Universidad Politécnica de Valencia

Departamento de Producción Vegetal

Efectos del riego deficitario y de la carga de cosecha sobre las relaciones hídricas y la respuesta agronómica del ciruelo japonés cv. Black-Gold

Tesis Doctoral

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Agradecimientos

Siempre he deseado llegar a este momento, por lo que ello supone, la verdad es que, ahora, no me salen muchas palabras.

Quiero expresar mi sincero agradecimiento al Dr. Juan Ramón Castel por su colaboración y ayuda prestada, así como sus acertadas sugerencias, a lo largo de estos años. Además, debo agradecerle muy especialmente la muy rápida, corrección de los artículos y de la memoria de esta tesis. Creo que ha sido muy enriquecedor para mi emprender este camino con él.

También agradezco al Prof. Bernardo Pascual haber aceptado la tutoría de este trabajo y estar agilizando todos los tramites de lectura de la tesis en la universidad.

Un agradecimiento especial al Dr. Emilio Carbonell y a Jordi Perez, no sólo por su siempre atenta ayuda, sino también sus enseñamientos de estadística.

Debo agradecer al IVIA la concesión de la beca predoctoral que ha financiado mis estudios, y extender el agradecimiento a gran parte de su personal, con el que he disfrutado de muy buenos momentos.

Agradezco también la revisión de algunos de los artículos por parte de los Drs. Carlos Ramos, Amos Naor y Elías Fereres.

Este trabajo no hubiera sido posible sin el esfuerzo de los técnicos y el personal de campo de la Cooperativa de Llíria, que han mantenido con más cuidado de lo normal, la parcela donde se han realizado los ensayos. Agradezco en particular a Belén Tamargo y Pepe Micó la comprensión que han tenido a lo largo de estos años.

Tampoco debo olvidar mucha de la gente que ha colaborado en las labores de campo; Javier Velez, Fernando Galindo y Jordi Sepúlveda. El resultado final de este trabajo es también fruto de su esfuerzo.

Debo agradecer a la gente de Requena, que, si bien en esta tesis no esté reflejado el trabajo que hemos realizado juntos, si han sido de gran ayuda; en particular, Diego Pérez, Ernesto Navarro y Susana Pedrón.

Un agradecimiento especial a Ángela Martínez por ayudarme en gran parte del trabajo realizado.

Finalmente debo agradecer mucho a mi familia, mis padres y mi hermano, ya que ellos son los que me han enseñado a tirar siempre hacia delante sin mirar atrás. Sus esfuerzos a lo largo de muchos años ha consentido que yo llegara hasta aquí. Además, agradezco a mi madre por revisar la ortografía de este trabajo.

Un agradecimiento muy especial a Belén no sólo por lo que ella ya sabe, sino por su gran ayuda, en corregir y revisar conmigo los artículos, y por aguantar durante estos años los sacrificios y renuncias, para que esta tesis saliera adelante en el menor tiempo posible. Además, le agradezco su apoyo constante y sus consejos en los momentos difíciles. Esta tesis es un trabajo de los dos. Deseo poderte devolver, en un futuro, alguna de las cosas, de las que te he privado, a lo largo de estos años.

A mio nonno Dottore Sebastiano Intrigliolo

Resumen

En este trabajo se ha estudiado el efecto del riego deficitario en distintos periodos fenológicos y de la carga de cosecha, tanto sobre la respuesta agronómica como sobre las relaciones hídricas de una plantación joven de ciruelo japonés cv. Black-Gold, variedad de maduración intermedia. Además, se ha evaluado la utilidad de los sensores Watermark® para la medida del potencial matricial del suelo (Ψm), y la eficacia de los dendrómetros en tronco para estimar el estado hídrico de los árboles.

Los resultados muestran distinta sensibilidad del cultivo al riego deficitario según el periodo fenológico en el que se aplique. En post-cosecha, las restricciones hídricas permitieron ahorros de agua de hasta un 29%, sin afectar a la intensidad de floración ni al cuajado ni al crecimiento del fruto del año siguiente. Sin embargo, a medio plazo, tres años, el estrés hídrico aplicado en post-cosecha puede reducir la producción de la plantación, debido al efecto acumulado de las restricciones sobre el crecimiento del árbol. De todos modos, esta pérdida de producción podría ser compensada por los importantes ahorros en costes de cultivo, en particular poda y aclareo, que pueden conseguirse. Por tanto, el estrés hídrico en post-cosecha podría emplearse a escala comercial, no solamente en caso de escasez de recursos hídricos, sino además como herramienta para controlar el crecimiento del árbol.

El estrés hídrico llevado a cabo durante la fase II y toda la fase III del crecimiento del fruto, redujo su tamaño de forma proporcional a la integral de estrés, además de reducir el crecimiento del árbol cuando el estrés hídrico fue severo, o cuando iba asociado a una carga alta. La restricción severa del riego exclusivamente durante la fase II y el principio de la fase III, aunque redujo en un 12% el tamaño del fruto, permitió reducir el crecimiento vegetativo del árbol y seguramente por ello adelantar la maduración del fruto.

La restricción moderada del riego, antes y después de la cosecha, si bien permitió el mayor ahorro de agua (30%), provocó una reducción demasiado severa en el crecimiento del árbol, además de afectar al tamaño del fruto cuando el estrés acumulado durante el periodo de crecimiento del fruto superó el umbral de 45 MPa·día.

La carga alta de cosecha, 7-8 frutos/cm^2 sección de tronco, comparada con 4-5 frutos/cm^2 sección de tronco, en un año de ensayo, permitió aumentar la producción de la plantación en un 46%, ya que redujo el tamaño final del fruto en un 16%. Además, la carga alta también disminuyó el crecimiento vegetativo del árbol, aunque su efecto fue mayor sobre el crecimiento del tronco que sobre el desarrollo del área foliar.

El crecimiento del fruto fue afectado de forma similar por el estrés hídrico moderado independientemente del nivel de la carga de cosecha. Sin embargo, el crecimiento del tronco fue exclusivamente menor en los árboles regados deficitariamente cuando la carga fue alta.

La carga también afectó a las relaciones hídricas del árbol. En particular, en árboles bien regados aumentó en un 28% la máxima contracción diaria del tronco (MDC) y redujo en un 23% la tasa diaria de crecimiento del tronco (CT). Estos hechos indican que debe tenerse en cuenta el nivel de carga de los árboles, cuando se empleen estos indicadores para estimar el estado hídrico del árbol.

El MDC, el CT y el potencial de hoja no transpirante (Ψtallo) respondieron a los cambios en el estado hídrico de los árboles, por lo que pueden ser indicadores útiles del estrés hídrico. La variabilidad de las medidas fue mayor en el MDC y CT que en el Ψtallo, por lo que este último es el indicador más sensible.

Se han obtenido además unas ecuaciones de referencia para predecir el valor del MDC y del Ψtallo en función de la demanda evaporativa. Estas ecuaciones podrán emplearse en protocolos de riego basados en la medida del estado hídrico de los árboles. Para el Ψtallo deben emplearse dos ecuaciones de referencia a lo largo del ciclo anual de cultivo, una antes de la cosecha y otra después, debido a una progresiva reducción en el estado hídrico de los árboles. Para el MDC una única ecuación de referencia puede ser válida, debido a un cambio estacional en la relación MDC-Ψtallo que conlleva menores MDC para un mismo Ψtallo durante el periodo post-cosecha, y que por lo tanto compensa la reducción del estado hídrico de los árboles.

Se ha evaluado la influencia que tiene el tamaño de los árboles sobre el MDC. En un rango de diámetro de tronco de 8 a 14 cm, el MDC aumenta un 13% por cada cm de incremento en el diámetro del tronco, debido al mayor espesor de floema de los árboles más

grandes. Este resultado podría permitir extrapolar la predicción del Ψtallo, obtenida a partir de las relaciones empíricas entre Ψtallo y MDC, a árboles de otros tamaños.

Los sensores Watermark[®] respondieron a las restricciones del riego, en particular cuando fueron severas. Además, permitieron estimar con cierta precisión el estado hídrico del árbol, en particular para Ψm< -40 kPa, pero no permitieron determinar con la misma exactitud el Ψtallo en el rango húmedo (-20 kPa<Ψm< -10 kPa). Por ello, no se recomienda su empleo en los periodos fenológicos de mayor sensibilidad al estrés hídrico. Su mayor limitación es, de todos modos, la alta variabilidad de sus medidas (coeficiente de variación medio de 35-50%).

Abstract

The effects of deficit irrigation applied during different phenological periods, and of different crop load levels on the water relations and on tree productivity of young Japanese plum cv. Black-Gold trees have been evaluated. Moreover, the usefulness of Watermark[®] sensor for measuring matric soil water potential (Ψm) and of stem diameter sensor to estimate plant water status has been investigated.

This mid-season maturing cultivar showed different sensitivity to water deprivation depending upon the phenological period. Thus, deficit irrigation applied during post-harvest did not affect flowering, fruit set or fruit growth the next season, allowing for a 29% water saving. However, several seasons of drought after harvest could reduce productivity of young trees as a consequence of the cumulative effect of water deficit on tree growth. Nonetheless, the smaller tree size, allows easier pruning and fruit thinning, with potential cost-saving for producers.

   On the other hand, water restriction applied during stages II and III of fruit growth, reduced fruit size in proportion to the integrated water stress achieved and also affected tree growth when water restrictions were either severe or in conjuction with a high crop load level. Severe water deficit applied only during stage II of fruit growth and the beginning of stage III, reduced fruit size by a 12% but advanced fruit maturation probably due to the important reduction of shoot growth.

   Drouhgting based on a moderate, but continuous reduction of irrigation rates from phase II of fruit growth until the end of the season, led to a too severe reduction of tree growth, and may also reduce fruit size if integrated water stress during fruit growth overcomes the 45 MPa·day threshold value.

In a one-year experiment, increasing crop load from 4-5 fruit/cm^2 of trunk cross sectional area (TCSA) to 7-8 fruit/cm^2 of TCSA, allowed for a 47% increase in yield, as average fruit weight was only reduced by a 16%. High crop load also reduced the vegetative growth, with higher effect on trunk growth than on canopy development. It enhanced the sensitivity to water stress of trunk growth but not that of fruit growth.

Crop load also affected tree water relations. In well irrigated trees, high crop load considerably increased the maximum diurnal trunk shrinkage (MDS) and reduced daily trunk growth (TGR). Thus, these feactures have to be taken in consideration when using the short term trunk diameter variations for irrigation scheduling.

MDS, TGR and the water potential of non-transpiring leaves (Ψstem) all responded well in agreement to water reductions, therefore they are useful water stress indicators. However, higher variability of readings was obtained in MDS and TGR that on Ψstem, and therefore Ψstem was the most sensitive indicator.

Reference, base-line equations, have been obtained to predict Ψstem and MDS values as a function of the evaporative demand. These reference equations can be a useful guidelines for scheduling irrigation protocols based on Ψstem and MDS measurements.

A decrease in plant water status towards the end of the season occurred even in the well irrigated trees. Thus, for Ψstem, different reference equations have to be used at the beginning of the season (fruit growth) than at the end (after harvest). A seasonal change in the relation between MDS and Ψstem was observed, which compensated the decrease in plant water status, and therefore similar MDS values for well irrigated trees can be expected before or after harvest.

The influence of tree size on the relationship between MDS and Ψstem was also investigated. In a range of tree trunk diameter between 8 to 14 cm, MDS increased a 13% for each cm of increase of trunk diameter, due to the thicker phloem tissues of larger trees. This result may allow to extrapolate Ψstem prediction based on empirical relations with MDS to plum trees of different sizes.

Watermark$^{®}$ sensors readings were in reasonable agreement with the irrigation regime particularly under severe water restrictions. They showed good indication of plant water status in the dry range of Ψm, but not in the wet range (-20 kPa<Ψm< -10 kPa). Thus, its use is not recommended in those phenological periods of high sensitivity to water deprivation. Nonetheless, the most important drawback in their use was the high variability of readings (typical coeficient of variation of 35-50%) increasing at the lower Ψm range.

