' to 2011 season

'Red Beaut' is characterized by having a more vertical shoot growth habit than 'Angeleno', the former being more vigorous. However, the effect we would like to validate with 'Red Beaut' is the effect of different maturity time and the derived shifts in time in the source-sink relationships. In summary, we are validating 'Angeleno-2010' parameters against growing conditions that differ in both vigor and source-sink relationships. Because differences in the source-sink relationship should appear after 'Red Beaut' is harvested, in the validation we have focused on the post-harvest period of 'Red Beaut' when 'Angeleno' has not yet been harvested. In the simulation, we have used the tree dimension characteristics and orchard layout corresponding to the 'Red Beaut' experimental orchard.

The results indicate that the validation was not successful and that measured K_c in the 'Red Beaut' orchard was consistently higher than simulated K_c using 'Angeleno-2010' parameters with 'Red Beaut' tree size and layout characteristics (Fig. 4.9B; Fig. 4.10A). This seems to confirm that higher vigor conditions favor higher water consumption for any given value of light interception and that the presence of fruit imbedded in 'Angeleno-2010' parameters could not counterbalance the positive impact on higher vigor of Red-Beaut. Ψ_{stem} was also not successfully validated and differences between measured and simulated Ψ_{stem} varied during the considered period of validation (Fig. 4.9C, Fig. 4.10B).

It could be reasonable to assume lower water use during 'Red Beaut' post-harvest period was due to fruit removal, but by that time 'Red Beaut' trees were undergoing important vegetative growth (≈ 60% of annual vegetative growth occurs after harvest in 'Red Beaut'). It seems therefore interesting to perform 'Red Beaut' parameterization of $K_{c\ fc}$ and C_{max} for purposes of comparison with 'Angeleno-2010' parameters. Such a parameterization was performed following the same procedure as for 'Angeleno', giving values for both $K_{c,fc}$ and C_{max} that were higher than 'Angeleno-2010', at least until mid-August (2200 accumulated degree days) (Fig. 4.11). This explains the higher K_c in 'Red Beaut' (Fig. 4.9). The higher values in 'Red Beaut' for C_{max} reflect the influence of high vigor conditions rather than a reduced source sink effect. Such an effect would produce higher Ψ_{stem} under equal plant transpiration conditions. Because 'Red Beaut' also transpired more than 'Angeleno', the effect on Ψ_{stem} was not notably distinctive between cultivars (Fig. 4.10 B).

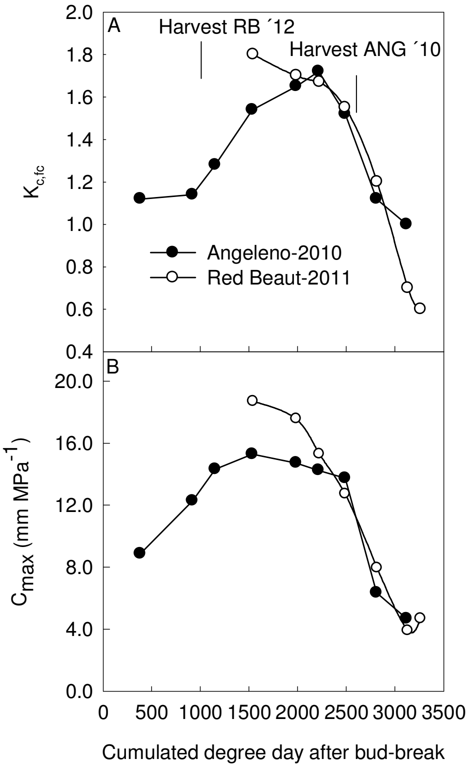

Fig. 4.11 Seasonal evolution of the CropSyst parameter crop coefficient at full canopy ($K_{c,fc}$) (A) and maximum plant hydraulic conductance (C_{max}) (B) to accumulated thermal time, for 'Angeleno-2010' and 'Red Beaut' 2011 parameterized following identical protocol for 'Angeleno' 2010.

In summary, the use of different $K_{c,fc}$ and C_{max} values throughout the season allowed CropSyst to provide realistic information on tree water consumption. Moreover, the results of the validation indicated that CropSyst could successfully account for the changes in weather and F_{IPARd} between seasons and be used to study irrigation scheduling requirements. However, CropSyst should consider a different set of parameters depending on the cultivar used for Japanese plum whenever changes in vigor are expected.

4.5. Conclusions

Seasonal multiple values for the CropSyst parameters of $K_{c,fc}$ and C_{max} were required to accurately predict ET_c, K_c and Ψ_{stem} in 'Angeleno' plums growing under different canopy sizes and seasons. Such parameters exhibited a seasonal pattern very similar to that observed for pear, with vigor the feature that allowed a better interpretation of their seasonal fluctuations. The use of a cultivar like ‘Red Beaut’, of greater vigor than ‘Angeleno’, required a different set of CropSyst parameters. The influence of fruit sink presence in the tree in Japanese plum appears to exert a minor influence compared to tree vigor.

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Chapter 5: Determining tree water consumption and crop coefficient with sap flow and water balance techniques in early and late maturing Japanese plum cultivars

Abstract

The development of an affordable method to estimate seasonal crop evapotranspiration (ET_c) would be of great benefit to irrigated agriculture. We examined under non-limiting water conditions, for 2012 and 2013 seasons, the sap flow (SF) and soil water balance (WB) methods for determining crop evapotranspiration (ET_{c_SF} and ET_{c_WB}, respectively) and the crop coefficient (K_{c_SF} and K_{c_WB}, respectively) of two Japanese plum cultivars of different vigor and maturing time (*Prunus salicina* Lindl. 'Red Beaut' and 'Angeleno'). Relationships between canopy size (using the daily fraction of Intercepted Photosynthetically Active Radiation (F_{IPARd}) and leaf area index (LAI)) and the obtained K_{c_SF} and K_{c_WB} were also evaluated from fruit set to harvest. Both the sap flow and water balance methods seemed to provide useful ET_c and K_c values for 'Red Beaut' and 'Angeleno' plums, but there were notable differences in seasonal ET_c and K_c values between the two cultivars. Daily ET_{c_SF} values increased with time from fruit set to harvest, from 0.7 to 7.6 mm day^{-1} for 'Red Beaut' and from 0.6 to 7.7 mm day^{-1} for 'Angeleno'. After fruit harvest, daily ET_{c_SF} decreased with time until the end of the season to final values of 1.4 mm day^{-1} for 'Red Beaut' and 1.7 mm day^{-1} for 'Angeleno'. Seasonal patterns of K_{c_SF} increased from 0.40 and 0.33 at fruit set to maximum pre-harvest values of 1.16 and 1.25 for 'Red Beaut' and 'Angeleno', respectively. After harvest, K_{c_SF} values exhibited a progressive reduction to 0.55 and 0.65 for 'Red Beaut' and 'Angeleno', respectively, at the end of the season. Pre-harvest K_{c_WB} and K_{c_SF} showed a good correlation with F_{IPARd} which could be used as a tool to estimate water use for irrigation scheduling under our growing

conditions and orchard managements. However, the relationships were different between cultivars; the best correlation was obtained with K_{c_SF} for 'Red Beaut', but with K_{c_WB} for 'Angeleno'.

Key words: transpiration, soil evaporation, soil water, crop evapotranspiration, irrigation, fraction of intercepted solar radiation

5.1. Introduction

Accurate irrigation scheduling ensures that the amount of water applied matches the requirements of the crop (Ayars et al., 2003). The development of a simple method to estimate seasonal crop evapotranspiration (ET_c) for different crops, including woody, perennial horticultural crops would be of great benefit to the agricultural industry (Williams and Ayars, 2005). The most direct method of estimating ET_c is by using lysimeters, although these are expensive and are not generally available to growers. In the case of Japanese plum, there is no information available on ET_c with the precision offered by lysimeters. Other methods such as the soil water balance (WB) have been proposed to estimate irrigation needs, and therefore crop coefficient (K_c) values. The soil water balance method uses the law of mass conservation (Faures et al., 1995; Moreno et al., 1996; Sanchez-Cohen et al., 1997) as $ET_c = P + I - D - R - \Delta S$, where ET_c is crop evapotranspiration, P is effective rainfall, I is irrigation, D is drainage, R is runoff and ΔS is the change in soil storage (all in mm day^{-1}). This method can also be employed to estimate ET_c for longer time periods than a day (e.g., week-long or ten-day periods), and has been widely used to quantify seasonal ET_c of different crops such as almonds (Fereres et al., 1981a; 1981b; Andreu et al., 1997), olive (Moreno et al., 1988), apricot (Abrisqueta et al., 2001) or citrus (Castel et al., 1987; García-Petillo and Castel, 2007).

While a number of reviews have previously described ET_c determinations (Rana, 2000; Burt et al., 2005; Farahani et al., 2007; Li et al., 2009; Tanny, 2013), studies to separately determine the ET_c components are less numerous. The micro-lysimeter methods to measure soil evaporation (E_S) under-canopy (Boast and Robertson, 1982; Shawcroft and Gardner, 1983; Walker, 1984; Bonachela et al., 1999, 2001; Paço et al., 2011) and sap flow (SF) measurements of transpiration through the stomata of plants (T) (Čermák et al., 1973; Granier, 1985) paved the way to more robust verification of the individual components (Kool et al., 2013). The compensation heat-pulse method (Swanson and Whitfield, 1981; Green and Clothier, 1988) has proved to be a reliable technique for continuously measuring sap velocity in woody crops and is a suitable method for estimating T. A number of studies based on SF measurements have been described for assessing the crop water needs of fruit trees (Ginestar et al., 1998; Giorio and Giorio, 2003; Nadezhdina et al., 2007; Fernandez et al., 2008a, b; Villalobos et al., 2013).

Calculation of intercepted solar radiation has been considered useful for irrigation scheduling (Auzmendi et al., 2011). It represents the energy that can be absorbed by the canopy and therefore be used for T, and it has been assumed that the relationship between absorbed energy and T does not change throughout the season (Pereira et al., 2007). It has been shown that K_c is highly correlated with canopy light interception (Johnson et al., 2002, 2005; Ayars et al., 2003; Consoli et al., 2006; Girona et al., 2011; Auzmendi et al., 2011). K_c also correlates well with leaf area index (LAI) (Williams and Ayars, 2005; Picon-Toro et al., 2012) and canopy cover (Testi et al., 2004; Villalobos et al., 2009; Allen and Pereira, 2009; Picon-Toro et al., 2012).

Studies of differential water use between different cultivars of the same fruit tree species are scarce. In Japanese plum, research efforts have focused on the effect of pre-harvest and/or post-harvest deficit irrigation on yield and fruit size (Johnson et al., 1994; Naor, 2004; Naor et al., 2004; Intrigliolo and Castel, 2005, 2010), but no studies have been published on the water need patterns of different Japanese plum cultivars depending on their maturing time. Irrigation schedulings are normally made using the recommended K_c values for plum trees included in the stone fruit section of the FAO Irrigation and Drainage Paper No. 56 guidelines (Allen et al., 1998). However, this guide does not distinguish between European and Japanese plum, although they are different species. The first are mainly grown for dried fruit, while fresh fruit is mainly obtained from the Japanese plum cultivars. In fruit trees, the dependency of K_c on crop characteristics and management practices such as crop load or tree vigor also adds uncertainty to its use when these factor vary considerably. Lower crop load levels typically reduce stomatal conductance and photosynthetic rate in peach, apple, pear and olive (Chalmers et al., 1975; Crews et al., 1975; DeJong and Goudriaan, 1989; Reyes et al., 2006; Marsal et al., 2008, Martin-Vertedor et at., 2011) and therefore reduce T and water uptake due to the decrease in demand of assimilates (Chalmers et al., 1983). However, an experiment performed with different irrigation treatments and fruit thinning levels in our experimental orchard showed that crop load did not affect tree water status (Samperio et al., submitted to Irrigation Science (IR)) and these results concurred with those from previous studies of Intrigliolo and Castel (2010). A specific study of the water use of plum trees trained to different canopy trainings (Chootummatat et al., 1990) found that mature trees under a Tatura training system, with trees of closer spacing, consumed more water when well watered than other systems with a wider spacing (e.g. Palmette, Vase or Lincoln). Previous studies in

Japanese plum have also shown that differences in tree vigor between cultivars with different maturity time result in different ET_c and K_c patterns (Martin-Vertedor et al., 2010; Samperio et al., submitted to Agricultural Water Management (AWM)). These results agree with those reported by Girona (2013) in peach trees, where lower K_c values at crop development stage were obtained for late-maturing than for early-maturing cultivars. The difference in harvest date between cultivars could be responsible for this trend, as previously observed by Basile et al. (2002) in two plum cultivars (mid-June and mid-July maturing) with fruit growth patterns that appeared to be related to source availability during the season and also to genetic constraints.