Resum

S'ha estudiat l'efecte de les restriccions hídricques en distints períodes fenológics, i de la càrrega de collita sobre la resposta agronómica i les relacions hídricques d'una plantació jove de prunera Japonesa cv. Black-Gold, varietat de maduració intermèdia. A més, s'ha avaluat la utilitat dels sensors Watermark®, per a la mesura del potencial matricial del sòl (Ψm), i l'eficàcia, dels dendrómetres per a estimar l'estat hídricc dels arbres.

Els resultats mostren distinta sensibilitat del cultiu al reg deficitari segons el període fenológic en el qual s'aplique. En poscollita, les restriccions hídricques van permetre estalvis d'aigua de fins a un 29% sense afectar ni a la intensitat de floració ni el quallat ni el creixement del fruit de l'any següent. No obstant això, a mitjà termini, tres anys, l'estrès hídricc aplicat en poscollita pot reduir la producció de la plantació a causa del efecte acumulat de les restriccions sobre el creixement de l'arbre. De totes maneres, aquesta pèrdua de producció podria ser compensada pels importants estalvis en costos de producció, en particular poda i aclarit, que poden aconseguir-se. Per tant, l'estrès hídricc en poscollita podria utilitzar-se a escala comercial, no solament en cas d'escassesa de recursos hídriccs, sinó a més com ferramenta per a reduir el creixement de l'arbre.

L'estrès hídricc portat a terme durant les fases II i tota la fase III del creixement del fruit, va reduir el seu tamany de forma proporcional a la integral d'estrès, a més de reduir el creixement de l'arbre quan l'estrès hídricc va ser sever, o quan anava associat a una càrrega alta. En canvi, la restricció severa del reg exclusivament durant la fase II i el principi de la fase III, encara que va reduir en un 10% la grandària del fruit, va permetre reduir el creixement vegetatiu de l'arbre i segurament per això avançar la maduració del fruit.

La restricció moderada del reg, abans i després de la collita, encara que va permetre el major estalvi d'aigua (30%), va provocar una reducció massa severa en el creixement de l'arbre, a més d'afectar al creixement del fruit quan l'estrès acumulat durant aquest període va superar el llindar de 45 MPa•dia. La càrrega alta de collita, 7-8 fruits/cm2 secció de tronc, comparada amb una càrrega de 4-5 fruits/cm2 secció de tronc en un any d'assaig, va reduir el tamany final del fruit en un 16%, però va permetre augmentar la collita en un 46%. A més, la càrrega alta també va afectar el creixement vegetatiu de l'arbre, encara que

el seu efecte va ser major sobre el creixement del tronc que sobre el desenvolupament de l'àrea foliar.

El creixement del fruit va ser afectat de forma similar per l'estrès hídricc moderat independentment del nivell de la càrrega de collita. No obstant això, el creixement del tronc va ser exclusivament menor en els arbres regats deficitàriament quan la càrrega va ser alta.

La càrrega també va afectar a les relacions hídricques de l'arbre. En particular, en arbres bé regats, va augmentar de forma considerable la màxima contracció diària del tronc (MDC) així com va reduir la taxa diària de creixement del tronc (CT). Aquests fets indiquen que deu tenir-se en compte el nivell de càrrega dels arbres, quan s'utilitzen aquests indicadors per a estimar l'estat hídricc de l'arbre.

El MDC, el CT i el potencial de fulla no transpirante (Ψbrot) van respondre als canvis en l'estat hídricc dels arbres, pel que poden ser útils indicadors d'estrès hídricc. La variabilitat de les mesures va ser major en el MDC i CT que en el Ψbrot, pel que aquest últim és l'indicador més sensible a l'estrès hídricc.

S'han obtingut a més unes equacions de referència per a predir el valor del MDC i de el Ψbrot en funció de la demanda evaporativa. Aquestes equacions podran utilitzar-se en protocols de reg basats en la mesura de l'estat hídricc dels arbres. Mentre per a el brot deuen utilitzar-se dues equacions de referència al llarg del cicle anual de cultiu, una abans de la collita i una altra després, a causa de una progressiva reducció en l'estat hídricc dels arbres, per al MDC, una única equació de referència pot ser vàlida, a causa de un canvi en la relació MDC- Ψbrot després de la collita.

S'ha avaluat l'efecte del tamany dels arbres sobre el MDC. En un rang de diàmetre de tronc de 8 a 14 cm, el MDC augmenta un 13% per cada cm d'increment en el diàmetre del tronc, a causa del major espessor de floema dels arbres més grans. Aquest resultat podria permetre extrapolar la predicció de el Ψbrot obtinguda a partir de les relacions empíriques entre Ψbrot i MDC, a arbres d'altres tamanys.

Els sensors Watermark® van respondre raonablement bé a les restriccions del reg, en particular quan van ser severes, i permeten estimar amb certa precisió l'estat hídricc de l'arbre, en particular per a $\Psi m<-40$ kPa. Per això, no es recomana el seu ús en aquells períodes fenológics sensibles a l'estrès hídricc. La seua major limitació és, de totes maneres, l'alta variabilitat de les seues mesures (coeficient de variació de 35-50%).

Índice

1.- Introducción general

En una explotación frutícola el objetivo final es obtener cosechas de la máxima calidad intentando reducir costes e insumos. Para ello el agricultor debe conjugar los factores genéticos (conjunto de un patrón y una variedad), los factores edafoclimáticos, y las técnicas de cultivo. Si bien la elección del sistema porta-injerto/variedad adecuado a una condiciones edáficas y climáticas, no fácilmente modificables, es un primer paso fundamental, cultivar el sistema genético elegido de forma apropiada es un segundo paso no menos importante.

Del mismo modo, mientras el potencial de crecimiento de cualquier órgano del árbol viene definido fundamentalmente por sus características genéticas, su tasa de crecimiento real está limitada por una serie de factores tanto internos al propio árbol, como externos. Estos últimos pueden afectar al potencial fotosintético del árbol, alterar el reparto de los fotoasimilados o incluso modificar la capacidad de demanda de los órganos sumideros.

En este contexto tanto el riego como el nivel de carga son los dos factores que a corto plazo influyen en mayor medida sobre el crecimiento del árbol y en particular, sobre los principales parámetros de calidad del fruto (tamaño y características organolépticas).

El riego es una técnica de cultivo con la que se pretenden cubrir las necesidades hídricas de la planta a fin de evitar situaciones de estrés hídrico, y de este modo incrementar la biomasa producida y en muchos casos la cosecha (Fereres et al., 2003). Hoy día, sin embargo, dado que el agua es un recurso natural escaso y no fácilmente renovable y que la agricultura consume cerca del 87% de los recursos hídricos en todo el mundo (FAO, 2003), puede no ser justificable, aún cuando fuera posible, proporcionar a la plantación toda el agua que requiera.

Además, el riego debe encuadrarse dentro del resto de técnicas de cultivo para optimizar el rendimiento de la explotación frutícola. Por ello el riego puede servir como herramienta para, por un lado, controlar el crecimiento del árbol (Ebel et al., 1995) y, por otra parte, alterar el reparto de fotoasimilados dentro del mismo (Faust, 1989a).

Desde este enfoque surgió la idea del riego deficitario controlado, RDC (Chalmers et al., 1981), el cual se basa en aportes reducidos de agua en periodos determinados de baja

sensibilidad al déficit y en cubrir las necesidades hídricas durante el resto del ciclo fenológico del árbol (Behboudian y Mills, 1997).

Con esta estrategia de riego se pretende no solamente ahorrar agua y costes de producción, reduciendo las necesidades de poda y aclareo, sino también favorecer el crecimiento y la calidad del fruto incrementando su disponibilidad de carbohidratos y su exposición a la radiación solar.

Así pues, en frutales de hueso, el estrés hídrico se suele llevar a cabo durante el periodo de endurecimiento del hueso (Agustí, 2000) durante el cual el potencial de crecimiento del fruto es menor (Pavel y DeJong, 1993) y por lo tanto está afectado en menor medida por aquellos factores, como el déficit hídrico, que pueden limitar la fuente de fotoasimilados o el transporte de agua y nutrientes al fruto. Durante este periodo, en cambio, el crecimiento vegetativo es notable (Berman y DeJong, 2003) a consecuencia del menor efecto de competencia del fruto, y puede ser eficazmente controlado mediante el estrés hídrico (Li et al., 1989a; Girona et al., 2003).

Así, los primeros ensayos de RDC llevados a cabo en Australia en melocotoneros de maduración tardía (Chalmers et al., 1981; Mitchell y Chalmers, 1982), demostraron la eficacia del RDC, ya que se obtuvieron, incluso incrementos en el tamaño del fruto y en su calidad interna, debido fundamentalmente a un incremento de los sólidos solubles totales por efectos metabólicos (ajuste osmótico del fruto).

En ensayos posteriores los resultados no fueron tan prometedores (Girona, 1989; Goldhamer et al., 2002), y demostraron que otros factores como la profundidad o permeabilidad del suelo y la climatología pueden condicionar los resultados.

En particular, el ciclo fenológico de la variedad en estudio (Flore, 1994) es un factor crítico. Así, en variedades de maduración temprana, la fase de endurecimiento del hueso es muy breve o incluso inexistente (DeJong et al., 1987), por lo que resulta difícil someter a la planta a estrés hídrico exclusivamente durante ese periodo. En cambio, en estas variedades la fase de post-cosecha es un periodo largo de tiempo, que, al no estar presente el fruto, debería ser ideal para recortar la dosis de riego. Sin embargo, se debe prestar atención al posible efecto perjudicial del estrés hídrico sobre la diferenciación floral (Faust, 1989b) y sobre la acumulación de reservas (Oliveira y Priestley, 1988), procesos que ocurren después de la cosecha. En este sentido un estrés hídrico no demasiado severo en post-cosecha puede

incluso favorecer la acumulación de carbohidratos de reserva (Dichio et al., 2004) ya que al reducir la elongación de los brotes de final del verano-otoño hay una mayor disponibilidad de fotoasimilados para otros sumideros.

En muchas especies de frutales, el aclareo de frutos es otra técnica de cultivo frecuentemente empleada para disminuir la competencia entre los frutos, favorecer su crecimiento y aumentar la calidad de los que quedan (Agustí, 2004). Aún así es importante definir una intensidad de aclareo óptima que garantice un tamaño y características organolépticas del fruto adecuadas a las exigencias y precios del mercado, pero que también permita obtener producciones rentables. Además, cabe tener en cuenta que el nivel de carga no afecta solamente al crecimiento del fruto, sino que puede modificar el crecimiento del resto de órganos de la planta. De hecho, en los árboles con mayor nivel de carga aunque mayor es la producción de materia seca por unidad de área foliar (Palmer, 1992; Inglese et al., 2002), es menor el reparto de fotoasimilados hacia los órganos leñosos (Palmer, 1992) o a los tejidos de reserva. Por ello, un nivel de carga alta puede reducir sensiblemente el crecimiento del árbol y a largo plazo, en particular en árboles jóvenes, reducir su productividad (Webster y Brown, 1980).

Por otra parte, la carga puede tener un efecto sobre las relaciones hídricas del árbol reduciendo su estado hídrico, en particular en condiciones de limitada disponibilidad de agua en el suelo (Berman y DeJong, 1996; Naor, 2004). Además, el nivel de carga puede modular la respuesta del cultivo al estrés hídrico, aumentando su sensibilidad cuando la carga sea alta (Goode et al., 1978; Berman y DeJong, 1996; Girona et al., 2004; Intriglioo et al., 2004), o al revés, minimizando los efectos negativos del estrés hídrico cuando la carga sea baja (Freeman et al., 1979). Por ello es importante tener en cuenta este factor a la hora de establecer un programa de riego deficitario.

Los mecanismos fisiológicos implicados en esta mayor sensibilidad del cultivo al déficit hídrico con cargas altas pueden ser varios. Por un lado, el propio efecto de la carga de reducir el estado hídrico de los árboles en definitiva conlleva, para una misma cantidad de agua aplicada, un mayor estrés hídrico en los árboles con carga alta con respecto a los de carga baja. Pero, por otra parte, debe tenerse en cuenta el efecto combinado que pueden

tener una carga alta y el déficit hídrico en reducir la disponibilidad de fotoasimilados para los órganos en crecimiento.

En particular en programas de riego deficitario, es importante determinar el estrés hídrico realmente impuesto para evitar que un déficit hídrico moderado y potencialmente beneficioso pueda convertirse en demasiado severo. A tal efecto es preciso disponer de herramientas que permitan evaluar el estado hídrico del suelo o mejor aún de la planta.

En cuanto a la información derivada del suelo, su principal dificultad estriba en obtener una medida representativa del agua disponible para la planta (Russo y Bresler, 1982; Schmitz y Sourell, 2000), dada la alta variabilidad espacial de las características hidráulicas del suelo (Warrick y Nielsen, 1980) y la heterogeneidad en el contenido de agua en el bulbo húmedo en riego localizado. Además, existe amplia evidencia de que muchos de los procesos fisiológicos básicos para la planta, dependen en mayor medida del estado hídrico de los tejidos en cuestión, que del estado hídrico del suelo (Hsiao, 1973). A pesar de estas limitaciones, la información derivada del suelo ha sido ampliamente utilizada (Klein, 1983; Li et al., 1989b) ya que es de fácil y directa interpretación al no depender de las condiciones ambientales.

En la actualidad existen un buen número de instrumentos de medida del estado hídrico del suelo (Leib et al., 2003). Entre los más empleados, por su bajo coste y facilidad de manejo, son los tradicionales tensiómetros y los sensores de matriz granular (SGM). Estos últimos han sido objeto de amplio estudio en cultivos herbáceos (Schock et al., 1988a; 1988b), pero su utilidad en frutales ha sido menos estudiada.

La planta integra el efecto tanto de la disponibilidad de agua en el suelo como de la demanda evaporativa y por ello proporciona una información más adecuada para determinar el efecto de las restricciones del riego sobre su estado hídrico y para la programación del mismo (Jones, 2004); sin embargo, tiene el inconveniente de estar afectada por las condiciones ambientales. Por ello, la determinación del estado hídrico de la planta, si no se toma antes del amanecer, puede ser poco informativa si no va acompañada de una medida de referencia obtenida en árboles sin limitación de agua en el suelo. Para obviar este inconveniente, pueden emplearse árboles de referencia regados sin limitaciones en la misma parcela (Goldhamer et al., 2001; Velez et al., 2005), o bien obtener

previamente unas ecuaciones de referencia, que determinen el valor esperado para un árbol bien regado según las condiciones ambientales (Goldhamer y Fereres, 2004). Estas ecuaciones de referencia han sido obtenidas en almendro (Fereres y Goldhamer, 2003) y ciruelo para pasificación (McCutchan y Shackel, 1992) en ambientes secos y con riegos que mojaban toda la superficie del suelo, y en olivo (Moriana y Fereres, 2004). No existe en cambio información al respecto en climas más húmedos y en particular para riego localizado, donde hay evidencia de que la planta tiende a tener un estado hídrico menor a consecuencia del reducido volumen de suelo mojado por los goteros (Lampinen et al., 2001).

Numerosos trabajos en frutales (Shackel et al., 1997; Naor, 2000) han puesto de manifiesto la utilidad de la medida de potencial hídrico de hoja no transpirante (Ψtallo). Su eficacia radica en su baja variabilidad (McCutchan y Shackel, 1992), buena representatividad del agua en el suelo disponible para la planta (Naor, 2004), menor influencia de las condiciones ambientales que en el potencial hídrico de hoja (McCutchan y Shackel, 1992) y buena predicción de la respuesta del cultivo al estrés hídrico (Naor et al., 1995). Además el Ψtallo integra los efectos, tanto de las restricciones hídricas, como del nivel de carga de cosecha sobre el estado hídrico del árbol (Naor et al., 2001). A pesar de todo esto, al ser una determinación no fácilmente automatizable, en los últimos años ha cobrado interés estudiar la eficacia de otras técnicas que permitan estimar en continuo el estado hídrico de la planta (Jones, 2004) y que además puedan actuar directamente sobre los controladores de riego.

La medida en continuo del flujo de savia, en particular mediante la técnica de compensación del pulso de calor (Smith y Allen, 1996), permite estimar la tasa de transpiración y el consumo hídrico de la planta. Dicha medida ha demostrado su eficacia en estudios de ecofisiología (Alarcón et al., 2003), pero su efectividad a escala comercial para la programación del riego ha sido cuestionada debido a la alta variabilidad de estas determinaciones y a su carácter invasivo (Zreik et al., 2000).

La medida de la temperatura del dosel vegetal ha sido también ampliamente evaluada en particular en cultivos herbáceos (Jackson, 1982). Su principal inconveniente radica en la gran influencia que tienen las condiciones ambientales sobre esta medida a pesar de las correcciones propuestas (Idso et al., 1981).

Finalmente una de las técnicas más empleadas en cultivos leñosos, por su robustez y no excesivo precio, es la medida en continuo de las variaciones de diámetro del tronco (VDT) mediante los dendrómetros. En la actualidad se emplean principalmente dos variables derivadas del análisis de las VDT: el crecimiento del tronco (CT) y la máxima contracción diaria (MCD). El CT depende en parte del estado hídrico de la planta (Hsiao, 1973), por lo que, tanto su evolución a corto plazo, una semana, o a más largo plazo, puede servir para estimar el estado hídrico del árbol. No obstante, hay que tener en cuenta que otros factores, que en definitiva afectan al reparto de carbohidratos en la planta (Chalmers y van den Ende, 1974), pueden influir sobre esta variable, por ejemplo: la edad del cultivo (Goldhamer y Fereres, 2001), la etapa fenológica (Marsal et al., 2002; Intrigliolo et al., 2005) el nivel de carga (Blanco et al., 1995; Berman y DeJong, 2003) y también la integral térmica. Además su empleo no es aconsejable en aquellos momentos fenológicos en los que el crecimiento del tronco es nulo o muy pequeño (Ginestar y Castel, 1996). Por ello, este indicador parece más adecuado en plantaciones jóvenes en las que la tasa de crecimiento del tronco suele ser mayor (Goldhamer y Fereres, 2001; Moriana y Fereres, 2002) y donde además optimizar el crecimiento del árbol es el principal objetivo agronómico.

La MCD, en cambio, se debe fundamentalmente a la contracción de los tejidos elásticos del tronco, el floema (Molz y Klepper, 1973). Durante las horas centrales del día hay un flujo radial de agua desde el floema hacia el torrente transpiratorio cuya fuerza motriz es el potencial hídrico xilemático. Así, en periodos cortos de tiempo existe una buena correlación entre el Ψtallo y la MCD (Cohen et al., 2001). Sin embargo, otros factores, como el mismo crecimiento del tronco (McBurney y Costigan, 1984), pueden afectar a la relación entre MCD y Ψtallo. De hecho, en algunos trabajos realizados en especies del género *Prunus* se ha comprobado que a lo largo de todo un ciclo de cultivo no existe una única relación entre la MCD y el Ψtallo (Marsal et al., 2002; Fereres y Goldhamer, 2003). A pesar de ello en numerosos cultivos como melocotonero (Goldhamer et al., 1999), almendro (Fereres y Goldhamer, 2003), manzano (Naor y Cohen, 2003), vid (Myburg, 1996) y cítricos (Ortuño et al., 2004) se ha demostrado la eficacia del MCD como indicador del estado hídrico de los árboles, pero no existe información al respecto en ciruelo.

Dados estos antecedentes, en este trabajo se han planteado dos ensayos de campo en una plantación joven de ciruelo japonés cv. Black-Gold, variedad de maduración intermedia, para cumplir con los siguientes objetivos generales:

- Estudiar la respuesta agronómica (crecimiento vegetativo y producción) a corto y medio plazo al riego deficitario aplicado en distintos periodos fenológicos: i) post-cosecha, ii) crecimiento del fruto iii) ambos periodos (Capítulo 2).

- Evaluar la utilidad de distintas herramientas para la medida del estado hídrico de la planta (Ψtallo, MDC y CT) y del suelo (sensores SGM) (Capítulo 2, 3, 4 y 5).

- Estudiar el efecto del riego deficitario aplicado durante el crecimiento del fruto, de la carga de cosecha y de la interacción de ambos, sobre la respuesta agronómica (crecimiento vegetativo, producción y tamaño y calidad del fruto) y sobre las relaciones hídricas (potencial mátrico de agua en el suelo, conductancia estomática, Ψtallo, MCD y CT). (Capítulo 3).

2.- Effects of regulated deficit irrigation on growth and yield of young Japanese plum trees

Effects of regulated deficit irrigation on growth and yield of young Japanese plum trees

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SUMMARY

Drought was applied to a 4 year-old, mid-season Japanese plum (*Prunus salicina* cv. 'Black-Gold') orchard over 4 years in Valencia, Spain and the impact on tree water status, growth, yield and fruit size recorded. Water was restricted during Phases II and III of fruit growth, or after harvest, replacing 33% or 66% of tree evapotranspiration (ET_c), or during both periods at 66% of ET_c. Water deficit during fruit growth reduced average fruit weight, with a negative correlation between fruit size and integrated midday stem water potential. In contrast, drought after harvest did not affect flowering, fruit set, fruit growth or yield, in the short-term. However, in the last year of the experiment there was a 10% reduction in yield compared with control plots because the droughted trees were smaller. Thus, in young trees, post-harvest droughting may reduce productivity, in the long-term, as a consequence of the cumulative effects of water deficit on tree growth. Savings in water applications were similar with deficit irrigation applied after harvest, or before and after harvest. However, deficit irrigation applied during both periods not only reduced fruit growth, but also had a greater effect on tree growth. Post-harvest droughting, despite its moderate detrimental effect in the long-term, should be considered in commercial orchards not only in cases of water scarcity, but also as a tool to control vegetative growth.

Water is an increasingly scarce resource, with irrigated agriculture accounting for up to 85% of global water consumption (van Schilfgarde, 1994). Regulated deficit irrigation (RDI) was developed in the 1980s as a strategy to save water and improve the productivity of fruit trees (Chalmers *et al.*, 1981; Mitchell and Chalmers, 1982; Behboudian and Mills, 1997).

Growth of shoots, flowers and fruit in deciduous trees, occurs at different times (Flore, 1994) and therefore the timing of RDI can influence the result. In stone fruit, Phase II of fruit growth has been identified as an appropriate period for RDI. During this period, fruit growth is minimal and therefore generally not affected by drought, while shoot growth can be reduced (Li *et al.*, 1989; Girona *et al.*, 2003). However, in early cultivars, this Phase is very short, or non-existant, providing little saving of water. In these cultivars, the main period of shoot growth occurs after harvest, and thus may be an ideal time for droughting (Johnson and Handley, 2000).

Drought after harvest has been reported to have a negative or no effect on yield of several deciduous trees species. In mature peach trees, drought after harvest reduced shaded area, trunk growth and root density, but there was no loss of production over 4 years of moderate water deficits (Johnson *et al.*, 1992; Larson *et al.*, 1988), whereas in apricot (Torrecillas *et al.*, 2000) and almond (Goldhamer and Viveros, 2000) drought reduced yield in the following year due to decreased flowering and fruit set.

The effects of water restrictions have not been investigated extensively in young deciduous orchards where possible reductions in trunk and root growth due to post-harvest droughting may have a greater impact on

future orchard productivity. The objective of this work was to study the effects of RDI applied before or after harvest in young Japanese plum trees, and RDI during both periods on vegetative growth, flowering, fruit set and fruit size, with the aim of comparing its impacts on short- and long-term orchard productivity.

MATERIAL AND METHODS
Experimental plot

The experiment was performed over 4 consecutive years (2000-2003), in a commercial Japanese plum orchard (*Prunus salicina* cv. 'Black Gold' grafted on 'Mariana GF81' rootstocks) at Líria, Valencia, Spain, (40°N, elevation 300m). The soil was a sandy loam, 32% (w/w) stones, with an effective depth of 80 cm. The irrigation water had an average electrical conductivity of 1.1 dS m^{-1} and an average Cl^- ion concentration of 122 mg l^{-1}. Trees were planted in 1997 at a spacing of 5 × 3.5 m. *P. salicina* cvs. 'Black-Diamond' and 'Black-Amber' were planted in guard rows as pollinators. 'Black-Gold' flowers in late February, with 300–400 flowers m^{-1} of branch, and 25–30% fruit set. About 95% of fruit are removed in an effort to obtain good fruit size. At the beginning of the experiment, the trees had an average trunk circumference of 0.23 m, with the canopy shading 12% of the ground area.