The objectives of this research were to: (i) know tree water use and the resulting crop coefficient of two Japanese plum cultivars, differing in vigor and maturing time ('Red Beaut' and 'Angeleno') using the sap flow and water balance methods, (ii) evaluate the two techniques for determining tree water consumption in an orchard, and (iii) compare the relationships between canopy size (using the daily fraction of Intercepted Photosynthetically Active Radiation (F_{IPARd}) and leaf area index (LAI)) and crop coefficients in 'Red Beaut' and 'Angeleno' plums.

5.2. Materials and methods

5.2.1. Experimental orchard and climatic conditions

The experiments were carried out during the irrigation seasons of 2012 and 2013 (February 26 - October 18 in 2012 and April 17 - October 20 in 2013) in a 2.0 ha Japanese plum orchard at "Finca La Orden-Valdesequera" experimental farm, Badajoz (38°51'N, 6º40'W, elevation 184 m), Spain. Two Japanese plum cultivars differing in time to maturity were studied: 'Red Beaut' (early-maturing) and 'Angeleno' (late-maturing), both grafted on Mariana 2629 rootstock in spring 2005 at a spacing of 6 x 4 m and in an East-West row orientation (5º towards North). Trees were trained to an open vase system with four main scaffold branches per tree. Additionally, four other cultivars were planted as guard rows for pollination: ‘Black Diamond’ and ‘Ambra’ for the early-maturing cultivar, and ‘Larry Ann’ and ‘Fortune’ for the late. Bee hives were used at flowering to ensure optimal pollination.

The soil is a loam of homogeneous texture, both vertically and horizontally, with mean values of 19.4% clay, 40.2% silt, and 40.4% sand. The upper limit of drained water content at field capacity (soil matric potential of -33 kPa) was 0.261 $cm^3 cm^{-3}$ and the lower limit at wilting point (soil matric potential of -1,500 kPa) was 0.123 $cm^3 cm^{-3}$. The soil depth is greater than 2.5 m and with low stone content.

The area has a Mediterranean climate with mild Atlantic influence, dry and hot summers, with high daily irradiance and evaporative demand. Average potential evapotranspiration (ET_o) and precipitation (P) values in the area are 1294 mm and 428 mm, respectively (period 1992-2013). Summer pruning in ‘Red Beaut’ was carried out by early-July in 2012 (DOY 185) and end-June in 2013 (DOY 177) and in ‘Angeleno’ by end-May in 2012 (DOY 144) and early-June in 2013 (DOY 163). In ‘Red Beaut’, fruit were harvested in different picks according to local commercial criteria. In 2012, they were harvested on 31 May (DOY 152), 6 and 13 June (DOY 158 and 165) and in 2013 they were harvested on 4 and 10 June (DOY 155 and 161). ‘Angeleno’ fruit were harvested in a single pick. In 2012, they were harvested on 6 September (DOY 250) and in 2013 on 4 September (DOY 247). Fertilization practices and pest control were of the type commonly used in commercial orchards, and weeds were eliminated by chemical treatment.

5.2.2. Irrigation management

The trees were irrigated on a daily basis by a drip irrigation system with four pressure-compensated emitters per tree (4 l h^{-1} for each dripper). There was a single pipeline per tree row, which was located close to the trunk. Trees received full replacement crop evapotranspiration (ET_c) minus effective rainfall to ensure non-limiting soil water availability. ET_c for irrigation scheduling was calculated by multiplying the reference evapotranspiration (ET_o), calculated with the Penman-Monteith equation, and a crop coefficient (K_c) (Allen et al., 1998). Irrigation was controlled by a commercial irrigation controller operating an electro-hydraulic valve. The irrigation volumes were recorded daily by digital water meters.

5.2.3. Experimental plot

One experimental plot in each cultivar was used. Each experimental plot consisted of four adjacent rows of four trees. The four central trees in the second and third rows were used for data collection and the other trees in the plot were guard trees, including four trees located in the first and fourth row-column which were of a different cultivar.

5.2.4. Soil water content measurements

Soil water content was recorded once a week early in the morning throughout the irrigation season in the rootzone of one representative tree of each cultivar. Description of the procedure is found in Samperio et al. (submitted to AWM). Briefly, twelve access tubes for a neutron probe (CPN 503DR Hydroprobe, CPN International, Inc., Port Chicago Highway, CA, USA) were installed in the area occupied by each tree. The first sets (tubes of length 2.0 m) were installed perpendicular to the measuring tree row and the second sets (tubes of length 3.0 m) were installed 1.0 m apart from the first set. In both cases, the distance between two consecutive tubes was 1 m. Measurements in each tube set were made from 0.30 to 1.80 and from 0.30 to 2.70 m, respectively, in 0.3 m increments. The neutron probe readings were calibrated for the experimental soil *in situ* with undisturbed soil samples (see Samperio et al., submitted to AWM).

5.2.5. Soil water balance

The soil water balance was used as an indirect method for determining crop evapotranspiration (ET_{c_WB}); it was calculated using the law of mass conservation as:

$$ET_{c\_WB} = P + I - D - R - \Delta SWC$$

$$\Delta SWC = \Sigma\ (\theta_i - \theta_{i-1})\ Z$$

where P is effective rainfall, I is irrigation, D is drainage, R is runoff, ΔSWC is the change in soil water storage between two consecutive dates, and Z is the depth of each layer. The R was insignificant because the orchard was on level ground and no R was observed. D was considered to occur if ΔS were positive from maximum root depth. All terms are expressed in mm for a given period. After calculating ET_{c_WB}, the crop coefficients for water balance (K_{c_WB}) were estimated as the ratio between ET_{c_WB} and ET_o.

5.2.6. Sap flow measurements

Tree transpiration was measured with a sap-flow system device developed and assembled at the IAS in Cordoba and described in Testi and Villalobos (2009). The system uses the Compensation Heat Pulse method plus the Calibrated Average Gradient technique (Testi and Villalobos, 2009); the latter is used when sap velocities lower than 12 cm h^{-1} prevents the use of the former method, or reduces its accuracy. A set of heat-pulse probes was installed in areas free of scars and other irregularities in the trunks of four fully irrigated trees of each cultivar, 15 cm above ground level. Each set consisted of a stainless steel heater and two temperature probes, spaced at 1.0 and 0.5 cm down- and up-stream of the linear heater probe, respectively. Each temperature probe had four embedded thermocouples, at 0.5, 1.5, 2.5 and 3.5 cm depth from the cambium. The system was controlled by a datalogger (CR1000, Campbell Scientific Inc., Logan, UT, USA), executing a measurement cycle every 15 min. The values of heat pulse velocity were corrected for wounding effects (Swanson and Whitfield, 1981) assuming a 2.6 mm wound diameter (Villalobos et al., 2013), then converted to sap velocity and integrated first along the trunk radius (using the radial velocity profile curve given by the probe) and then around the azimuth angle (Green et al., 2003). The resulting values of each set of probes were averaged to derive the sap flux in the trunk (SF, $l\ h^{-1}$), as well as the daily transpiration of the single tree (T_{c_SF}, mm day^{-1}).

5.2.7. Soil evaporation

Direct evaporation (E_s) from bare soil was measured with micro-lysimeters installed on both sides of the tree along the row in the fully irrigated field trees based on the model of Bonachela et al. (2001). Bonachela's model was site calibrated for the growing conditions of 2008 by Martin-Vertedor (2010). Crop evapotranspiration according to the sap flow method (ET_{c_SF}) was calculated from E_s and T_{c_SF}. Crop coefficients according to the sap flow method (K_{c_SF}) were estimated as the ratio between ET_{c_SF} and ET_o.

5.2.8. Meteorological data

Weather data of air temperature, rainfall, daylight hours and solar radiation were recorded at an automated weather station located at a distance of 600 m from the plum orchard over a reference surface. Daily reference evapotranspiration (ET_o) was calculated using the Penman-Monteith equation (Allen et al., 1998). Daily vapour pressure deficit (VPD) was calculated from minimum and maximum temperature and relative humidity data (Allen et al., 1998).

5.2.9. Canopy growth

The fraction of Intercepted Photosynthetically Active Radiation (F_{IPARm}) by tree canopy was determined at solar noon on cloudless days with a linear ceptometer (probe length 80 cm; Accupar Linear PAR; Decagon Devices, Pullman, WA, USA). For below canopy data, 60 readings were taken according to the protocol followed by Auzmendi et al. (2011). F_{IPARm} was used to estimate daily F_{IPAR} (F_{IPARd}) by the experimental linear relationship obtained in previous years:

$F_{IPARd} = 0.9427\ F_{IPARm} + 0.0562$ ($R^2 = 0.99$; $P<0.0001$)

Leaf area index (LAI) was determined using a digital image analyzer for canopy analysis (WinSCANOPY, Regent Instruments Inc., Quebec, Canadian). On each cultivar, LAI was obtained from ten measurements taken at fixed positions by placing the digital image analyzer below the canopy of the trees at soil level in the centre of a ten-quadrant grid into which the planting frame was divided, between the second and third rows of the trees. The grid consisted of two parallel lines 1 m apart from each other and perpendicular to the line of drip tubing and tree trunks. Each line had 5 equidistant measuring points which were 1 m apart, with the first measuring point 1 m from the drip tubing, the 2nd 2 m from the drip tubing, etc. The obtained measurements of LAI (LAI_m) were corrected (LAI_c) using an empirical relation determined from destructive measurements taken previously in the same cultivar and training system by collecting all the leaves trapped by nets covering three trees before leaf fall. The dry weight of the leaves was determined and a sample of leaves was used to establish a relationship between leaf dry weight and area. Leaf area was measured with a belt-driven leaf area meter (model LI-3100, LI-COR, Lincoln, Nebraska). The experimental equation was:

$LAI_c = 3.4014 \times LAI_m - 0.1116$ ($R^2 = 0.99$; $P<0.001$)

5.2.10. Tree water status

Midday stem water potential (Ψ_{stem}) was measured with a Scholander pressure chamber (Model 3005; Soil Moisture Equipment, Santa Barbara, CA, USA.) once a week. Two covered shaded leaves per tree located close to the trunk base, from the four trees per cultivar instrumented with sap flow probes, were sampled ($n = 8$). Selected leaves were bagged in aluminum foil for 2 h before measurement (Shackel et al., 1997).

Stomatal conductance (g_l) was measured with a steady-state, continuous flow porometer (PP Systems PMR-5, Hitchin, Hertfordshire, UK) between 10:00 and 11:00 h solar time from two leaves for each experimental tree ($n = 8$). We selected mature, well-exposed sunlit leaves located in the middle of current growth year shoots. Ψ_{stem} and g_l were measured the same day.

5.3. Results

5.3.1. Environmental conditions

All the parameters concerning the evaporative demand of the atmosphere increased from the beginning of the experiment until reaching maximum values in summer and then decreasing until the end of the experiment (Fig. 5.1). Daily mean air temperature reached maximum values of 30 ºC in early July and around 29 ºC during mid-August (Fig. 5.1A and B). During the irrigation season, total effective rainfall was 55 mm in

2012 and 16 mm in 2013, mainly occurring during April, first half of May and mid-October (Fig. 5.1A and B). Daily ET_o values increased with time until they reached a peak during early July of about 7.2 (2012) and 7.8 (2013) mm day^{-1} (Fig. 5.1C and D). Thereafter, daily ET_o values decreased with time following a similar pattern to their previous increase (Fig. 5.1C and D). Total ET_o during the irrigation season was 1100 mm in 2012 and 891 mm in 2013. Daylight hours, VPD and solar radiation fluctuated widely during the experimental period, showing maximum values in early July and minimum values in early October (Fig. 5.1C, D, E and F). Daytime VPD over the season was in the range of 0.5 – 3.5 kPa.