The trees received 150, 33 and 145 kg ha^{-1} $year^{-1}$ of N, P and K, respectively. Agricultural practices were those common for the area. Fruit was thinned in April to provide 300–400 fruit per tree. However, in 2000 and 2002, some treatments had lower or higher crop loads because of irregularities in the hand-thinning procedure. Weather was recorded at an automated weather station

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near the orchard. During the irrigation season, seasonal precipitation and reference evapotranspiration (ET_o), calculated from the Penman-Monteith equation using hourly data according to Allen *et al.* (1998), were (respectively): 375 mm and 1022 mm in 2000; 220 mm and 805 mm in 2001; 406 mm and 897 mm in 2002; and 387 and 912 mm in 2003.

Treatments

Drip irrigation was applied with four emitters per tree in 2000 and 2001, and six emitters per tree in 2002 and 2003, delivering 3.85 l h^{-1} and located in a double line, parallel to each tree row. Treatments were: (i) control trees irrigated at 100% of estimated crop evapotranspiration (ET_c) over the whole season; (ii) trees irrigated at 33% (33-I) or 66% (66-I) ET_c, respectively, during Period I, from pit hardening in mid-May to harvest in early July and at 100% ET_c for the rest of the season; (iii) trees irrigated at 100% ET_c until harvest and from then until the end of the season (Period II), irrigated at 33% (33-II) or 66% (66-II) ET_c, respectively; and (iv) trees irrigated at 66% ET_c during period I and II (66-I+II), from pit hardening to the end of the season in late October.

Crop evapotranspiration, was estimated as the product of ET_o and the crop coefficient (K_c), obtained from Doorenbos and Pruitt (1977) and adjusted for tree size (Fereres and Goldhamer, 1990). Average K_c was 0.15 during 2000 and 2001, 0.2 in 2002, and 0.3 in 2003. Reductions in the amount of water applied during the deficit treatments were achieved by reducing the duration of irrigation, with all treatments irrigated once a week in early Spring and Autumn, and 4 times a week during Summer.

The experimental design was a randomised complete block, with three replicates per treatment. Each plot had three rows, with eight trees per row. The six central trees of the middle row were used for data collection.

Tree water relations

Stem water potential (Ψs) (McCutchan and Shackel, 1992) was measured with a pressure chamber (Soil Moisture Equipment Corp., Model 5100A), with 4 leaves from 2 trees per treatment. Mature, northern-facing leaves were enclosed in plastic bags covered with silver foil 2 h before measurements. Measurements were taken (Turner, 1981), between 1200h and 1300h approx. every 2 weeks from April to October. The water stress integral ($\Sigma\Psi s$) in MPa days (MPa d)(Myers, 1988), was calculated as:

$$\Sigma\Psi s = \sum_{i=1}^{i=1} (\Psi s_{i,i+1} - c)\, n$$

Where $\Psi s_{i,i+1}$ is the Ψs value at the end of each interval $i, i+1$; $c = -0.3$ MPa, the maximum Ψs during the study, and n is the number of d in the interval.

Yield determination

Fruit from each tree was harvested and the average fruit weight and fruit number per tree were determined using a commercial grading machine (Fomesa SA, Spain). Relative crop load was calculated as the number of fruit per tree per unit of trunk cross-sectional area (TCSA).

Tree growth

Trunk perimeter was measured about 0.2 m above the ground on each tree in early Spring, after harvest, and after leaf fall. Relative trunk growth (RTG) was then calculated as Δtrunk perimeter/initial trunk perimeter. Tree-shaded area (SA) was measured on each tree in 2000, 2001, 2003 and on 2 trees per plot in 2002, at the end of the irrigation season, during September, using a point grid method (Wünsche *et al.*, 1995). A plastic sheet with grid points spaced 50 × 50 cm was laid under the canopy, and the percentage of shaded area of each grid point estimated. Total tree-shaded area was calculated and corrected for solar elevation.

Flowering and fruit set

The number of flowers per unit branch length, just before anthesis, was recorded on 4 branches per tree, with three replicates. Fruit set was estimated before thinning by counting the number of fruit on the sames branches used for flowering.

Statistical analysis

For all variables, except Ψs, analysis of variance was performed separately each year, according to a complete randomised block design with six treatments, also considering the block by treatment interaction, whereas Ψs was analysed using a one-way ANOVA. Dunnett's test for comparison of means against a control used the 'glm' procedure (SAS Institute, 1994). At the beginning of the experiment, there were differences in average tree trunk perimeter in the treatments, hence this factor was included as a co-variant in the analysis of yield and tree-shaded area. Average fruit weight was analysed, with crop load as co-variant, giving an adjusted mean fruit weight (Steel and Torrie, 1980).

RESULTS
Water relations

Average Ψs differed across years (Table I). There was reduction in Ψs toward the end of the season, even in the controls which had average Ψs of -0.7 to -1.2 MPa during fruit growth and -1.2 to -1.8 MPa after harvest. Before harvest, treatments '66-I', '66-I+II', and in particular '33-I', had generally lower average Ψs than the controls, with a minimum of about -2.0 MPa, except in 2002 when '33-I' did not reach -1.5 MPa (data not shown). After-harvest average Ψs in the drought treatments were about -1.6 to -2.2 MPa (Table I).

TABLE I
Average Ψs (MPa) in the different Periods under different (deficit) irrigation treatments

Year	Control	'33-I'	'66-I'	'33-II'	'66-II'	'66-I+II'
		Fruit growth (Period I) Ψs				
2000	−1.18	−1.31	−1.36	−	−	−
2001	−1.16	−1.24	−1.14	−	−	−1.39*
2002	−0.73	−0.84*	−0.72	−	−	−0.71
2003	−0.99	−1.26*	−1.14*	−	−	−1.18*
		Post–harvest (Period II) Ψs				
2000	−1.22	−	−	−1.62*	−1.70*	−1.60
2001	−1.80	−	−	−1.92	−2.11*	−2.37*
2002	−1.29	−	−	−1.57*	−1.47*	−1.48*
2003	−1.19	−	−	−1.52*	−1.32*	−1.38*

Values are averaged over each period.
Asterisks indicate significant differences with respect to control based on Dunnett's test at $P < 0.05$.

Water applications (mm) in the various treatments, with (%) savings[a] compared to controls in parentheses

Year	Control	'33-I'	'66-I'	'33-II'	'66-II'	'66-I+II'
2000	211	165 (22)	183 (13)	156 (26)	183 (13)	145 (31)
2001	207	182 (12)	197 (5)	140 (32)	182 (12)	152 (27)
2002	234	196 (16)	208 (11)	161 (31)	185 (21)	160 (32)
2003	301	214 (29)	254 (16)	219 (27)	247 (16)	211 (30)
Mean	238	189 (21)	210 (12)	169 (29)	199 (16)	167 (30)

[a]Defined as: 1–irrigation in the treatment/irrigation in the control × 100

Drought before harvest

Drought before harvest led to water savings of 21% and 12%, in '33-I' and '66-I' trees respectively, compared with control plots (Table II). However, in 2003, when fruits were harvested later, on July 21, the water saving in '33-I' was 29%.

Average fruit weight decreased with drought (Table III). Fruit weight in '33-I' was lower than in the control, except in 2002 where a milder water deficit was achieved. After the 4 years of drought in Period I there was a clear reduction in fruit weight in '33-I' and '66-I' (Figure 1), and in total crop yield in '33-I'.

Deficit irrigation during Period I did not affect flowering or fruit set in the following year (Table IV).

RTG before harvest decreased in '33-I' in all seasons compared with the controls, and in '66-I' in 2001 (Table V). Across the treatments, there was a weak relationship between RTG and integrated Ψs (Figure 2). RTG after harvest in '33-I' and '66-I', in 2002, was significantly ($P < 0.05$) higher than in the control (Table V). There was a compensation in growth in Period II when 100% ET_c was applied to droughted trees. Over the 4 years, there was an average reduction of 15% in RTG in the more severe treatment ('33-I').

Effect of irrigation on yield, crop load, adjusted fruit weight and trunk perimeter at the beginning of each season and on tree-shaded area (SA) at the end of each season

Year	Control	'33-I'	'66-I'	'33-II'	'66-II'	'66-I+II'
			Yield (kg tree^{-1})			
2000	26.8	29.1	29.4	28.1	37.9*	25.9^T
2001	20.3	19.2	22.7	20.5	20.6	16.8^T
2002	23.6	20.8	20.9	16.4*	23.2	18.1^T
2003	38.4	30.4*	38.1	34.9	34.8	32*^{T}
		Crop load (No. fruit per unit TCSA)				
2000	7.9	9.9	10.0	8.8	13.6*	9.3
2001	6.2	6.3	6.8	6.5	6.4	5.9
2002	5.0	4.8	5.0	4.0	5.4	4.9
2003	4.7	4.9	5.8*	4.7	4.7	5.3
			Av. fruit wt. (g)			
2000	80.9	70.8*	74.9	78.8	69.8*	70.1*
2001	63.1	58.3*	61.7	62.3	66.0*	59.8*
2002	70.5	69.2	67.8	71.8	72.6	68.3
2003	104.7	83.1*	94.1*	105.4	103.8	94.5*
		Trunk perimeter (mm)				
2000	234	231	225	230	227	219*
2001	260	259	258	254	249*	236*
2002	296	281*	283*	279*	277*	260*
2003	319	304*	310*	298*	297*	278*
		Shaded area (m^2 tree^{-1})				
2000	2.1	2.1	2.2	2.0	2.1	2.0
2001	3.4	3.1	3.3	3.4	3.3	2.8*^{T}
2002	4.4	3.6	4.6	3.5	3.9	3.9
2003	5.2	3.9*	4.4*	4.0*	4.5*	3.8*^{T}

Data are means of 18 trees per treatment except for SA in 2002 which is mean of 6 trees per treatment.
Asterisks indicate significant differences with respect to control based on Dunnett's test at $P < 0.05$.
^{T}Indicates that the effect of the combined stress period is different from the sum of the individual periods based on contrasts at $P < 0.05$.
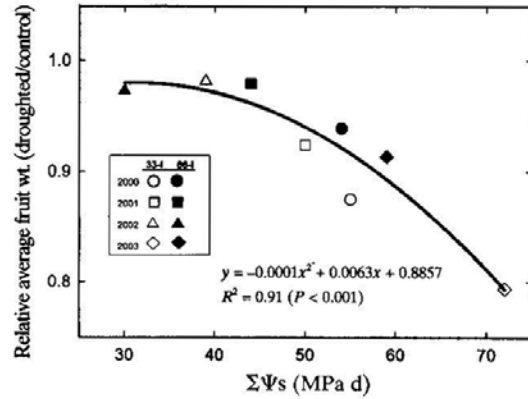
The relationship between relative average fruit weight (droughted/control) and $\Sigma\Psi$s before harvest for treatments '33-I' and '66-I'. Values are averages for each treatment over 4 years (n = 8).

Drought after harvest

Water restrictions after harvest gave greater water savings than those achieved before harvest (Table II). Treatment '33-II' provided an average saving of 29% compared with the control.

Yield in '33-II' was not affected by deficit irrigation, except in 2002 when it was lower (Table III). Yield in '66-II' was also unaffected by droughting in Period II, except in 2000 when it was higher than the control due to lower fruit-thinning and therefore higher crop load. Because of the higher crop load in 2000, treatment '66-II' had lower average fruit weight (Table III) and RTG before harvest (Table V), since the deficit irrigation was applied only after harvest in the first year. Average relative fruit weight was not related to the integrated Ψs in Period II in the former season ($P > 0.05$).

Average RTG over the four seasons decreased with deficit irrigation after harvest (Table V). Tree-shaded area, was also lower with droughting in the last season (Table III). Deficit irrigation decreased canopy size slightly each year, with a significant cumulative effect in 2003.

Effect of irrigation on flowering, fruit set and number of fruit harvested

Year	Control	'33-I'	'66-I'	'33-II'	'66-II'	'66-I+II'
		No. Flowers cm^{-1} of branch				
2000	2.1	2.1	2.6	2.6	2.1	2.6
2001	5.6	6.3	4.7	5.4	4.9	5.4
2002[a]	–	–	–	–	–	–
2003	3.0	2.5	2.5	2.7	2.6	2.6
			Fruit set (% flowers)			
2000	20.8	20.1	26.2	25.7	20.8	21.4
2001	27.5	20.3	29.6	25.7	20.8	25.9
2002[a]	–	–	–	–	–	–
2003	35.1	36.9	36.2	30.4	30	30.8
		No. Fruit harvested tree^{-1}				
2000	343	417	414	367	557*	355
2001	334	339	363	335	311	264
2002[a]	349	305	308	235*	322	264*
2003	383	369	419	337	331	322

[a]Flowering and fruit set rates were not determined in 2002.
Data are means of 12 trees per treatment for flowering and fruit set, and 18 trees per treatment for the number of fruit harvested.
Asterisks indicate significant differences with respect to control based on Dunnett's test at $P < 0.05$.

TABLE V
Effect of irrigation on relative trunk growth[a] (%)

Year	Control	'33-I'	'66-I'	'33-II'	'66-II'	'66-I+II'
			Period I			
2000	6.3[b]	3.9*	4.9	7.3	4.4*	4.3*
2001	5.7	2.4*	2.3*	4.5	6.6	5.0
2002	3.1	2.1*	2.6	2.8	2.6	2.7
2003	3.4	2.1*	2.6	4.1	4.1	3.0
			Period II			
2000	6.0	4.7	5.8	2.8*	4.1*	3.3*
2001	4.1	3.1	4.1	2.5*	2.1*	2.8*
2002	4.6	5.9*	6.4*	3.8	4.4	2.9*
2003	2.5	2.9	3.1	1.3*	1.0*	1.5*
			Seasonal			
2000	12.7	8.8*	10.9	10.4	8.6*	7.8*T
2001	9.9	5.6*	6.5*	7.2*	8.8	7.3*
2002	7.9	8.2	9.2	6.7	7.1	5.7*T
2003	6.0	4.9	5.8	5.4	5.2	4.6*T
			Total (2000-2003)			
	45.0	38.3*	45.3	36.9*	38*	32.5*T

[a]Calculated as (final-initial) × 100/initial values of trunk perimeter recorded for each period.
[b]Data are means of 18 trees per treatment.
Asterisks indicate significant differences with respect to control based on Dunnett's test at $P < 0.05$.
[T]Indicates that the effect of the combined stress period was different from the sum of the individual periods based on contrasts at $P < 0.05$.

Water stress after harvest did not effect flowering or fruit set following year (Table IV).

Drought before and after harvest
Treatment '66-I+II', had a milder, but longer duration of drought, and gave the highest (30%) water saving (Table II). Yield was lower than the control only in 2003 (Table III). Average fruit weight in '66-I+II' was lower than the controls in three out four seasons (Table III). Average RTG in '66-I+II' was 28% lower than controls (Table V), and greater than the summed reduction of '66-I' and '66-II'.

Flowering and fruit set were not affected by this treatment compared with controls (Table IV).

DISCUSSION
Ψs in our control trees are similar to those reported by Lampinen *et al.* (2001) and Naor *et al.* (2004), but lower than those reported by McCutchan and Shackel (1992) for prune trees with the entire orchard floor irrigated. Thus tree water status is lower when only part of the orchard soil is irrigated. According to Lampinen *et al.* (2001) this is due to the greater proportion of roots in the dry part of the soil, particularly towards the end of the season.

Drought during fruit growth, saved up to a 29% of normal water use, but reduced fruit size. This shows that Phase III of fruit growth, is highly sensitive to water deficits, as observed in peach (Naor *et al.*, 2001), apricot (Torrecillas *et al.*, 2000) and Japanese plum (Naor, 2004; Naor *et al.*, 2004). However, a moderate deficit equivalent to a Ψs < -1.5 MPa and $\Sigma \Psi$s < 40 MPa d ('33-I' in 2002) did not affect fruit growth.

Average fruit weight was correlated with $\Sigma \Psi$s (Figure 1) as in apple (Ebel *et al.*, 2001). Thus Ψs appears to be a useful tool for irrigation scheduling, as previously found in plum (Intrigliolo and Castel, 2004; Naor, 2004) and in other deciduous trees (Naor, 2000; Shackel *et al.*, 1997).

Water deficit after harvest did not effect flowering, fruit set or fruit growth the next season, even in the '33-II' treatment. In early maturing peach, yield and fruit
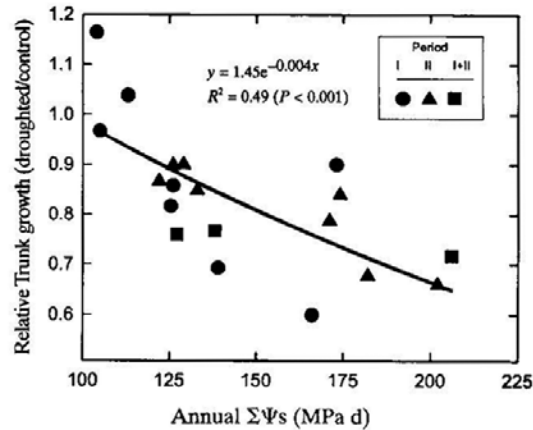

FIG. 2
The relationship between relative seasonal trunk growth (droughted/control) and seasonal $\Sigma \Psi$s. Values are average for each treatment and year (n = 23). Ψs for treatment '66-I+II' in 2000 was not calculated

size were not affected by progressive water restrictions after harvest (Johnson *et al.*, 1992; Larson *et al.*, 1988). In plum, there was a decrease in yield with decreasing average Ψs in the previous year, but no effect on fruit weight (Johnson *et al.*, 1994), probably due to a more severe water deficit.

In the present work, a post-harvest drought reduced RTG and canopy area, leading, in 2003, to smaller trees with fewer fruit per tree for a similar crop load; and, as a consequence, to a slightly (10%) but not significantly reduced yield compared to controls (Tables III and IV). It can be concluded that several seasons of drought after harvest could reduce the productivity of young trees, as a consequence of the cumulative effect of water deficit on tree growth.

A small reduction in trunk and canopy growth in fruit trees will be associated with only a small yield loss. However, the smaller trees provide for easier harvest, pruning and fruit thinning, with potential cost-savings for producers. In modern fruit production, new cultivars and orchards have a short life. Thus RDI offers scope for closer tree spacing.

The '33-II' and '66-I+II' trees had similar water savings (30%), although yield and tree growth were lower under the more severe watering regime of '66-I+II' (Tables III and V). Therefore, RDI applied only after harvest can reduce tree size with only a small effect on productivity.

In other *Prunus* species, such as almond (Goldhamer and Viveros, 2000) and apricot (Torrecillas *et al.*, 2000), water deficit after harvest reduced yield because of an impact on flowering or fruit set the next season. However, this strategy may not necessarily lead to lower production in plum because heavy fruit thinning is usually required to obtain acceptable fruit weight.

In plum, flower initiation occurs just after harvest in late July to early August (Faust, 1989). In the present work, drought after harvest was imposed gradually and therefore the lowest Ψs were reached at the end of the season, after bud differentiation. 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 peach, water deficit after harvest has been found to increase the number of double fruit (Johnson *et al.*, 1992) or fruit with a "deep suture" (Handley and Johnson, 2000), but none of these disorders were observed in our experiment. Johnson *et al.* (1994) reported similar results in Japanese plum cvs. 'Red Beaut', 'Ambra' and 'Durado' and the same with cv. 'Black-Amber' (A. Naor, personal communication). These results indicate that these disorders are not common in Japanese plum.

Drought can reduce trunk growth. This response was predicted by the annual $\Sigma\Psi$s (Figure 2), as recorded by Shackel *et al.* (1997) in almond. Crop load also influenced trunk growth, with a clear effect of treatment '66-II' in 2000. This treatment reduced RTG during fruit growth, due to its higher crop load and greater fruit to shoot growth competition. In peach, Berman and DeJong (2003) reported a similar effect of the crop on shoot growth. This suggests that crop load should be controlled when tree canopy is not fully developed.

CONCLUSIONS

Mid-season maturing Japanese plum trees showed different sensitivities to water deprivation depending upon the phenological Period. Water restriction during fruit growth reduced fruit size in proportion to the severity of water stress achieved. Post-harvest droughting, despite reducing tree size, had no detrimental effects on flowering, fruit set or fruit growth and, after 3 years, did not significantly reduce yield. Droughting based on a moderate but continuous reduction of irrigation rates from Phase II of fruit growth until the end of the season is not recommended as fruit size may be reduced together with severe reductions of tree growth.

REFERENCES

ALLEN, R. G., PEREIRA, L. S., RAES, D. and SMITH, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper* **56**, Rome, Italy. 15–27.

BEHBOUDIAN, M. H. and MILLS, T. M. (1997). Deficit irrigation in deciduous orchards. *Horticultural Reviews*, **21**, 125–31.

BERMAN, M. E. and DEJONG, T. M. (2003). Seasonal patterns of vegetative growth and competition with reproductive sinks in peach (*Prunus persica*). *Journal of Horticultural Science & Biotechnology*, **78**, 303–9.

CHALMERS, D. J., MITCHELL, P. D. and VAN HEEK, L. (1981). Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. *Journal of the American Society for Horticultural Science*, **106**, 307–12.

DOORENBOS, J. and PRUIT, W. O. (1977). Crop water requirements. *FAO Irrigation and Drainage Paper* **24**, Rome, Italy, 49.

EBEL, R.C., PROEBSTING, E. L. and EVANS, R. G. (2001). Apple tree and fruit responses to early termination of irrigation in a semi-arid environment. *HortScience*, **36**, 1197–201.

FERERES, E. and GOLDHAMER, D. A. (1990). Deciduous fruit and nut trees. In: *Irrigation of Agricultural Crops* (Stewart, B. A. and Nielsen, D. R., Eds.). A.S.A. Monograph, Madison, Wisconsin, USA. **30**, 987–1017.

FAUST, M. (1989). Fruiting. In: *Physiology of Temperate Zone Fruit Trees*. Wiley-Interscience Publication, New York, USA. 169–88.

FLORE, J. A. (1994). Stone fruit. In: *Handbook of Environmental Physiology of Fruit Crops. Vol I. Temperate Crops*. (Schaffer, B. and Andersen, P. C., Eds.) CRC Press Inc., Boca Raton, Florida, USA. pp. XXX–XX

GIRONA, J., MATA, M., ARBONES, A., ALEGRE, S., RUFAT, J. and MARSAL, J. (2003). Peach tree response to single and combined regulated deficit irrigation regimes under shallow soils. *Journal of the American Society for Horticultural Science*, **128**, 432–40.

GOLDHAMER, D. A. and VIVEROS, M. (2000). Effects of preharvest irrigation cutoff durations and postharvest water deprivation on almond tree performance. *Irrigation Science*, **19**, 125–31.

HANDLEY, D. F. and JOHNSON, R. S. (2000). Late summer irrigation of water stressed peach tress reduces fruit double and deep sutures. *HortScience*, **35**, 771.

INTRIGLIOLO, D. S. and CASTEL, J. R. (2004). Continuous measurement of plant and soil water status for irrigation scheduling in plum. *Irrigation Science*, **23**, 93–102.

JOHNSON, R. S. and HANDLEY, D. F. (2000). Using water stress to control vegetative growth and productivity of temperate fruit trees. *HortScience*, **35**, 1048–50.

JOHNSON, R. S., HANDLEY, D. F. and DEJONG, T. M. (1992). Long-term response of early maturing peach trees to postharvest water deficits. *Journal of the American Society for Horticultural Science*, **117**, 881–6.

JOHNSON, R. S., HANDLEY, D. F. and DAY, K. R. (1994). Postharvest water stress of an early maturing plum. *Journal of Horticultural Science & Biotechnology*, **69**, 1035–41.

LAMPINEN, B. D., SHACKEL, K. A., SOUTHWICK, S. M. and OLSON, B. (2001). Deficit irrigation strategies using midday stem water potential in prune. *Irrigation Science*, **20**, 47–54.