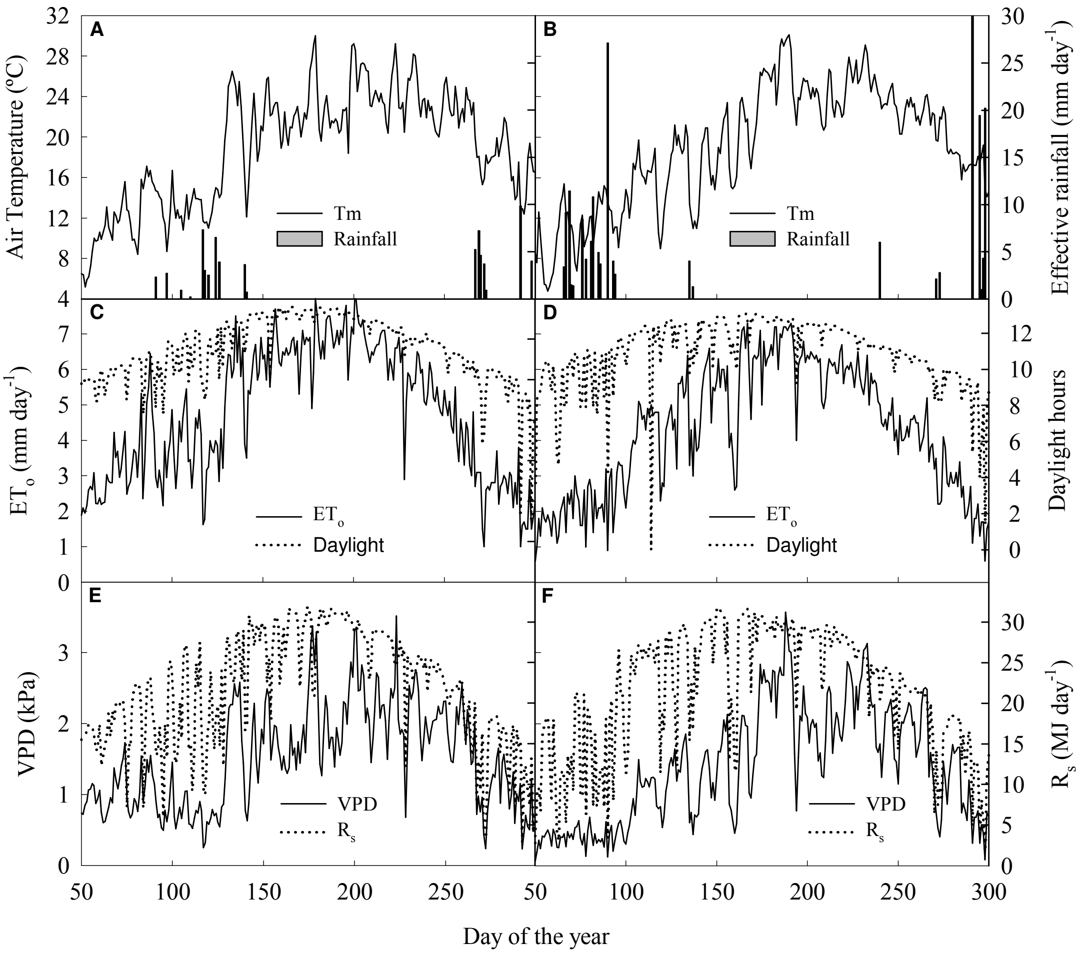

Fig. 5.1 Seasonal patterns of daily mean air temperature and daily effective rainfall (A, B), reference evapotranspiration (ET_o) and daylight hours (C, D), daily mean air vapour pressure deficit (VPD) and solar global radiation (R_s) (E, F) during seasons 2012 (A, C, E) and 2013 (B, D, F).

5.3.2. Canopy growth and tree water status

The seasonal courses of F_{IPARd}, LAI, g_l and Ψ_{stem} in the two experimental cultivars are shown in Fig. 5.2A-H Both 'Red Beaut' and 'Angeleno' trees exhibited a progressive increase in F_{IPARd} over the course of the experiment disrupted by summer pruning (Fig. 5.2A and B). The F_{IPARd} pattern was similar during the years 2012 and 2013. In 'Red Beaut', F_{IPARd} increased from 0.57 to 0.70 before summer pruning and from 0.56 to 0.76 for 'Angeleno' in the same period (Fig. 5.2A and B). After summer pruning, F_{IPARd} decreased in both cultivars to around 0.57 in 2012 (Fig. 5.2A) and around 0.65 in 2013 (Fig. 5.2B). Maximum F_{IPARd} was reached before summer pruning in 'Red Beaut' and at the end of the irrigation period in 'Angeleno', with 'Red Beaut' trees exhibiting lower values of F_{IPARd} than 'Angeleno' trees (Fig. 5.2B).

In LAI there was a similar pattern to that in F_{IPAR}, with maximum LAI values before summer pruning of 2012 in 'Red Beaut' and at the end of the irrigation period of 2012 in 'Angeleno', with around 4.0 m^2 m^{-2} in both cases (Fig. 5.2C and D). The seasonal patterns of g_l showed increasing values early in the season and before 'Red Beaut' harvest with similar patterns and values in both cultivars (Fig. 5.2E and F). From this time 'Angeleno' trees maintained higher values of g_l than 'Red Beaut' trees until harvest in 2012 and until 20 days before harvest in 2013. In the last case, it could be that fruit growth rate in fresh weight slowed down over the final 20 days before harvest (data not shown). Thereafter, g_l values decreased until early October and then tended to recover slightly (Fig. 5.2E and F). With respect to Ψ_{stem}, the two cultivars reflected a decreasing trend as the irrigation season progressed with minimum values of about -0.85 for 'Red Beaut' and -1.1 MPa for 'Angeleno' in early September (DOY 250) (Fig. 5.2G and H). As a general rule, 'Red Beaut' had less negative Ψ_{stem} values than 'Angeleno', especially from the end of May (DOY 150) to early September when the late-maturing cultivar, 'Angeleno', had fruits. By the end of summer, Ψ_{stem} values were tending to recover (Fig. 5.2G and H).

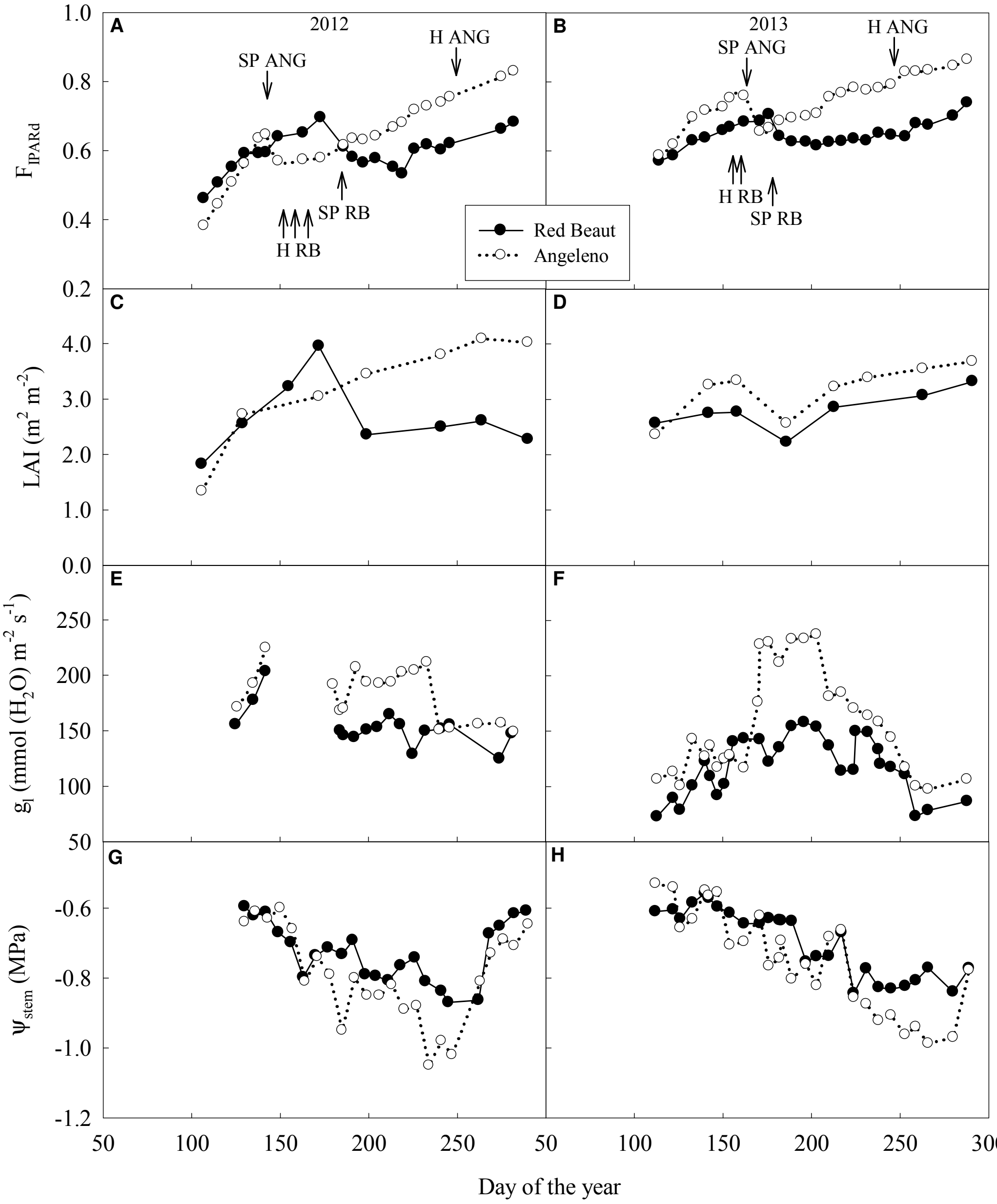

Fig. 5.2 Seasonal evolution in the daily fraction of Intercepted Photosynthetically Active Radiation (F_{IPARd}) (A, B), leaf area index (LAI) (C, D), stomatal conductance (g_l) (E, F) and midday stem water potential (Ψ_{stem}) (G, H) for 'Red Beaut' and 'Angeleno' plums during seasons 2012 (A, C, E, G) and 2013 (B, D, F, H). SP RB and SP ANG indicate summer pruning for 'Red Beaut' and 'Angeleno', respectively. H RB and H ANG indicate harvest time for 'Red Beaut' and 'Angeleno', respectively.

5.3.3. Soil water balance

The ET_{c_WB} data for ‘Red Beaut’ and ‘Angeleno’ plums are shown in Figs. 5.3 and 5.4, respectively. The results for 2012 show only the balance between DOY 75 and DOY 233. For 2013, the results are shown for the period from DOY 115 to DOY 293. The water balance components were: effective rainfall of 33 (2012) and 16 (2013) mm, irrigation of 564 (2012) and 688 (2013) for ‘Red Beaut’ and 591 (2012) and 771 (2013) mm for ‘Angeleno’, drainage of 54 (2012) and 84 (2013) mm for ‘Red Beaut’ and 61 (2012) and 91 (2013) mm for ‘Angeleno’ and ET_c of 723 (2012) and 743 (2013) mm for ‘Red Beaut’ and 664 (2012) and 837 (2013) mm for ‘Angeleno’. Soil water storage throughout the soil profile in ‘Red Beaut’ was maintained from the onset of the irrigation season to mid-June (2012) and mid-July (2013) at field capacity, after which water storage increased in 2012 (Fig. 5.3A) and decreased in 2013 (Fig. 5.3B) to the end of the irrigation season. For ‘Angeleno’, water storage in 2012 was maintained from the onset of the irrigation season to end-June at field capacity, after which water storage decreased (Fig. 5.4A). In 2013, water storage fell steadily from the onset of the irrigation season to the end (Fig. 5.4B). In this case, after the end of the rainy period (DOY 133-137 and DOY 240), soil water storage throughout the soil profile recovered slightly (Fig. 5.4B), but the renewed moisture affected only the first 30 cm of the soil at most. This water did not infiltrate as it rapidly evaporated.