LARSON, K. D., DEJONG, T. M. and JOHNSON, R. S. (1988). Physiological and growth response of mature peach trees to post-harvest water stress. *Journal of the American Society for Horticultural Science*, **113**, 296–300.

LI, S. H., HUGUET, J. G., SCHOCH, P. G. and ORLANDO, P. (1989). Responses of peach tree growth and cropping to soil water deficit at various phenological stages of fruit development. *Journal of Horticultural Science*, **64**, 541–52.

McCUTCHAN, H. and SHACKEL, K. A. (1992). Stem water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. 'French'). *Journal of the American Society for Horticultural Science*, **117**, 607–11.

MITCHELL, D. and CHALMERS, D. J. (1982). The effect of reduced water supply on peach tree growth and yields. *Journal of the American Society for Horticultural Science*, **107**, 853–6.

MYERS, B. J. (1988). Water stress integral. A link between short-term stress and long-term growth. *Tree Physiology*, **4**, 315–23.

NAOR, A. (2000). Midday stem water potential as a plant water stress indicator for irrigation scheduling in fruit trees. *Acta Horticulturae*, **537**, 447–54.

NAOR, A. (2004). The interaction of soil- and stem-water potential with crop level, fruit size and stomatal conductance of field-grown 'Black-Amber' Japanese plum. *Journal of Horticultural Science & Biotechnology*, **79**, 273–80.

NAOR, A., HUPERT, H., GREENBLAT, Y., PERES, M., KAUFMAN, A. and KLEIN, I. (2001). The response of nectarine fruit size and midday stem water potential to irrigation level in stage III and crop load. *Journal of the American Society for Horticultural Science*, **126**, 140–3

NAOR, A., PERES, M., GREENBLAT, Y., GAL, Y. and BEN AIRE, R. (2004). Effects of pre-harvest irrigation regime and crop level on yield, fruit size distribution and fruit quality of field grown 'Black Amber' Japanese plum. *Journal of Horticultural Science & Biotechnology*, **79**, 281–8.

SAS INSTITUTE (1994). *SAS/STAT User's Guide.* SAS Inst. Inc., Cary, NC, USA.

STEEL, G. D. and TORRIE, J. H. (1980). *Principles and Procedures of Statistics.* McGraw-Hill, XXXX, XXX. 401-37.

SHACKEL, K. A., AHMADI, H., BIASI, W., BUCHNER, R., GOLDHAMER, D., GURUSINGHE, S., HASEY, J., KESTER, D., KRUEGER, B., LAMPINEN, B., MCGOURTY, G., MICKE, W., MITCHAM, E., OLSEN, B., PELLETRAU, K., PHILIPS, H, RAMOS, D., SCHEANKL, L., SIBBERT, S., SNYDER, R., SOUTHWICK, S., STEVENSON, M., THORPE, M., WEINBAUM, S. and YEAGER, J. (1997). Plant water status as an index of irrigation need in deciduous fruit trees. *HortTechnology*, **7**, 23-9.

TORRECILLAS, A., DOMINGO, R., GALEGO, R. and RUÍZ-SÁNCHEZ, M. C. (2000). Apricot tree response to withholding irrigation at different phenological periods. *Scientia Horticulturae*, **85**, 201-15.

TURNER, N. C. (1981). Techniques and experimental approaches for the measurement of plant water status. *Plant and Soil*, **58**, 339-66.

VAN SCHILGARDE, J. (1994). Irrigation a blessing or a curse? *Agricultural Water Management*, **25**, 203-19.

WÜNSCHE, J. N., LAKSO, A. N. and ROBINSON, T. L. (1995). Comparison of four methods for estimating total light interception by apple trees of varying form. *HortScience*, **30**, 272-6.

3.- Effects of crop load and deficit irrigation on water relations, vegetative growth, yield and fruit quality of plum trees

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Running head: Crop loads and deficit irrigation effects on plum

Summary We investigated the effects of a combination of two different crop load (CL) levels (low, commercial CL, and high), with three different irrigation strategies, on plum water relations, tree growth and fruit size and quality. Deficit irrigation strategies, compared to fully watered trees, were both based on monitoring plant water status. In the '-1.5MPa' treatment, moderate deficit irrigation was applied until harvest; whereas in the 'St-Rec' there was a more severe water restriction during stage II and the first part of phase III of fruit growth, and water was returned at full dosage 25 days before harvest. On average for the two deficit irrigated strategies, the more cropping trees, required 9% more water applied, compared to the low cropping ones, to be kept at similar plant water status.

In well-watered plants, high CL increased stomatal conductance, particularly during the last phase of fruit growth. Despite that, stem water potential was not different between crop loads, whereas considerable differences were observed for the maximum diurnal trunk shrinkage (MDS). This higher sensitivity of MDS to CL is probably due to both the increase in transpiration rates and the lower trunk growth of the heavy cropping trees.

Deficit irrigation reduced both fruit and vegetative growth, however, the 'St-Rec' treatments affected more canopy growth than the '-1.5MPa' ones, due to the different timing in water deficit application. Fruit size, was similarly reduced by both deficit irrigation strategies, since they had similar integrated water stress. Fruit ripening was only advanced in the 'St-Rec', which led to softer and sweeter fruits, probably due in part to higher light interception of the interior part of the canopy. This increased fruit quality was also maintained during cold storage.

High CL, reduced fruit growth and decreased fruit quality, and also affected the vegetative growth with greater effects on trunk growth than on canopy growth. Deficit irrigation similarly reduced fruit size in both crop loads, but trunk growth was only severely

affected by water restrictions in the high CL level. This was probably due to a source limitation derived from the combined effect of high CL and water deficit, and not to an effect of CL on lowering plant water status, because the higher cropping deficit irrigated trees had the same water status than those with light crop load.

Introduction

Crop load (CL) and irrigation are the main factors that affect short term stone fruit tree productivity (Naor et al. 1999, Naor et al. 2004).

High CL is known since long to reduce fruit growth (Weinberger 1931), and it may also affect the growth of other organ sinks (Flore and Layne 1997). These effects are probably due to an increased competition for photoassimilates among fruit themselves and also, between the fruit and other organs simultaneously developing (Grossman and DeJong 1994). In peach, high cropping trees have generally reduced vegetative growth (Grossman and DeJong 1995a, Berman and DeJong 2003) and root growth (Chalmers and Van Den Ende 1975).

CL may also affect tree water relations, either by increasing transpiration rates (Hansen 1971, Chalmers et al. 1983) as a consequence of an increased assimilate demand, or by reducing water uptake due to restricted root growth. The effects of CL on leaf (DeJong, 1986a) or stem (Naor et al. 2001, Naor 2004) water potential, stomatal conductance (DeJong 1986a,), leaf photosynthesis (DeJong 1986b, Gucci et al. 1994) and fruit water relations (McFayden et al. 1996) have been studied. However, there is a lack of information about effects of CL on daily trunk diameter variations (TDV). In this sense, CL may affect TDV not only by increasing transpiration rates, but also by directly affecting trunk growth. Therefore, in order to use TDV in stone fruit tree irrigation management, it is deemed necessary to evaluate the effects of CL on TDV.

Deficit irrigation, particularly when applied during the last linear phase of fruit growth, normally reduces fruit growth (Li et al. 1989, Naor et al. 2004). In a previous work (Intrigliolo and Castel 2005), we identified a threshold value of plant water stress (-1.5 MPa

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of stem water potential and 45 MPa·day of integrated water stress) that did not reduce fruit size, even when water deficit was applied during stage III of fruit growth.

Since there is evidence that high CL may enhance the sensitivity of fruit growth to water stress (Goode et al. 1978, Berman and DeJong 1996, Girona et al. 2004), we thought necessary to check the validity of our previous threshold water stress values for higher CL.

The interaction between CL and deficit irrigation has been investigated for fruit fresh and dry weight (Berman and DeJong 1996, Girona et al. 2004), yield and fruit size (Naor et al. 1999, Naor et al. 2004) and plant water status (Berman and DeJong 1996, Naor 2004), but there is less information on the possible interaction of both factors on seasonal trunk growth. The objectives of our work were to study the responses of plum trees to different CL levels, in combination with moderate deficit irrigation strategies, and their possible interaction on: i) tree water relations, including TDV, ii) vegetative growth, iii) fruit growth and iv) fruit quality at harvest and after cold storage.

Material and methods

Experimental plot and climatic conditions

The experiment was performed during the 2004 season in a commercial Japanese plum orchard (*Prunus salicina*, 'Black Gold' grafted on 'Mariana GF81' rootstock) at Líria, Valencia, Spain, (39º 45'N, 0 38'º W, elevation 300 m). The soil was a sandy loam 32% (w/w) stones, with an effective depth of 80 cm. The irrigation water had an average EC of 1.1 dS m^{-1} and an average Cl$^-$ concentration of 122 mg l^{-1}. Trees were planted in 1997 at a spacing of 5 x 3.5 m. *Prunus salicina* 'Black-Diamond' and 'Black-Amber' were planted in guard rows as pollenizers. At the beginning of the experiment, percentage of shaded area

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and trunk circumference were 29% and 0.32 m, respectively. The trees received 150-33-145 kg ha^{-1} year^{-1} of N, P and K, respectively. Agricultural practices followed were those common for the area. Fruit were manually thinned at the end of April, when the different crop load levels were established.

Weather was recorded at an automated meteorological station near the orchard and daily average air vapour pressure deficit (VPD) and daily reference evapotranspiration (ETo) were calculated according to Allen et al. (1998). During the experimental period, (March to July), precipitation and ETo were respectively 275 and 503 mm, however during June and July precipitation was only 17 mm.

Treatments

Treatments were a factorial combination of three irrigation strategies, and two crop loads levels. Crop levels were: low (L, commercial CL, with 4 to 5 fruits cm^{-2} of trunk cross sectional area, TCSA), and high (H, 7 to 8 fruits cm^{-2} of TCSA). Thus, the six treatments were: i) two irrigated at 100% of estimated crop evapotranspiration (ETc) '100-L' and '100-H', ii) two deficit irrigated '-1.5MPa-L' and '-1.5MPa-H' where irrigation rates were reduced in order to allow a progressive decline towards harvest of midday stem water potential (Ψs) to -1.5MPa, and iii) 'St-Rec-L' and 'St.Rec-H' where irrigation rates were reduced in order to allow a sharper decline on Ψs to -1.5MPa and after that, irrigation applied was progressively, in one week, returned at 100% ETc.

Trees were drip irrigated with six emitters per tree, each delivering 3.85 l h^{-1} and located in a double line parallel to the tree row. Irrigation frequency was the same for all treatments and varied from once a week in early spring to six times a week during July. Crop

evapotranspiration, was estimated as the product of ETo and crop coefficient (Kc), obtained from Doorenbos and Pruitt (1977) and adjusted for tree size (Fereres and Goldhamer 1990).

The experimental design was a factorial of three irrigation regimes and two crop loads with three replicates per treatment. Each plot had three rows, with eight trees per row. The six central trees of the middle row were used for data collection of yield and growth determinations, while the two central trees were used for water relations.

Water relations

Matric soil water potential (Ψm), was measured with eight granular matrix sensors per treatment only on treatments '100-L', '100-H', '-1.5MPa-L' and 'St-Rec-L', according to procedures described by Intrigliolo and Castel (2004).

Midday stem water potential (Ψs) was measured with a pressure chamber, following procedures described by Turner (1981). Two leaves per tree on two trees per treatment were determined. Mature leaves from the north face near the trunk, were enclosed in plastic bags covered with silver foil at least two hours prior to the measurements, which were carried out between 12:00 and 13:00 h solar time. The water stress integral ($\Sigma\Psi$s) was calculated from the determinations of Ψs as reported in Myers (1988).

Stomatal conductance (Gs) was determined, in the same plants used for Ψs measurements, on five fully expanded sun-facing leaves per plant. Measurements were performed around solar midday using a dynamic diffusion porometer (AP4, Delta-T Devices, Cambridge, UK).

The variations of tree trunk diameter (TDV) were measured continuously following procedures described by Intrigliolo and Castel (2004), only on treatments '100-L', '100-H',

'-1.5MPa-L' and 'St-Rec-H'. Linear variable differential transformers (LVDT, Schlumberger Mod. DF-2.5) were installed, in the main trunk of six trees of similar size per treatment, at about 20 cm from the ground on the north side by a metal frame of Invar (a metal alloy with a minimal thermal expansion). From TDV we calculated three different indexes: maximum daily trunk diameter (MXTD), trunk growth rate (TGR) as the difference between the MXTD of two consecutive days, and maximum daily shrinkage (MDS), obtained as the difference between the maximum diameter reached early in the morning and the minimum reached normally during the afternoon.

Vegetative growth

Trunk circumference was measured in early spring and after harvest at marked sections located about 0.2 m above the ground on each tree. Relative trunk growth (RTG) was then calculated as Δtrunk perimeter/initial trunk perimeter.

Tree shaded area (SA) was measured by a point grid method (Wünsche et al. 1995) on each tree after harvest. A plastic sheet with grid points spaced at 50 X 50 cm was laid under the canopy, and percentage of shaded area of each grid estimated. Total tree shaded area was calculated and corrected for solar elevation.

The percentage of photosynthetically active radiation (PAR) reaching the internal part of the canopy (RAD) was measured by means of an Accupar Linear PAR Ceptometer (Decagon Devices, Inc., Pullman, Wash.). On each experimental tree, just after harvest, two measurements of incident PAR were performed on both sides of tree row at 80 cm from tree trunk and at 100 cm height from the ground. RAD was then calculated considering the PAR radiation at full sun exposure.

Yield

Fruit from each tree were individually harvested in two commercial picks, on 13th and 19th July. The percentage of fruit collected in the first pick (1FC) was then obtained, and used as a maturity earliness variable. Average fruit weight (FW), was obtained using a commercial grading machine (Fomesa SA, Spain) and relative crop load, was calculated as the number of fruit per tree per unit of TCSA, .

Fruit quality

Two samples of 50 fruits from each plot, six independent samples per treatment, were used for fruit quality assessment. Fruit were randomly selected from those collected during the first harvest and half were used for determination of fruit quality at harvest, while the other half, was stored during 14 days at 4°C and 82% RH for determination of post-harvest quality. Flesh firmness (FF) was obtained with an 8 mm tip fruit pressure tester using two measurements per fruit from two opposite peeled sides.

Juice was extracted from combined samples of longitudinal unpeeled slices from each fruit of the sample. Total soluble solids concentration (TSS) was determined with a temperature compensated digital refractometer (Atago, Co., Japan) and tritable acidity (TA) by tritating to an end point, pH 7.0, with a 0.1M NaOH and expressed as g malic acid l^{-1}. Dry matter fraction (DM) (dry weight/fresh weight) was determined at harvest in a sample of 25 fruits per treatment collected from those of the first pick. Each fruit was weighed, and dried at 65°C in a forced air draft oven, and dry weight recorded.

Statistical analysis

The effects of irrigation and crop load on yield, yield components, vegetative growth and fruit quality were analysed as a factorial ANOVA with irrigation, crop load and blocks as main factors, also exploring the significance of the irrigation x crop load interaction. Dunnett's test for means comparisons against the control ('100' for irrigation and 'low' for crop load) was carried out using the 'glm' procedure (SAS Institute 1994).

Since there were differences in the crop load of the different irrigation strategies, FW, RTG, SA and RAD, were analysed, with actual crop load level of each irrigation strategy as covariant, giving an adjusted mean of each variable (Steel and Torrie 1980).

For the water relation variables, differences between treatments were assessed by Dunnett's test against the '100-H' (Control) and by designed contrasts among treatment pairs.

Simple linear regression analysis to explore relationships between variables was carried out using the 'reg' procedure (SAS Institute 1994).

Results

Water relations

Crop load effects on well-irrigated trees

During the entire experimental period Ψm of the well-irrigated treatments showed nearly stable values around -20 to -30 kPa, without differences between crop load levels (Figure 1B).

Stomatal conductance in the well-irrigated plots did not differ (p>0.181) between crop loads until day of the year (DOY) 170, one month prior to harvest; thereafter, '100-H' had

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higher (p<0.05) Gs than '100-L' (Figure 1C). On a seasonal basis average Gs was significantly (p<0.05) higher in the high CL (285 mmol m^{-2}s^{-1}), than in the low one (249 mmol m^{-2}s^{-1}).

No significant differences (p>0.201) in Ψs were observed on all days of measurement (Figure 1D), but instead, there were large differences in MDS (Figure 2A). Thus, in most instances, after DOY 140, trees of the 100-H treatment had higher (p<0.05) MDS than those of the100-L. The slope of the linear regression equation of MDS versus VPD was higher (p<0.05) for the more cropping trees (Figure 3).

Trunk growth rates of the high CL level tended to be lower (Figure 2C), but differences were in most cases only statistically significant at 0.05<p<0.1, due to the high variability of the measurements. Averaged throughout the period, TGR of the high CL was 28.7 μm/day, which was significantly lower (0.05<p<0.1) than TGR of low cropping trees (37.2 μm/day).

Deficit irrigated treatments

Despite the different timing in water restriction application (Figure 1A) similar water savings, compared to fully watered trees, and similar ΣΨs were obtained with both deficit irrigation strategies (Table 1). The evolution of plant water status was as planned. In the 'St-Rec' treatments, there was a sharp decline in Ψs, up to -1.5 MPa (Figure 1D). When water was returned at full dosage, Ψm recovered soon to similar values of the '100' treatments, but Ψs and Gs remained significantly (p<0.05) lower than in control trees (Figure 1). In the '-1.5MPa' treatments, the decline in Ψs was more progressive, reaching a minimum value of -1.45 MPa by harvest.

The evolution of Ψs was similar for both crop load levels within each deficit irrigation strategy. However, more water had to be applied to the more cropping trees, to keep them at a same level of plant water status than the light cropping trees (Figure 1 and Table 1).

In both irrigation strategies Gs of the more cropping trees was higher ($p<0.05$) than in the low crop load levels, only during the last two measurement days (Figure 1C). However, pooling data from all treatments and days, the intercepts of the regression lines Gs-Ψs between high and light cropping trees differed at $p<0.05$ (Figure 4).

The 'St-Rec-H', during the period of water restriction, had the highest MDS among all treatments. It also had a significantly ($p<0.05$) severe reduction in TGR. The '-1.5MPa-L' had higher ($p<0.05$) MDS values than the '100-L' from DOY 140 to harvest, in agreement with the differences reported for Ψs. However, despite this reduction in plant water status, TGR and MXTD in the '100-L' were not statistically different ($p>0.321$) than in the '100-L' during the entire experimental period.

Vegetative growth

Both deficit irrigation and high CL reduced the vegetative growth (Table 2). While RTG was reduced by both deficit irrigation strategies, SA was only significantly ($p<0.05$) reduced in the 'St-Rec' treatment, that in concordance had higher ($p<0.05$) RAD inside the canopy. CL reduced both RTG and SA, but in the latter the reduction was significant only at $0.05<p<0.1$ (Table 2). For RTG there was also a significant ($p<0.05$) effect of the interaction between CL and irrigation (Table 2). In fact, with low crop load, RTG was unaffected by deficit irrigation, but in the more cropping trees RTG was severely reduced by the water stress (Figure 5).

Crop load, crop yield and fruit size

Deficit irrigated treatments had unplanned higher crop loads than control trees (Table 3). This was due to irregularity on the hand thinning procedure as indicated by the observation of no differences in flowering and fruit set rates between treatments at the beginning of the experiment (not shown). Thus, despite deficit irrigation reduced the adjusted average fruit weight (FW) by 10 to 12%, crop yield was unaffected by irrigation (Table 3). High crop load allowed for a 47% increase in yield, as FW was only reduced by a 16%. No interaction on FW was found between irrigation and crop load (Table 3). In fact, the slopes of the linear regressions between FW and CL were similar for all three irrigation strategies (Figure 6).

Fruit quality

The 'St-Rec' irrigation strategy increased the 1FC, indicating that fruit ripening was advanced by this treatment. Low crop load also had higher 1FC, although this effect was significant only at $0.05 < p < 0.1$ (Table 4).

At harvest, TSS was higher in the deficit irrigated treatments and in light cropping trees. However, TA was not significantly affected by either irrigation rate nor crop load (Table 4). DM was higher in both deficit irrigated treatments. FF was decreased by the St-Rec treatments and in high cropping trees (Table 4).

After the 14 days cold storage period, TSS was still higher in the deficit irrigated treatments and lower in the high cropping trees, and again there were not significant differences in TA. FF was still lower in 'St-Rec' treatments and in the high CL level, however in the latest one, the effect was only significant at $0.05 < p < 0.1$ (Table 5).

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Discussion

Several works have reported the effects of crop load, water stress and their interaction on tree and fruit growth. However, most of them have involved only comparisons between unthinned and non-fruiting trees, and under severe water stress, which are not real field conditions. The present work, has explored the whole plum tree response to both factors at near commercial levels: moderate water deficit and not too heavy CL.

In well-irrigated plots, CL increased Gs, by a 14%, the effect being more pronounced during the last phase of fruit growth. Towards harvest, fruit dry matter accumulation rate is at its highest (Grossman and DeJong 1995b) and the growth of other sinks, i.e. shoot growth, stops (Grossman and DeJong 1995a). Because of that, the fruit effect on the leaf conductance or assimilation rate is more pronounced by the end of fruit growth, as frequently reported in apple (Palmer 1992, Palmer et al. 1997) and peach (DeJong 1986b). Despite this increase in leaf conductance, Ψs of the high cropping, well irrigated trees, was only 6% lower than in the light ones, and moreover not significantly (p>0.201) different from theirs. This indicates that soil water availability was enough to account for the extra transpiration rate of the high cropping trees. In fact, in many studies (Berman and DeJong 1996, Naor 2004), a null effect of CL on Ψs in well-irrigated trees has been reported. However, MDS was 28% higher in the treatment '100-H' than in the '100-L'. This higher sensitivity of MDS than Ψs to CL, may be explained considering the reduction in TGR observed in the more cropping trees. In fact, as trunk growth opposites to trunk shrinkage (McBurney and Costigan 1984, Genard et al. 2001), the reduction of trunk growth observed

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in the high cropping trees, may have enhanced the effect of the higher transpiration rates. Thus, in the high CL, larger MDS for a given VPD are predicted by equations reported in Figure 3. This finding is significant, because it implies that to base irrigation on MDS, related to a reference previously established (Goldhamer and Fereres 2004), different reference equations should be used according to the tree CL.

The effect of CL on Ψs is more often observed when wather is restricted (Berman and DeJong 1996, Naor 2004). In the present work, in the deficit irrigated trees, there were not differences in Ψs according to crop loads, probably due to the extra water applied to the high cropping, deficit irrigated trees, in comparison to the light ones (Table 1). In the 'St-Rec-H' a 5% more water was applied than in the 'St-Rec-L', while the '-1.5 MPa-H' needed 13% more of water compared with the '-1.5 MPa-L' (Table 1). This difference may be explained considering that, towards harvest, coinciding with the enhanced Gs effect by fruit sink, the 'St-Rec' treatments were fully watered, while in the '-1.5 MPa' ones, water stress continued.

Both deficit irrigation strategies affected similarly fruit size despite the different timing of water restrictions (Table 3). This is because in this cultivar, similarly to early maturing peach trees (DeJong et al. 1987), reduction of fruit growth rate by pit hardening is not clear, and therefore fruit growth is rather linear after the first exponential growth phase (not shown). Considering the $\Sigma\Psi$s reached (Table 1) this reduction was very close to that predicted by our previous work (Intrigliolo and Castel, 2005), even though the deficit irrigated trees, did not surpass the previously identified Ψs threshold value (-1.5 MPa). This indicates that fruit growth respond better to the integral of stress applied, than to a maximum stress level reached during the deficit period. Instead, canopy growth was more

affected in the 'St-Rec' strategy than in the '-1.5 MPa' (Table 2) since it had higher plant water stress, early in the season when most part of shoot growth occurs. Similarly, CL had a greater effect on TGR than on SA due to their different timing of growth. While trunk growth continued until harvest (Figure 2C), shoot growth in part occurred before fruit thinning and stopped by June.