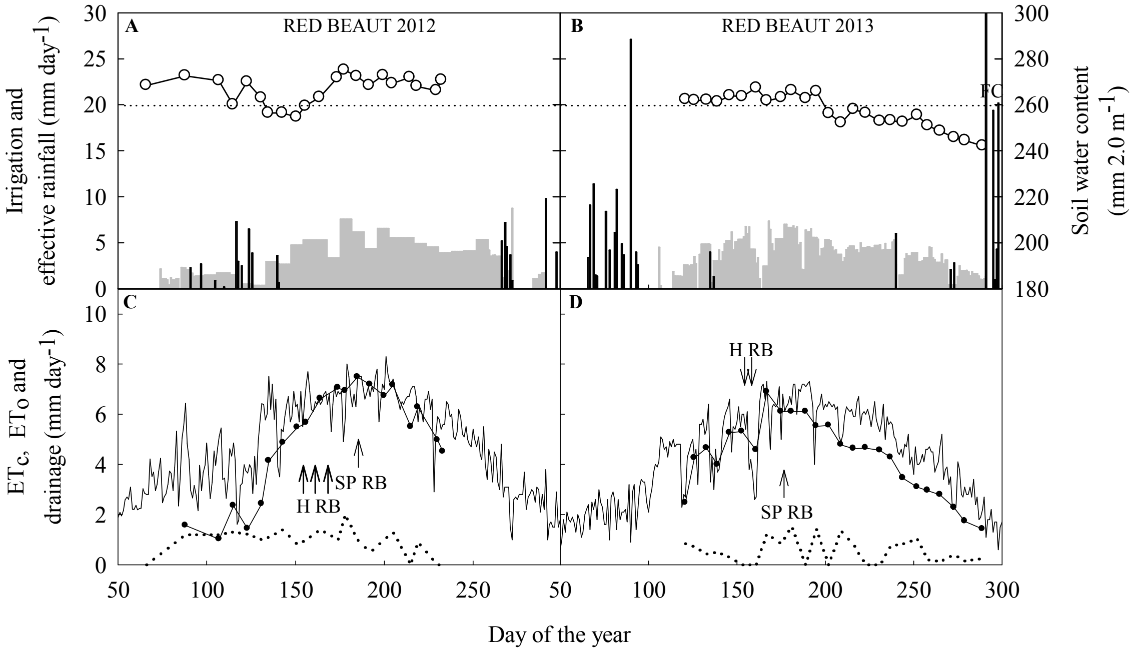

Fig. 5.3 Seasonal evolution of irrigation (I) and effective rainfall (R) and soil water content (SWC) (A, B), crop evapotranspiration (ET_c), reference evapotranspiration (ET_o) and drainage (D), (C, D) for 'Red Beaut' plums during seasons 2012 (A, C) and 2013 (B, D). Dot-dashed lines in the upper panel represent field capacity (FC). SP RB and H RB indicate summer pruning and harvest time, respectively for 'Red Beaut'.

Symbols represent: ▌I; ▌R; ○ SWC; ● ET_c; — ET_o; ⋯ D

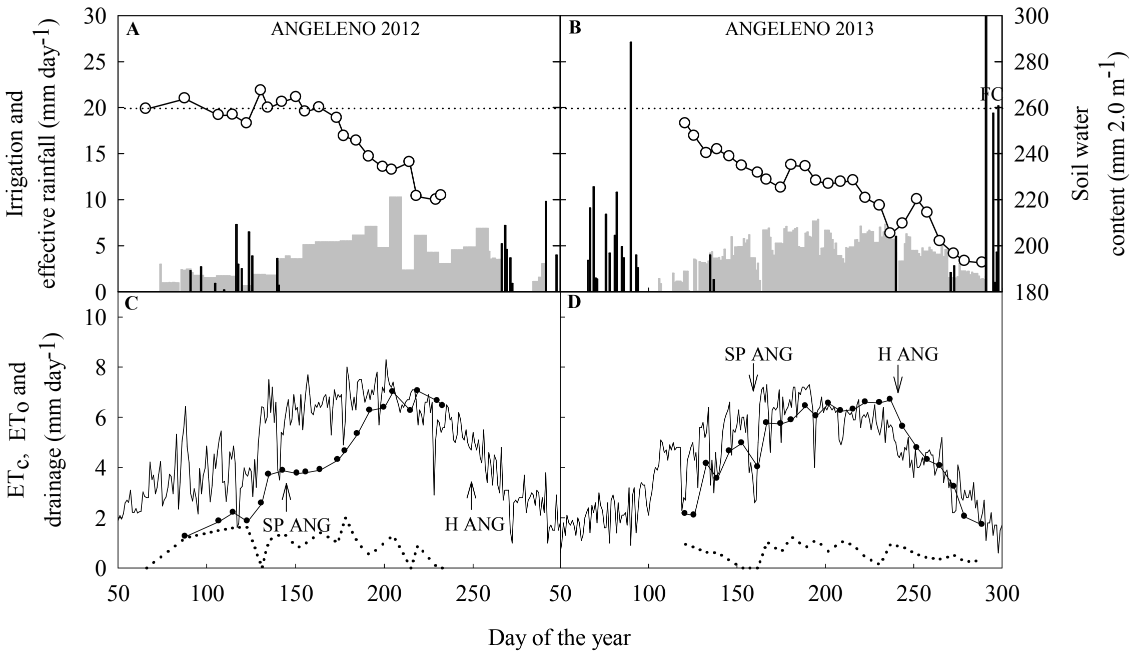

Fig. 5.4 Seasonal evolution of irrigation (I) and effective rainfall (R) and soil water content (SWC) (A, B), crop evapotranspiration (ET_c), reference evapotranspiration (ET_o) and drainage (D), (C, D) for 'Angeleno' plums during seasons 2012 (A, C) and 2013 (B, D). Dot-dashed lines in the upper panel represent field capacity (FC). SP ANG and H ANG indicate summer pruning and harvest time, respectively for 'Angeleno'.

Symbols represent: ▌I; ▌R; ○ SWC; ● ET_c; — ET_o; ⋯ D

5.3.4. Soil evaporation and canopy transpiration

Soil evaporation from early May until mid-September remained at values between 0.6 to 1.4 mm day^{-1}, and rarely rose above this value. After mid-September and until the end of the irrigation period, evaporation decreased progressively to values close to 0.2 mm day^{-1} (Fig. 5.5). Total soil evaporation values were observed of 90 (2012) and 140 (2013) mm for 'Red Beaut' and 92 (2012) and 116 (2013) mm for 'Angeleno'.

Transpiration rates were variable among years, through the year and among cultivars (Fig. 5.5) increasing from early May to mid-June in 'Red Beaut' and to early September in 'Angeleno' and then decreasing in both cultivars until the end of the irrigation season. Maximum values in the summer were around 6 mm day^{-1} for both cultivars.

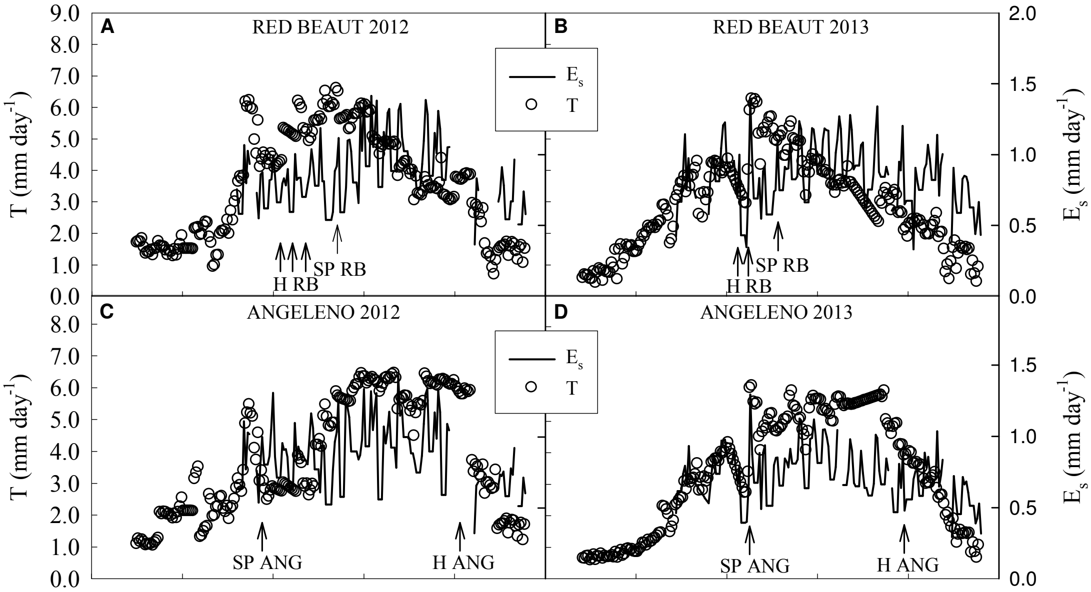

Fig. 5.5 Daily patterns of soil evaporation (E_S) and canopy transpiration (T) estimated from micro-lysimeters and sap flow measurements for 'Red Beaut' (A, B) and 'Angeleno' (C, D) during seasons 2012 (A, C) and 2013 (B, D). SP RB and H RB indicate summer pruning and harvest time, respectively for 'Red Beaut'. SP ANG and H ANG indicate summer pruning and harvest time, respectively for Angeleno'.

5.3.5. Crop evapotranspiration and crop coefficient determined with sap flow and water balance techniques

Seasonal patterns of ET_{c_WB}, ET_{c_SF}, K_{c_WB} and K_{c_SF} for 'Red Beaut' and 'Angeleno' are shown in Figs. 5.6 and 5.7. Daily ET_{c_SF} values increased with time from fruit set until harvest (Figs. 5.6A and B and 5.7A and B). At this moment, daily ET_{c_SF} values reached a peak of 7.6 (2012) and 7.3 (2013) mm day^{-1} for 'Red Beaut' (Fig. 5.6A and B) and 7.7 (2012) and 6.7 (2013) mm day^{-1} for 'Angeleno' (Fig. 5.7A and B). After fruit harvest, daily ET_{c_SF} decreased with time until the end of the irrigation season in both cultivars, falling to values of 1.4 (2013) mm day^{-1} for 'Red Beaut' (Fig. 5.6B) and 1.7 (2013) mm day^{-1} for 'Angeleno' (Fig. 5.7B).

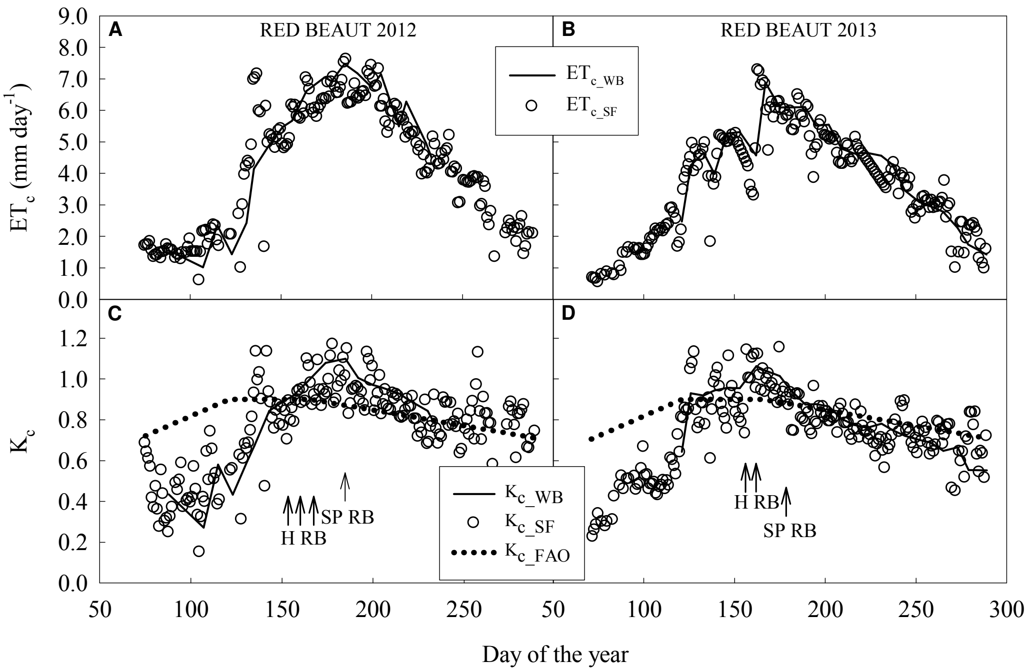

Fig. 5.6 Daily patterns of crop evapotranspiration (ET_c) (A, B) and crop coefficients (K_c) (C, D) estimated from sap flow measurements, water balance method and calculated using FAO-56 guidelines (Allen et al., 1998) for 'Red Beaut' plums during seasons 2012 (A, C) and 2013 (B, D). SP RB and H RB indicate summer pruning and harvest time, respectively for 'Red Beaut'.

At the onset of the irrigation season, initial K_{c_SF} values were about 0.40 (2012) and 0.60 (2013) for 'Red Beaut' (Fig. 5.6C and D) and 0.30 (2012) and 0.50 (2013) for 'Angeleno' (Fig. 5.7C and D). There is an extended period of increase in the K_{c_SF} value beginning with fruit set in early-April until reaching its maximum value around harvest, at some point after which it began to fall. This period of increase is longer in 'Angeleno' than in 'Red Beaut'. For 'Red Beaut' plums, maximum values of K_{c_SF} were 1.16 (2012) and 1.14 (2013) (Fig. 5.6C and D). For 'Angeleno' plums, maximum values of K_{c_SF} were about 1.25 (2012) and 1.20 (2013) (Fig. 5.7C and D). Irrespective of the cultivar, K_{c_SF} values exhibited an immediate reduction after summer pruning and a progressive decrease after fruit sink removal at harvest (Figs. 5.6B and C and 5.7C and D). Near the end of the irrigation season, final K_{c_WB} values were about 0.65 (2012) and 0.55 (2013) for 'Red Beaut' and 0.70 (2012) and 0.65 (2013) for 'Angeleno' plums (Figs. 5.6C and D and 5.7C and D). Although not identical, the seasonal patterns of ET_{c_WB} and K_{c_WB} agreed reasonably well with the patterns of ET_{c_SF} and K_{c_SF} (5.6 and 5.7). Linear regression between K_{c_SF} and K_{c_WB} produced slopes of 0.77 and 0.84 for 'Red Beaut' and 'Angeleno', respectively. The respective coefficients of determination were 0.61 and 0.80 (regressions not shown).

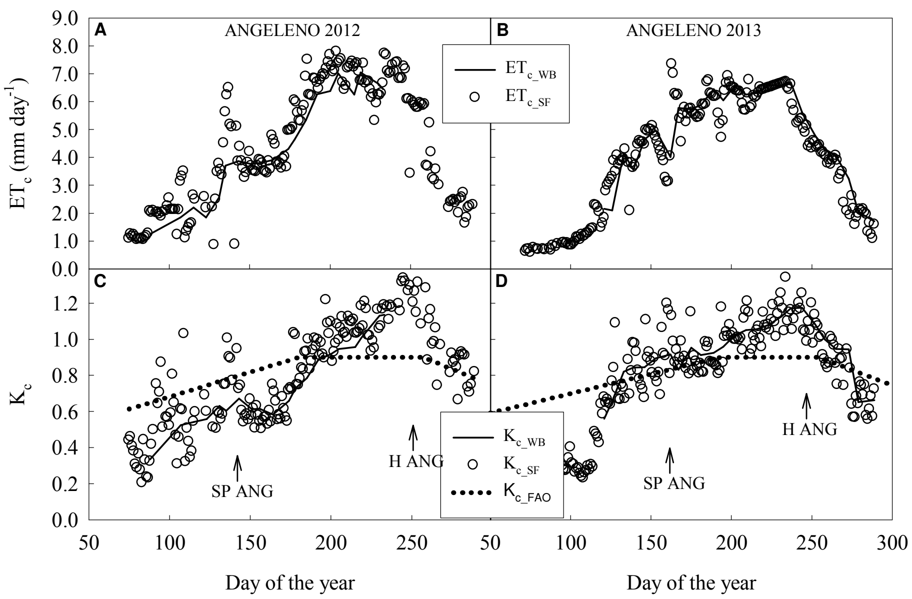

Fig. 5.7 Daily patterns of crop evapotranspiration (ET_c) (A, B) and crop coefficients (K_c) (C, D) estimated from sap flow measurements, water balance method and calculated using FAO-56 guidelines (Allen et al., 1998) for 'Angeleno' plums during seasons 2012 (A, C) and 2013 (B, D). SP ANG and H ANG indicate summer pruning and harvest time, respectively for Angeleno'.

5.3.6. Relationships between crop coefficient and canopy growth parameters

The relationships between K_{c_WB} or K_{c_SF} and tree canopy development as determined by F_{IPARd} and LAI are presented in Figs. 5.8 and 5.9. During the pre-harvest period there is a linear relationship between K_{c_WB} or K_{c_SF} and F_{IPARd} (Fig. 5.8A and C) or LAI (Fig. 5.8B and D), though some scatter is present. In the post-harvest period, this relationship was not significant (data not shown). Irrespective of the cultivar, K_{c_WB} and K_{c_SF} increased with increases in the F_{IPARd} and LAI. F_{IPARd} seems the best predictor of the K_{c_WB} and K_{c_SF}. When only fully irrigated days in pre-harvest were considered and considering both years together, the R^2 value for the relationship between K_{c_WB} and F_{IPARd} was 0.68 for 'Red Beaut' (Fig. 5.8A) and 0.75 for 'Angeleno' (Fig. 5.9A). The R^2 value for the relationship between K_{c_SF} and F_{IPARd} was 0.77 for 'Red Beaut' (Fig. 5.8C) and 0.68 for 'Angeleno' (Fig. 5.9C). As for LAI, the R^2 values were 0.49 and 0.75 for 'Red Beaut' for the relationships with K_{c_WB} and K_{c_SF}, respectively (Fig. 5.8B and D) and 0.46 and 0.64 for 'Angeleno' (Fig. 5.9B and D).

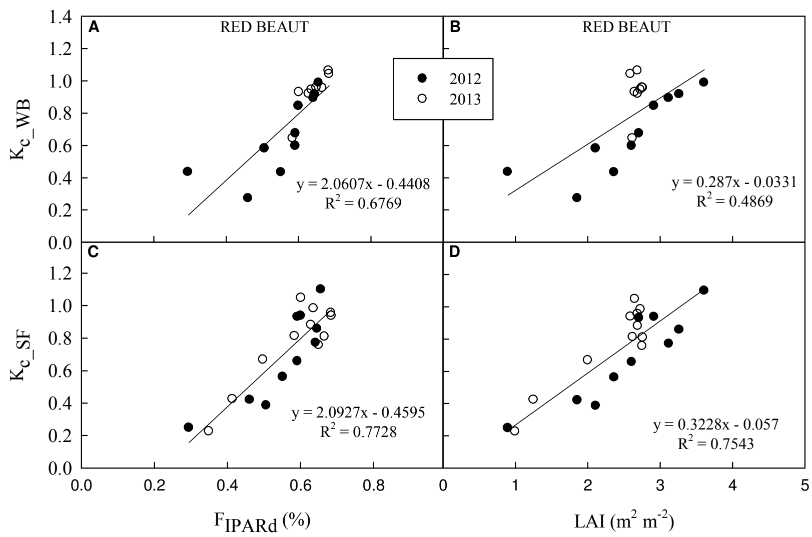

Fig. 5.8 Relationships for fully irrigated plums during the fruit growing season for 'Red Beaut' between daily crop coefficients obtained from water balance (K_{c_WB}) (A and B) and sap flow (K_{c_SF}) (C and D) and: A and C) daily fraction of Intercepted Photosynthetically Active Radiation (F_{IPARd}); B and D) Leaf Area Index (LAI). Relationships were fitted to a simple linear model for the two years of evaluation. Plots A and B: n=18. Plots C and D: n=21.

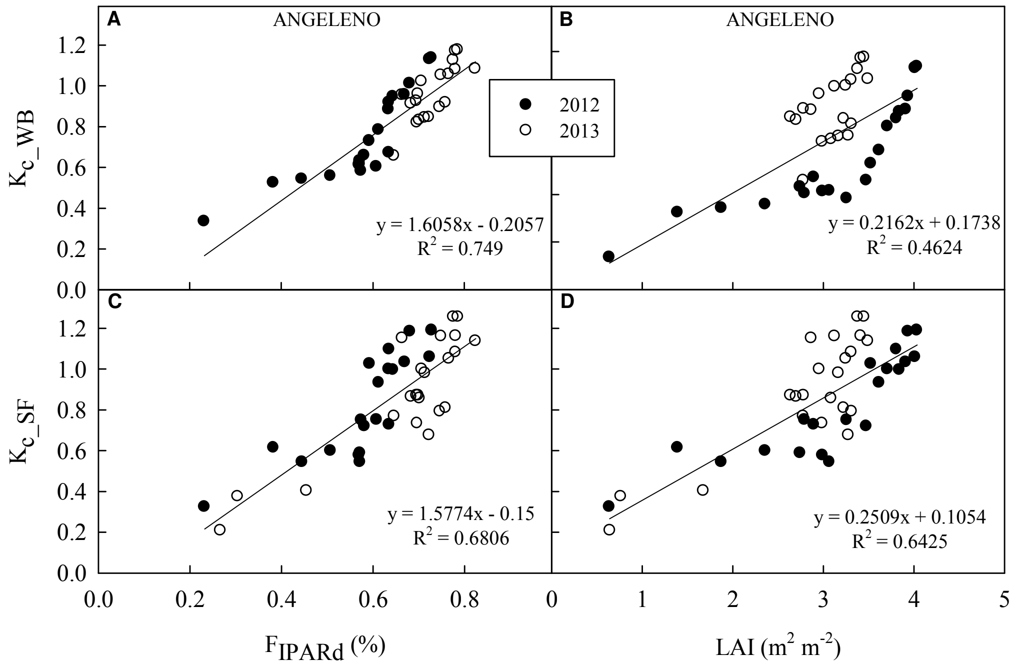

Fig. 5.9 Relationships for fully irrigated plums during the fruit growing season for 'Angeleno' between daily crop coefficients obtained from water balance (K_{c_WB}) (A and B) and sap flow (K_{c_SF}) (C and D) and: A and C) daily fraction of Intercepted Photosynthetically Active Radiation (F_{IPARd}); B and D) Leaf Area Index (LAI). Relationships were fitted to a simple linear model for the two years of evaluation. Plots A and B: n=40. Plots C and D: n=73.

5.4. Discussion

In this experiment, we obtained K_c data of well-irrigated plum trees using the water balance method and thus accurate estimations of ET_c are desirable. Results obtained from the water balance method seem to provide reasonable estimations of K_{c_WB} in the context of fruit trees (Fereres et al., 1981a; 1981b; Castel et al., 1987; Moreno et al., 1988; Andreu et al., 1997; Abrisqueta et al., 2001; García-Petillo and Castel, 2007). The maximum K_{c_WB} values before harvest in our study of 1.09 and 1.17 for 'Red Beaut' and 'Angeleno', respectively (Figs. 5.6C and 5.7D), fall within the expected range for an orchard having a large groundcover of between 70 and 80% before harvest (Allen et al., 1998). Accurate estimations of soil water content depend on sample size to compensate for induced heterogeneities in soil humidity by the irrigation system. A soil water content estimation per day was derived from 90 direct soil water content measurements for each cultivar. This sampling size seems sufficient to provide a consistent seasonal pattern in soil water content (Figs. 5.3 and 5.4). The estimates of soil water content indicate that at the beginning of the season the soil was at field capacity in 'Red Beaut' or slightly lower in 'Angeleno' (Figs. 5.3A and B and 5.4A and B). As the season progressed, soil water content tended to decline because the soil areas not wetted by the irrigation system started to dry out (data not shown). By midsummer, average soil water content values were indicative of being drier than field capacity, but it should be noted that this estimation was the result of averaging dry with wet parts of the soil. Drainage occurred at maximum rates close to 2.0 mm during summer and this implies that irrigation rates were superior to actual ET_c and thus it can be inferred that trees did not undergo water stress (Figs. 5.3A and B and 5.4A and B). According to Intrigliolo and Castel (2010), plum tree water relations under well-watered conditions are characterized by a substantial decrease in Ψ_{stem} as a consequence of the effects of chemical signals from roots and an increase in the resistance to water flowing through the plant. Our results indicate that Ψ_{stem} values decreased along the season, falling to minimum values of around -0.85 MPa in 'Red Beaut' and -1.1 MPa in 'Angeleno'. These values are similar to those reported for Japanese plum in well-watered treatments (Johnson et al., 1994; Naor et al., 2004; Intrigliolo and Castel, 2010) and therefore may be indicative that there was no water stress.

Measured seasonal E_s from bare soil using the micro-lysimeter technique gave annual values for the area wetted by emitters under drip irrigation of about 400 mm. This is in line with previous studies using the same method and same orchard (Martín-Vertedor, 2010). Considering that 60% of total tree spacing was un-wetted by the irrigation system, E_s represented between 12 and 18.0% of estimated annual plum ET_c for 'Red Beaut' and 14.0% for 'Angeleno'. These results are similar to those measured in a pistachio orchard (Iniesta et al., 2008), olive orchards (Bonachela et al., 1999; Orgaz and Fereres, 2007), peach orchards (Paço et al., 2011; Abrisqueta et al., 2013) and those obtained from previous works performed in our experimental plum orchard, as reported by Samperio et al. (submitted to AWM).

ET_c and K_c increased with time until reaching a peak between DOY 160-190 in 'Red Beaut' and DOY 185-240 in 'Angeleno', with the latter case representing a shift of approximately 50 days compared to the peak of ET_o (DOY 165-190). In light of the results, we can confirm that after a summer pruning or after fruit sink removal at harvest there would be a reduction in ET_c and K_c values (Figs. 5.6A and B and 5.7A and B) due to reductions in canopy photosynthetic efficiency (Fig. 5.2A and B) and stomatal conductance (Fig. 5.2E and F), and so a fall in tree transpiration would be expected. This has also been confirmed for the vine, where K_c decreased after shoot topping (Picón-Toro et al., 2012). While the dip in ET_c and K_c due to summer pruning was only temporary and could therefore be due to adjustments in tree water use (Chootummatat et al., 1990; Ayars et al., 2003; Reyes et al., 2006; Marsal et al., 2008), the decrease after harvest continued until the end of the irrigation season. Auzmendi et al. (2011) explained these post-harvest declines as a reduction in the ratio of transpiration to intercepted radiation as a result of fruit removal. Consistent with this, in 'Red Beaut', values of T/IPAR$_d$ ratio, also known as transpiratory radiation use efficiency (TRUE, l mol^{-1}) (Auzmendi et al., 2011) increased from 0.16 l mol^{-1} at fruit set to 0.30 l mol^{-1} at harvest, with values of 0.27 and 0.24 l mol^{-1} before and after summer pruning, respectively, and then decreased to 0.03 l mol^{-1} at the end of the season. In 'Angeleno', values increased from the same 'Red Beaut' value of 0.16 l mol^{-1} at fruit set to 0.22 l mol^{-1} at harvest with values of 0.27 and 0.25 l mol^{-1} before and after summer pruning, respectively, and then decreased to 0.04 l mol^{-1} at the end of the season. This effect was also observed in various studies on peach, apple, pear and vine (Marsal and Girona, 1997; Reyes et al., 2006; Girona et al., 2011; Picón-Toro et al., 2012; Abrisqueta et al., 2013) where it was reported that leaf conductance and tree transpiration, and therefore K_c, decrease when fruit are thinned or harvested. Ayars et al. (2003) also indicated that the reduction in post-harvest K_c may be due to some abscission of interior, shaded leaves which might be expected to result in a decrease in tree transpiration.

Seasonal ET_{c_SF} during the irrigation season in 'Red Beaut' was 775 (2012) and 710 (2013) mm (Table 5.1) and in 'Angeleno' was 810 (2012) and 804 (2013) mm (Table 5.2), respectively. These values are within the range reported by Abrisqueta et al. (2013) in early-season peach, but lower than those reported by Ayars et al. (2003) for water use of late-season peach cultivar during a 4-year-long experiment. The differences between our results and those of Ayars et al. (2003) may be due to differences in production practices such as pruning level, canopy size, canopy management practices involving summer pruning, irrigation systems and frequencies, and prevailing climatic conditions. Differences between cultivars in terms of water use may also be due to different seasonal behavior in relation to canopy cover and the duration of the period of fruit growth, with similar flowering period. Fruit growth in 'Red Beaut' and 'Angeleno' was continuous from fruit set until harvest, resulting in a period of about 55-70 days for 'Red Beaut' and 150-160 days for 'Angeleno' (data not shown). Water use by fruit trees has been related to canopy size (Fereres et al., 1982), leaf area index (Atkinson, 1973) and leaf gas exchange (Martin-Vertedor, 2010). The differences in growth habits between cultivars in our study may therefore partially explain the discrepancy between the respective K_c values (Figs. 5.6B and 5.7B). LAI, F_{IPARd} and g_l were measured during the irrigation period to evaluate growth habits: 'Angeleno' trees had higher LAI, F_{IPARd} and g_l than 'Red Beaut' canopies, suggesting that these differences in growth habits and

CO_2 assimilation were responsible for the higher water consumption in 'Angeleno' than in 'Red Beaut'.

The FAO-56 method was used to calculate the monthly ET_{c_FAO} and K_{c_FAO} for comparison with the data measured by the sap flow and water balance techniques (Tables 5.1 and 5.2). The calculated annual total ET_{c_FAO} values were 11% and 5% higher than the measured ET_{c_SF} and ET_{c_WB} values, respectively, for 'Red Beaut' (Table 5.1) and 6% higher and 1% lower than the measured ET_{c_SF} and ET_{c_WB} values, respectively, for 'Angeleno' (Table 5.2). Also, monthly K_{c_WB} and K_{c_SF} values for 'Red Beaut' were higher than K_{c_FAO} during June, July and August in 2012 and during May and June in 2013 (Table 5.1). For 'Angeleno', monthly K_{c_WB} and K_{c_SF} were higher than K_{c_FAO} during June, July and August in both years (Table 5.2). The K_c values for each cultivar were also plotted along with those of FAO-56 (Allen et al., 1998) for non stressed, well-managed crops, no ground cover, no frosts and maximum crop height of 3.0 m. The results suggest that K_{c_WB} and K_{c_SF} of 'Red Beaut' and 'Angeleno' did not correspond well with the simplified FAO-56 (Figs. 5.6A and B and 5.7A and B), although the overall ET_c was close for the three procedures. These direct measurement methods gave lower values during crop development and late season stage and higher values during the mid-season stage than those given by FAO-56. The higher K_c values can be attributed to the taller trees in our experiment than the maximum crop height in FAO-56, with our plum trees therefore having a higher percentage of F_{IPAR} (Fig. 5.2A and B). In addition, the FAO manual does not include the effects on crop transpiration of crop load, thinning, harvesting and other cultural practices such as summer pruning. When evaluating the utility of the FAO crop coefficient for irrigation scheduling in relation with that obtained from the orchard measurements, the important consideration is the temporal distribution of the applied water. So, early and late season over-irrigation is not desirable because it will not allow the crop to use soil water stored in spring and autumn, respectively (Ayars et al., 2003). Over-irrigation early in the growing season may also result in excessive deep percolation and transportation of nutrients and other agricultural chemicals to the groundwater below (Ayars et al., 2003), as well as a lack of oxygen in the root-zone (root asphyxiation). Under-irrigation during the mid-season stage may lead to lower yield because water stress in this period can limit fruit growth. Potential fruit size will therefore not be reached unless the soil water reserves are able to compensate for the under-irrigation.

Table 5.1 Monthly reference evapotranspiration (ET_o) and soil evaporation (E_s), and crop evapotranspiration (ET_c) and crop coefficient (K_c) for 'Red Beaut' plums measured using the sap flow (SF), and water balance (WB) methods and calculated using the FAO-56 guidelines (Allen et al., 1998) during seasons 2012 and 2013.

Month	ET_o (mm)		E_s (mm)		ET_c (mm)						K_c					
	2012	2013	2012	2013	2012			2013			2012			2013		
					SF	WB	FAO	SF	WB	FAO	SF	WB	FAO	SF	WB	FAO
Mar.	63[1]		--	--	25[1]	27[1]	44[1]				0.43	0.41	0.70			
Apr.	108	24[2]	--	--	33	44	70	15[2]	15[2]	21[2]	0.20	0.39	0.80	0.61	0.64	0.89
May	168	152	15[3]	24	126	131	136	131	144	132	0.70	0.76	0.90	0.86	0.93	0.90
Jun.	198	172	23	23	185	206	178	165	174	154	0.94	1.04	0.90	0.97	1.01	0.89
Jul.	216	198	31	30	203	211	188	161	168	168	0.94	1.00	0.87	0.82	0.85	0.85
Aug.	128[4]	177	21[4]	31	105[4]	103[4]	105[4]	123	134	137	0.84	0.89	0.82	0.69	0.76	0.80
Sep.	119	123	6	21	66	-	69	81	84	88	0.41	-	0.76	0.63	0.68	0.76
Oct.	42[5]	45[6]	9[5]	11[6]	32[4]	-	30[5]	33[6]	25[6]	32[6]	0.76	-	0.72	0.74	0.55	0.72

[1] from March 15 to March 31
[2] From April 25 to April 30
[3] From May 9 to May 31
[4] From August 1 to August 20
[5] From October 1 to October 18
[6] From October 1 to October 20
- Neutron probe out of order
-- Without soil evaporation data

Table 5.2 Monthly reference evapotranspiration (ET_o) and soil evaporation (E_s), and crop evapotranspiration (ET_c) and crop coefficient (K_c) for 'Angeleno' plums measured using the sap flow (SF), and water balance (WB) methods and calculated using the FAO-56 guidelines (Allen et al., 1998) during seasons 2012 and 2013.

Month	ET_o (mm)		E_s (mm)		ET_c (mm)						K_c					
	2012	2013	2012	2013	2012			2013			2012			2013		
					SF	WB	FAO	SF	WB	FAO	SF	WB	FAO	SF	WB	FAO
Mar.	63[1]		--	--	21[1]	25[1]	40[1]				0.35	0.41	0.63			
Apr.	108	24[2]	--	--	48	58	59	12[2]	13[2]	18[2]	0.36	0.54	0.70	0.51	0.56	0.74
May	168	152	17[3]	21	102	106	117	116	120	113	0.56	0.63	0.78	0.76	0.78	0.78
Jun.	198	172	24	21	129	131	171	154	156	146	0.66	0.66	0.87	0.91	0.91	0.84
Jul.	216	198	30	26	214	211	194	191	196	177	1.00	0.98	0.90	0.98	0.99	0.90
Aug.	128[4]	177	21[4]	21	141[4]	133[4]	115[4]	188	198	154	1.13	1.16	0.90	1.06	1.12	0.90
Sep.	119	123	7	18	121	-	84	113	124	103	0.92	-	0.88	0.90	1.00	0.88
Oct.	42[5]	45[6]	9[5]	8	34[5]	-	34[5]	29[6]	29[6]	36[6]	0.82	-	0.81	0.66	0.66	0.81

[1] from March 15 to March 31
[2] From April 25 to April 30
[3] From May 9 to May 31
[4] From August 1 to August 20
[5] From October 1 to October 18
[6] From October 1 to October 20
- Neutron probe out of order
-- Without soil evaporation data

The individual relationhips between K_{c_WB} or K_{c_SF} and F_{IPARd} on the one hand or LAI on the other in trees under non-limiting soil water conditions showed that F_{IPARd} appears to be the most useful canopy size indicator (higher R^2) for estimation of water use during the pre-harvest period (Figs. 5.8 and 5.9). However, in the post-harvest period, these relationships were not significant (data not shown). In pear and apple trees, Girona et al. (2011) showed that different reference equations are required for the fruit-growth and post-harvest periods, probably due to the reduced range of variation in T and F_{IPARd} (Auzmendi et al., 2011). Nevertheless, the best correlation between F_{IPARd} and K_c during the pre-harvest period differed between 'Red Beaut' and 'Angeleno' trees. While 'Red Beaut' data fitted better with K_{c_SF} (Fig. 5.8A), 'Angeleno' data fitted better with K_{c_WB} (Fig. 5.9B). The lower correlation obtained in the regression between F_{IPARd} and K_{c_SF} in 'Angeleno' could be attributed to decreases in transpiration as a result of a reduction in the soil water content throughout the soil profile (Fig. 5.4). It has been suggested that the SF method is a less sensitive method for the detection of changes in soil water content (Ortuño et al., 2005, 2006 a, b; Conejero et al., 2007). The pre-harvest correlations between K_{c_WB} or K_{c_SF} and F_{IPARd} obtained in this experiment (Figs. 5.8 and 5.9) concur with those reported by Ayars et al. (2003) and Johnson et al. (2005) for peach irrigated at 100% of ET_c in San Joaquin Valley (California), where climatic conditions are similar to those of south-western Spain. Using a weighing lysimeter, Abrisqueta et al. (2013) measured an average K_c of 1.0 during summer in Murcia (Spain) in a peach orchard with 80% ground cover; a finding which is in almost perfect concordance with our results. However, experiments performed in apple and pear orchards with 40-50% ground cover indicated that the best fit between K_c and F_{IPARm} was obtained using exponential equations (Girona et al., 2011). It has been reported that the training system employed has a significant effect on tree water relations (Chootummatat et al., 1990; Li et al., 2002). The different growth habits between apple and pear trees (in hedgerows and with a more heterogeneous surface canopy covering) and plum and peach trees (open-vase) may therefore partially explain the discrepancy between the K_c and F_{IPARm} relationships. From these results, it seems that using the relationship between daily canopy light interception and crop coefficient would be an appropriate technique for scheduling irrigation for different species, cultivars and tree ages with the same training system.

5.5. Conclusions

The aim of the present work was to determine crop evapotranspiration and the resulting crop coefficient for fully-irrigated, early- and late-maturing plum cultivars based on continuous sap flow measurements and soil water content, and the relationships between canopy size indices and the K_{c_SF} and K_{c_WB} obtained during the fruit-growing season. The results of the sap flow and water balance method seem to provide useful K_c values for 'Red Beaut' and 'Angeleno' plums which could be used as a tool for irrigation scheduling under our growing conditions and orchard management techniques. However, it is important to adopt a different K_c value depending on the growth habit, crop management and type of plum cultivar in terms of harvest time. The maximum K_{c_SF} value was obtained from end-May to early-June for 'Red Beaut' and from end-August to early-September for 'Angeleno', indicating a higher water use for 'Red Beaut' than for 'Angeleno' during May and June and a role reversal in August and September. Under well-watered management conditions, F_{IPARd} would appear to be an appropriate technique to estimate K_c for Japanese plum during the pre-harvest period according to the linear relationships presented in this study for each variety.

Acknowledgements

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DISCUSIÓN GENERAL

La gestión del riego desde la perspectiva del uso eficiente del agua y de la adecuación del sistema de producción a los objetivos productivos, debería ser una de las prioridades del sector frutícola en zonas áridas y semiáridas. Actualmente, existen considerables conocimientos aplicables a la gestión del riego en las especies frutales de mayor importancia económica a escala mundial, pero en cultivos con menor superficie en producción como el ciruelo japonés, la información es todavía escasa y tiende a asimilarse a otros frutales de hueso, a pesar de presentar una serie de particularidades que crean cierta incertidumbre sobre la respuesta de los árboles frente a una determinada estrategia de riego.

El principal objetivo planteado con esta tesis doctoral ha sido incrementar el conocimiento disponible sobre la respuesta al riego del ciruelo japonés en las condiciones de cultivo de las Vegas del Guadiana, para de esta forma proponer programaciones de riego, ajustadas a las necesidades reales de las plantaciones, que integren estrategias de riego adecuadas para compatibilizar la maximización de los beneficios económicos con un uso eficiente del agua. De este modo se han contemplado aspectos clave en el balance estacional de agua de una plantación, como son el tipo de cultivar en relación con la duración del periodo de crecimiento del fruto y la influencia de prácticas agronómicas como el aclareo y la poda, que al influir sobre las relaciones fuente-sumidero y la superficie transpirante, necesariamente afecta al consumo de agua. De este estudio se ha obtenido información para poder ajustar las necesidades hídricas de las plantaciones, y determinar los momentos, duración e intensidad del estrés soportable en los periodos susceptibles de reducir el aporte de agua en estrategias de RDC, facilitando indicadores fiables de estado hídrico para poder realizar reajustes “in situ”.

Tomando como punto de partida la información disponible en ciruelo japonés y en otros frutales de hueso, se han diseñado estrategias de RDC adaptadas a cultivares de ciruelo japonés con claras diferencias en cuanto a la duración del periodo en que la fruta está presente en el árbol: ciclo corto 'Red Beaut' y ciclo largo 'Angeleno'.

En 'Red Beaut' (Capítulo I), se identificó "a priori" el periodo post-cosecha como el más adecuado para la restricción hídrica en estrategias de RDC (Johnson et al., 1994; Naor et al., 2006; Intrigliolo and Castel, 2005, 2010; Marsal et al., 2010). A lo largo de los cinco años de ensayo, se valoró que la adopción de esta estrategia suponía una ahorro anual de riego respecto de un riego destinado a cubrir el 100% de las necesidades hídricas de entre el 29 y 39% cuando se consideró un tratamiento con estrés moderado (RDI-60) y entre el 38 y 70% para el más severo (RDI-30) Este ahorro no dio lugar a síntomas que se pudiera relacionar con un decaimiento progresivo de los árboles y sí con una reducción significativa de la madera de poda, como consecuencia del efecto del déficit hídrico sobre el control del vigor (Hsiao, 1973). Estos resultados confirman los obtenidos para este mismo cultivar en California por Johnson et al. (1994) y son similares a los obtenidos en melocotón temprano por Johnson et al., (1992). Sin embargo, en otros trabajos el estrés post-cosecha ha supuesto pérdida de producción en la siguiente campaña en albaricoque (Ruiz-Sanchez et al., 1999; Torrecillas et al., 2000), almendro (Goldhamer y Viveros, 2000), melocotón (Girona et al., 2003) y peral (Naor et al., 2006), bien por tratarse de especies o cultivares más sensibles o porque soportaron niveles de estrés excesivamente severos.

Los niveles de estrés soportados por los árboles de un mismo tratamiento deficitario, al aplicarlo como un porcentaje de la ET_c estimada, fue diferente en cada uno de los 5 años de ensayo. Aunque en ningún caso se observaron efectos negativos sobre la cosecha, con este tipo de programaciones es difícil aventurar cuales serán los resultados para otras condiciones de cultivo, con una receta de este tipo. Este aspecto ya ha sido tratado por otros investigadores, que han propuesto valores de referencia de estado hídrico para condiciones de “no estrés”, así como para la aplicación de estrategias de RDC en los estados fenológicos menos sensibles (Fereres y Goldhamer, 1990; McCutchan y Shackel, 1992; Naor et al., 1997; Shackel et al., 1997; Marsal et al., 2002; Moriana et al., 2012). De los resultados obtenidos en el Capítulo I en ‘Red Beaut’, los umbrales de referencia de Ψ_{stem} para “no estrés” en pre-cosecha se sitúan entre -0.55 y -0.75 MPa, coincidiendo con los obtenidos en este mismo cv. por Johnson et al., (1994) y por Intrigliolo y Castel (2010) para un cv. de maduración media. Para el periodo post-cosecha el criterio recomendado es alcanzar un potencial de tallo mínimo de -1.75 MPa a mediados de Octubre, con una tasa máxima de descenso diaria de 0.014 MPa día^{-1}.

En ‘Angeleno’ (Capítulo II) se adoptó una estrategia de RDC combinada, en línea con las propuestas para melocotonero de ciclo largo y ciruelo japonés de ciclo medio (Girona et al., 2003; Naor et al., 2004; Intrigliolo et al., 2005), con un primer ciclo de estrés en la fase II de crecimiento del fruto y un segundo periodo tras la cosecha, separados por una fase III de no estrés. Esta fase II de crecimiento del fruto, según bibliografía, se corresponde a una fase de crecimiento lento del fruto que coincide con el endurecimiento del hueso (Tukey, 1981) que según Basile et al. (2002) en ciruelo japonés y DeJong et al., (1987) en melocotonero se corresponde con una fase de limitado sumidero del fruto.

En los Capítulos II y III se ha puesto en evidencia que el patrón de crecimiento del fruto en ‘Angeleno’ no coincide con lo descrito para otros frutales de hueso, ya que no se observa una fase clara de ralentización del crecimiento del fruto, ni un crecimiento final exponencial hasta la recolección, como si ocurriera en melocotonero (Girona y Fereres, 2012) y albaricoquero (Pérez-Pastor et al., 2014). Esto complica la gestión del periodo de estrés, en lo que se refiere a la duración máxima admisible para evitar pérdidas de calibre, ya que a diferencia de otros trabajos, no se ha observado un crecimiento compensatorio del fruto tras el periodo de estrés, como sucede en albaricoque (Torrecillas et al., 2000) y melocotón (Girona et al., 2003). Por otra parte, se ha comprobado, en contra de lo indicado por Faust (1998), que en cultivares tan tardías como la ensayada en este trabajo, la iniciación floral podría tener lugar hasta un mes antes de la cosecha, coincidiendo con el final del primer periodo de estrés. Se ha observado (Capítulo II) que un estrés moderado en este momento (potencial hídrico de tallo < -2.0 MPa), resulta en un incremento en el número de frutos en el año siguiente, mientras que prolongado y severo (entre -2.0 y -3.0 MPa), redujo el número de frutos al año siguiente. En este sentido, este trabajo abre la puesta a otros posteriores en los que se incida en una mejor delimitación de la fase de crecimiento del fruto menos sensible al déficit hídrico, así como en la determinación del momento en que tienen lugar los procesos de inducción y diferenciación floral, así como la influencia de un estrés hídrico creciente sobre esos procesos.

En base a los resultados obtenidos en el Capítulo II, los valores de Ψ_{stem} para asegurar condiciones de no estrés en ciruelo japonés de maduración tardía se sitúan entre -0.6 a -0.7 MPa durante la fase I, -0.6 a -0.8 MPa en fase II, -0.7 a -1.1 MPa en fase III y -0.9 to -1.1 MPa en post-cosecha, coincidiendo con los valores publicados para melocotón (Garnier and Berger, 1985), ciruelo europeo (McCutchan and Shackel, 1992) y ciruelo japonés (Johnson et al., 1994; Intrigliolo and Castel, 2010). Por otra parte, como estrategia de RDC se recomienda mantener en fase II un Ψ_{stem} por encima de -1,75 MPa, con un descenso máximo de 0.019 MPa día^{-1} durante esta fase y en post-cosecha de -1.35 MPa, con un descenso máximo 0.008 MPa día^{-1}.

En el caso de ‘Angeleno’, las estrategias de RDC fueron incluso más efectivas en el control del vigor que en Red Beaut, ya que el primer periodo de estrés coincidió con una fase muy activa de crecimiento vegetativo, que en Red Beaut se evitó para no afectar al crecimiento del fruto. En ambos casos el control del vigor mediante RDC (Hsiao, 1990; Moriana y Fereres, 2002; Nortes et al., 2005; Marsal et al., 2008) resulta muy atractivo ya que supone no solo reducir costes de poda, incluso suprimir la poda verde, sino que se puede llegar a mantener similar radiación interceptada a nivel de plantación, sin reducir por tanto el potencial productivo de la misma.

El paso definitivo para hacer atractivo el RDC para el agricultor-productor son los aspectos económicos que no es habitual abordar en los trabajos de esta índole. Los resultados obtenidos han demostrado que la estrategia ensayada conduce a un mayor beneficio económico en los tratamientos de RDC en comparación con el control. Este hecho se debe a los mayores ingresos brutos y menores costes de producción, principalmente por un aumento en la producción y una reducción de los costes anuales de poda (28%), agua aplicada y consumo eléctrico (26% en cada uno).

La importancia del tamaño de la fruta sobre el valor de la producción justifica una práctica cara y habitual en esta especie como es el aclareo de frutos. Como ya hemos visto, el RDC también puede afectar al calibre final del fruto y por tanto la interacción entre ambas prácticas adquiere interés (Capítulo III). Trabajos similares se han realizado en ciruelo japonés de ciclo medio (Naor et al., 2004; Intrigliolo y Castel, 2010) y melocotonero (Marsal et al., 2008; Lopez et al., 2010). El nivel de carga de los árboles influye sobre la producción y calidad, pero también puede incidir sobre el comportamiento fisiológico del árbol, modificando las relaciones hídricas, y como consecuencia la transpiración y en suma la demanda hídrica del árbol. Una estrategia propuesta para mantener calibres comerciales en frutos de melocotonero en condiciones de limitada disponibilidad de agua es intensificar el aclareo (Fereres y Soriano, 2007) y un nivel de carga alto puede incrementar la transpiración del árbol al aumentar la apertura estomática (Chalmers et al., 1975; Crews et al., 1975). En 'Angeleno' (Capítulo III) el nivel de carga frutal en un mismo año no modificó el estado hídrico de los árboles, el crecimiento vegetativo, el peso fresco del fruto y la calidad de la cosecha. Sin embargo, se observaron diferencias interanuales en g_l durante el crecimiento de los frutos, coincidiendo la mayor apertura estomática con años que de forma natural, traían más carga (Marsal et al., 2006). En este mismo sentido, los patrones de crecimiento vegetativo y reproductivo fueron modificados de un año a otro, como consecuencia de los mayores niveles de carga, reflejando la importancia de la carga frutal como regulador del crecimiento vegetativo y reproductivo (Basile et al., 2002).

Respecto a la calidad de los frutos, la carga no tuvo efectos sobre el contenido en sólidos solubles, al contrario que en melocotón (Crisosto et al., 1997; Walsh et al., 2007) y manzana (Johnson, D.S., 1995), y si afectó a la firmeza, acidez y el índice de jugo, cuyos valores descendieron al incrementarse la carga.

La falta de efecto del nivel de carga establecido año a año sobre los mencionados aspectos vegetativos, reproductivos y de calidad en este ensayo, y de interacción con la estrategia de riego parece más relacionado con niveles de carga bajos para la capacidad de asimilación del árbol: en las condiciones del ensayo hasta superar los 1100 frutos por árbol no se observó un efecto negativo sobre el tamaño del fruto y por lo tanto, hasta este límite el nivel de carga no debió ser limitante del mismo (DeJong y Grossman, 1995).

El desarrollo de un método simple para estimar las necesidades hídricas de una plantación sería un gran beneficio para la agricultura de regadío. El empleo de modelos de simulación de cultivos ha demostrado ser una herramienta de interés para ajustar las prácticas de cultivo, a las condiciones de de la parcela. La aplicación en frutales ha sido menos estudiada que en cultivos herbáceos y todavía son menores los estudios que simulan déficit hídrico en plantaciones frutales (Marsal and Stockle, 2012). La complejidad de la fisiología de un cultivo frutal, sometido a continuas intervenciones, que modifican aspectos críticos como el tamaño del árbol, la distribución de las ramas dentro de este, o el nivel de carga frutal son algunos de los aspectos que dificultan un correcto comportamiento de los modelos de simulación en plantaciones frutales.

En el **Capítulo IV** de esta tesis se ha utilizado el modelo CropSyst (Stockle et al., 2003) para predecir las necesidades hídricas en ciruelo japonés. El desarrollo y calibración del modelo se hizo bajo condiciones cambiantes de crecimiento. En estas condiciones incluyeron los cambios atmosféricos durante un periodo de 3 años, diferentes intensidades de poda, y el uso de dos cultivares de ciruelo japonés con diferente vigor y tiempo de maduración, 'Angeleno' y 'Red Beaut'.

Los resultados de este trabajo (Capítulo IV) han demostrado que la calibración del modelo CropSyst desarrollada para 'Angeleno' puede ser utilizada para predecir las necesidades hídricas (Marsal et al., 2013; 2014) y el potencial hídrico de tallo (Marsal et al., 2012) para otros años y tamaños de árbol. Sin embargo, la calibración para 'Angeleno' no fue adecuada para simular las necesidades hídricas y el potencial hídrico de tallo de 'Red Beaut'. El factor que puede explicar la necesidad de adoptar una nueva calibración para 'Red Beaut' fue la diferencia en vigor de los árboles y no la presencia del fruto en el árbol. Queda por saber si sería posible efectuar algún agrupamiento por tipos de cultivares, que ampliara la aplicabilidad del modelo ajustado de forma, que no sea necesario realizar un ajuste específico por cultivar.

Dado el estado actual de desarrollo de CropSyst, la calibración efectuada para 'Angeleno' es sobre todo válida para las condiciones de este estudio. Para correr

CropSyst en otra zona hay que tener en cuenta dos aspectos: (1) nueva evaluación de los parámetros del modelo, y (2) la disponibilidad de una nueva versión de CropSyst en la que se contemple el manejo de riego por goteo y drenaje bajo la zona radicular. Esta última aplicación probablemente aumentaría la capacidad de CropSyst para predecir necesidades hídricas, manejar estrategias de RDC y mejorar su aplicación práctica para poder ser usado por técnicos de explotaciones frutícolas.

Para realizar una programación de riego es necesario disponer de una estimación de las necesidades hídricas de la plantación a lo largo del ciclo de cultivo. El método del balance de agua propuesto en los manuales de FAO es el más utilizado en todos los regadíos del Mundo. Sin embargo, en la última actualización publicada de este manual (Allen et al., 1998) no existe información específica para el ciruelo japonés, sino que queda incluido dentro de un grupo recogido bajo la denominación general de “Albaricoque, Melocotón o Durazno, Drupas”, en el que además no se hace diferenciación entre tipos de cultivares. Para melocotonero, Ayars et al., (2003) ha publicado valores de coeficientes de cultivo específicos, obtenidos en lisímetros de pesada que se relaciona con parámetros medibles en la plantación de forma que los resultados pueden ser extrapolables a otras condiciones de cultivo.

En el **Capítulo V** de esta tesis se han determinado las necesidades hídricas del ciruelo japonés utilizando la metodología del balance de agua con sonda de neutrones y del pulso de calor con flujo de savia y microlisímetros para cuantificar la ET_c estacional y el correspondiente K_c en las dos cultivares, ‘Angeleno’ y ‘Red Beaut’.

Los resultados muestran que si bien ambas metodologías proporcionaron valores comparables de ET_c y K_c para ambos cultivares, existieron diferencias notables entre ellos. Los valores máximos de K_c obtenidos con el balance antes de cosecha fueron 1,09 y 1,17 para ‘Red Beaut’ y ‘Angeleno’, respectivamente. Por otra parte, los valores obtenidos con los flujos de savia fueron 1,16 y 1,25 para ‘Red Beaut’ y ‘Angeleno’, respectivamente. Estos valores se encuentran dentro del rango esperado para una plantación que tiene una cobertura vegetal entre 70 - 80% antes de cosecha (Allen et al., 1998). En ambos casos, e independientemente del cultivar, los valores de K_c descendieron después de cosecha, lo que teniendo en cuenta las diferencias de ciclo entre ambos, dio lugar a diferencias marcadas en el patrón estacional de K_c de los dos cultivares estudiados.

Los valores de K_c obtenidos con ambas metodologías fueron comparados con los propuestos por el manual FAO-56 (Allen et al., 1998), proponiéndose modificaciones que si bien no afectan considerablemente a la ET_c global, sí a la distribución estacional de la misma.

En la etapa pre-cosecha, los valores de K_c tanto del balance hídrico como de los flujos de savia, mostraron buena correlación con la fracción de intercepción de radiación fotosintéticamente activa, al igual que en melocotonero (Ayars et al., 2003), viña (Williams y Ayars, 2005), manzano (Auzmendi et al., 2011) y manzano y peral Girona et al., 2011). Sin embargo, las relaciones fueron diferentes entre los cultivares; la mejor correlación se obtuvo con los flujos de savia para ‘Red Beaut’, pero en ‘Angeleno’ fue con el balance de agua. Como consecuencia de este trabajo, cuantificando “in situ” de la radiación interceptada por los árboles en una plantación es posible obtener unos valores ajustados del K_c para la misma.

Como se ha mencionado al principio de esta discusión, el punto de partida de este trabajo ha sido una manifiesta falta de información, obtenida de forma específica en ciruelo japonés, necesaria para mejorar no solo el riego, sino el conjunto de las prácticas de cultivo. A lo largo de los 5 capítulos de este trabajo se han presentado una serie de avances que han contribuido en parte a paliar esta laguna, facilitando conocimientos que pueden mejorar la gestión del agua en las plantaciones de este frutal en las Vegas del Guadiana y en otras zonas regables del Mundo. Se han hecho aportaciones para mejorar y validar herramientas que pueden ser fundamentales para dar un paso más en la gestión de plantaciones frutales, como son los modelos de simulación de cultivos o los medidores de flujo de savia para cuantificar la transpiración de frutales. Por último, mencionar que este trabajo ha señalado aspectos en los que sería interesante incrementar el conocimiento con nuevos trabajos, entendiendo que el conocimiento es un camino que se recorre paso a paso.

CONCLUSIONES GENERALES

Las conclusiones y consideraciones finales que pueden establecerse de la presente tesis doctoral son las siguientes:

- La aplicación de RDC post-cosecha permitió ahorrar agua, reducir el crecimiento vegetativo (considerado como poda total), e incluso aumentar la producción y mantener la calidad del fruto.
- A largo plazo (cinco campañas) el RDC post-cosecha no produjo un efecto negativo debido a los efectos acumulados de un año a otro en el crecimiento vegetativo y en la producción, sin embargo, aumentó el rendimiento económico en comparación con el tratamiento Control.
- Los valores umbral de Ψ_{stem} para un tratamiento regado según sus necesidades totales fueron desde -0.55 MPa hasta -0.75 MPa durante pre-cosecha, y descendió hasta -1.2 MPa al final de la campaña de riego (mediados de Octubre).
- Permitir un estrés hídrico progresivo desde recolección (primeros de junio) hasta primeros de Agosto, a valores de Ψ_{stem} de -1.65 MPa, con una tasa de descenso diaria de 0.014 MPa día^{-1}, y Ψ_{stem} mínimo de -1,75 MPa al final de la campaña, parece ser una manera eficaz para aplicar estrategia de RDC en ciruelo japonés de maduración temprana.
- El déficit hídrico aplicado en fase II y post-cosecha reduce el crecimiento vegetativo, mantiene la producción e incrementa la eficiencia del uso de agua y el beneficio económico de la plantación, con ahorros de agua medios anuales entre un 29% y un 40% en comparación con un tratamiento Control.
- Un déficit hídrico severo y prolongado durante el crecimiento del fruto llevó a reducciones en el tamaño del fruto. Sin embargo, la reducción del período de déficit hídrico y la intensidad del estrés durante el crecimiento del fruto no tuvo efectos

perjudiciales sobre el crecimiento del fruto y la distribución del fruto en calibres comerciales.

- Los valores de Ψ_{stem} para asegurar condiciones de no estrés en 'Angeleno' se sitúan entre -0.6 a -0.7 MPa durante la fase I, -0.6 a -0.8 MPa en fase II, -0.7 a -1.1 MPa en fase III y -0.9 to -1.1 MPa en post-cosecha.
- Mantener el potencial hídrico de tronco y la conductancia estomática por encima de -1,5 MPa y 110 mmol (H_2O) m^{-2} s^{-1} respectivamente, durante fase II, no tuvo efectos negativos sobre la producción.
- Como estrategia de RDC se recomienda mantener en fase II un Ψ_{stem} por encima de -1,75 MPa, con un descenso máximo de 0.019 MPa $día^{-1}$ durante esta fase y en post-cosecha de -1.35 MPa, con un descenso máximo 0.008 MPa $día^{-1}$.
- Con estos niveles de estrés hídrico, la aplicación de aclareo de frutos no sería necesario, ya que no mejora el estado hídrico del árbol, se reduce la producción y se añade un coste extra que reduce los beneficios económicos. Sin embargo, con niveles de estrés hídrico severo podría ser una opción recomendable para mejorar el tamaño del fruto.
- El déficit hídrico durante fase II mejoró la calidad del fruto, aumentando la relación sólidos solubles / acidez y disminuyendo la firmeza.
- Diferentes valores a lo largo del año de los parámetros coeficiente de cultivo a máximo desarrollo vegetativo y máxima conductancia hidráulica de la planta fueron necesarios para predecir con el modelo CropSyst la ET_c, K_c y Ψ_{stem} en 'Angeleno', en árboles de distinto vigor y distintos años.
- El uso de un cultivar como 'Red Beaut', de mayor vigor que 'Angeleno', mostró que son necesarios diferentes valores de estos parámetros para poder predecir ET_c,

K_c y Ψ_{stem}. La influencia de la carga frutal en el árbol ejerció menor influencia en comparación con el vigor del árbol.

- CropSyst podría simular satisfactoriamente los cambios en clima y crecimiento del árbol de un año a otro y, por tanto, ser utilizado para estimar las necesidades de riego de una plantación bajo nuestras condiciones de cultivo. Sin embargo, son necesarias nuevas calibraciones en función del vigor del cultivar utilizado, para que CropSyst pueda estimar las necesidades hídricas.
- Los resultados del flujo de savia junto con los microlisímetros y el método de balance de agua proporcionaron valores de ET_c y K_c útiles para 'Red Beaut' y 'Angeleno', que podrían ser utilizados como una herramienta para la programación del riego bajo nuestras condiciones de cultivo y manejo de la plantación.
- Los máximos valores de K_c para 'Red Beaut' fueron alcanzados desde últimos de mayo hasta principios de junio, y para 'Angeleno' se alcanzaron desde finales de agosto hasta principios de septiembre. Es recomendable programar el riego adaptándolo al ciclo de maduración del cultivar.
- La utilización de los coeficientes de cultivos propuestos por el manual FAO-56 (Allen et al., 1998), infraestiman las necesidades máximas de ambos cultivares, de forma que al aplicar las necesidades estimadas, los árboles no satisfacen sus necesidades totales.
- El uso de la relación entre la fracción de intercepción de radiación fotosintéticamente activa diaria y el coeficiente de cultivo, sería una técnica apropiada para la programación de riego para diferentes especies, cultivares y edades de los árboles con el mismo sistema de formación que el de los árboles aquí ensayados.

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