Interestingly, RTG was only severely decreased by the conjunction of water deficit and high CL (Figure 5). Given the similar plant water status observed in both CL levels, this reduction in trunk growth has to be attributed to a source limitation derived from the combined effect of high CL and water deficit. CL enhanced the sensitivity to water stress of trunk growth but not of fruit growth. This is not surprising, considering that high CL has often been found to decrease dry matter allocation to woody tissues (Miller and Walsh 1988, Palmer 1992) and moreover, trunk is considered as smaller sink than fruit at least during the rapid fruit growth phase (Grossman and DeJong 1995a, Berman and DeJong 2003). Contarily to our work, Berman and DeJong (1996) and Naor et al. (2004), in peach and plum trees respectively, reported higher effect of water stress on fruit growth with increasing CL. This may be due to the fact that their high CL, water stressed trees, had lower plant water status than the light ones, as water application was the same for each CL. It should be noted that a limitation of our study was not having another set of high cropping trees, receiving the same amount of deficit irrigation than the light ones. This would have probably helped in understanding the physiological reasons of this frequently found higher sensitivity of fruit growth to water stress with high crop loads.

Fruit quality was also affected by both deficit irrigation and CL, but in a different manner. In the 'St-Rec' treatment, fruit physiological maturation was advanced, as indicated by the higher percentage of 1FC and decreased FF observed in this treatment

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(Table 4). The conjunction of water stress followed by its alleviation may have led to a faster ripening process. In fact, recent studies in peach trees submitted to deficit irrigation only during pit hardening, showed an earlier increase of fruit ethylene production and respiration (Gelly et al. 2003, Gelly et al. 2004). This fact supports the general consideration that stress occurring during fruit growth advances fruit maturation (Brady 1987, Saenz et al. 1997). However, the important vegetative growth reduction experienced by this treatment, which indeed increased the PAR radiation reaching inside the canopy (Table 2), may have also favoured the fruit ripening process (Gelly et al. 2003). On the other hand, the increased TSS observed in the 'St-Rec' treatment, cannot be attributed exclusively to advanced fruit maturation (Chapman et al. 1991), since it was also observed in the '-1.5MPa', which did not mature earlier. More likely it may be due to a dilution effect (Génard et al. 2003) or to fruit dehydration, since DM was higher in the deficit irrigated treatments (Table 4). TA was nonetheless unaffected by both deficit irrigated strategies as in apple (Mpelasoka et al. 2002), peach (Crisosto et al. 1994) or plum (Naor et al. 2004), but contrarily to other studies where TA decreased with water restrictions (Mills et al. 1996, Gelly et al. 2004).

High CL decreased TSS similarly to findings in peach (Crisosto et al. 1997) and apple (Johnson 1995), probably due to delayed fruit maturation (Chapman et al. 1991), as a consequence of the increased within-fruit competitions. However, in spite that fruit maturation was delayed in the high crop load, it had lower FF, most likely due to lower cellular density. DM was instead not affected by high crop load. This suggests that the high CL level here studied was not limiting fruit dry matter accumulation. In fact, similar to findings in apple (Wünsche et al 2000), only a significant decrease in the DM was observed for crop load levels higher than those here studied.

During the cold storage period it was observed a general increased in TSS, a decreased in FF, and an important drop in TA (Table 5). These changes are in agreement with general trends observed during fruit cold storage (Ebel et al. 1993, Gelly et al. 2004). However, differences in fruit quality between irrigation treatments and crop loads observed at harvest were maintained during the storage period.

In summary, this study reports the effects of crop load and deficit irrigation timing on the whole tree response of a mid-season plum cultivar. We studied, for the first time, the effects of CL on TDV and we found that in well-irrigated plots, crop load significantly increased MDS. We speculate that this may not only be due to an increased transpiration rate, but also to a reduction of trunk growth by CL. We also showed that water stress during fruit growth, followed by its alleviation before harvest, decreased fruit size by 12%, but it advanced ripening and increased fruit quality. Thus, this strategy may be an alternative to post-harvest water stress (Johnson et al. 1992, Intrigliolo and Castel 2005) in order to improve crop value in case of water scarcity. Deficit irrigation reduced fruit size similarly in high or low crop loads. However, caution should be taken when applying water restrictions with high crop loads, because their conjunction severely decreased RTG, which may reduce tree productivity in the longer term (Girona et al. 2005, Intrigliolo and Castel 2005). The enhanced sensitivity of RTG to water stress under high CL was not due to an effect of CL on lowering plant water status, but more likely to the interaction between both factors.

References

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage paper No 56. Rome, Italy, pp 15-27.

Berman, M.E. and T.M. DeJong. 1996. Water stress and crop load effects on fruit fresh and dry weights in peach (*Prunus persica*). Tree Physiol. 16:859-864.

Berman, M.E. and T.M. DeJong. 2003. Seasonal patterns of vegetative growth and competition with reproductive sinks in peach (*Prunus pesica*). J. Hortic. Sci. Biotech. 78:303-309.

Brady, C.J. 1987. Fruit ripening. Ann. Rev. Plant. Physiol. 38:155-178.

Chalmers, D.J. and B. Van Den Ende. 1975. Productivity of peach trees: factors affecting dry weight distribution during tree growth. Ann. Bot. 39:423-432.

Chalmers, D.J., K.A. Olsson and T.R. Jones. 1983. Water relations of peach trees and orchards: *In*: Water deficits and plant growth. T.T. Kozlowski Ed. Academic Press. New York, Vol VI, pp 197-232.

Chapman, G. W. Jr., R.J. Horvat and W.R. Jr. Forbus. 1991. Physical and chemical changes during the maturation of peaches. J. Agr. Food. Chem. 39:867-870.

Crisosto, C.H., R.S. Johnson, J.G. Luza and G. Crisosto. 1994. Irrigation regimes affect fruit soluble solid concentration and rate of water loss of 'O'Henry' peaches. HortScience. 29: 1169-1171

Crisosto, C.H., R. S. Johnson, T.M. DeJong and K.R. Day. 1997. Orchard factors affecting postharvest stone fruit quality. HortScience. 32:820-823.

DeJong, T.M. 1986a. Effects of reproductive and vegetative sink activity on leaf conductance and water potential in *Prunus Persica* L. Batsch. Sci. Hortic. 29:131-137.

DeJong, T.M. 1986b. Fruit effects on photosynthesis in *Prunus persica*. Physiol. Plant. 66:149-153.

DeJong, T.M., J.F. Doyle and K.R. Day. 1987. Seasonal patters of reproductive and vegetative sink activity in early and late maturing peach (*Prunus persica*) cultivars. Physiol. Plant. 71:83-88.

Doorenbos, J. and W.O. Pruitt. 1977. Crop water requirements. FAO Irrigation and Drainage Paper 24, Rome, Italy, pp 49.

Ebel, R.C., E.L. Proebsting and M.E. Patterson. 1993. Regulated deficit irrigation may alter apple maturity, quality, and storage life. HortScience. 28:141-143.

Fereres, E. and D.A. Goldhamer. 1990. Deciduous fruit and nut trees. *In*: Irrigation of Agricultural Crops (Stewart BA Nielsen DR Eds.) A.S.A. Madison, USA. Monography. 30, pp 987-1017.

Flore, J.A. and D.R. Layne. 1997. Prunus. *In* Photoassimilates distribution in plants and crops: sink-source relationship. Eds. E. Zamski and H. Scheffler. Marcel Dekker. Inc., New York, pp 825-849.

Gelly, M., I. Recasens, M. Mata, A. Arbones, J. Rufat and J. Girona. 2003. Effects of water deficit during stage II of peach fruit development and postharvest on fruit quality and ethylene production. J. Hortic. Sci. Biotech.. 78:324-330.

Gelly, M., I. Recasens, J. Girona, M. Mata, A. Arbones, J. Rufat and J. Marsal. 2004. Effects of stage II and postharvest deficit irrigation on peach quality during maturation and after cold storage. J. Sci. Food Agric. 84:561-568.

Génard, M., S. Fishman, G. Vercambre, J.G. Huguet, C. Bussi, J. Besset and R. Habib. 2001. A biophysical analysis of stem and root diameter variations in woody plants. Plant Physiol. 126:188-202.

Génard, M., F. Lescourret, L. Gomez and R. Habib. 2003. Changes in fruit sugar concentrations in response to assimilate supply, metabolism and dilution: a modelling approach applied to peach fruit (*Prunus persica*). Tree Physiol. 23:373-385.

Girona, J., J. Marsal, M. Mata, A. Arbones and T.M. DeJong. 2004. A comparison of the combined effect of water stress and crop load on fruit growth during different phenological stages in young peach trees. J. Hortic. Sci. Biotech. 79:308-315.

Girona J., M. Gelly, M. Mata, A. Rabones, J. Rufat and J. Marsal. 2005. Peach tree response to single and combined deficit irrigation regimes in deep soil. Agr. Water Manage. 72:97-108.

Goode J.E., K.H. Higgs and K.J. Hyrycz. 1978. Nitrogen and water effects on the nutrition, growth, crop yield and fruit quality of orchard-grown Cox's orange pippin apple trees. J. Hortic. Sci. 53:295-306.

Goldhamer, D.A. and E. Fereres. 2004. Irrigation scheduling of almond trees with trunk diameter sensors. Irrig. Sci. 23:11-19.

Grossman, Y.L and T.M. Dejong. 1994. PEACH: a simulation model of reproductive and vegetative growth in peach trees. Tree Physiol. 14: 329-45.

Grossman, Y.L and T.M. Dejong. 1995a. Maximum vegetative growth potential and seasonal patterns of resources dynamics during peach growth. Ann. Bot. 76: 473-482.

Grossman, Y.L and T.M. Dejong. 1995b. Maximum fruit growth potential and seasonal patterns of resources dynamics during peach growth. Ann. Bot. 75: 553-560.

Gucci, R., S. Corelli Grappardelli, S. Tustin and G. Ravaglia. 1994. The effect of defruiting at different stages of fruit developement on leaf photosynthesis of "Golden Delicious" apple. Tree Physiol. 15:35-40.

Hansen, P. 1971. The effect of fruiting upon transpiration rate and stomatal opening in apple leaves. Physiol. Plant. 25:181-183.

Intrigliolo, D.S. and J.R. Castel. 2004. Continuous measurement of plant and soil water status for irrigation scheduling in plum. Irrig. Sci. 23:93-102.

Intrigliolo, D.S. and J.R. Castel. 2005. Effects of regulated deficit irrigation on growth and yield of young Japanese plum trees. J. Hortic. Sci. Biotech. In press.

Johnson, R.S., D.F. Handley and T.M DeJong. 1992. Long-term response of early maturing peach trees to postharvest water deficits. J. Am. Soc. Hort. Sci. 117:881-886.

Johnson, D.S. 1995. Effect of flower and fruit thinning on the maturity of 'Cox's orange pippin apples at harvest. J. Hortic. Sci. 70:541-548.

Li, S.H., J.G. Hueguet, P.G. Schoch and P. Orlando. 1989. Responses of peach tree growth and cropping to soil water deficit at various phenological stages of fruit development. J. Hortic. Sci. 64:541-552.

McBurney, T. and P.A. Costigan. 1984. The relationship between stem diameter and water potentials in stem of young cabbage plants. J. Exp. Bot. 35:1787-1793.

McFayden, L.M., R.H. Huttton and E.W.R. Barlow. Effects of crop load on fruit water relations and fruit growth in peach. J. Hortic. Sci. 71:469-480.

Miller, A.N. and C.S. Walsh. 1988. Growth and seasonal partitioning of dry matrer in eight-year-old 'Loring' peach trees. J. Amer. Soc. Hort. Sci. 113:309-314.

Mills, T.M., M.H. Behboudian and B.E. Clothier. 1996. Water relations, growth, and the composition of 'Braeburn' apple fruit under deficit irrigation. J. Amer. Soc. Hort. Sci. 121:286-291.

Mpelasoka, B.S. and M.H. Behboudian. 2002. Production of aroma volatiles in response to deficit irrigation and to crop load in relation to fruit maturity for 'Braeburn Apple'. Postharvest Biol. Technol. 24:1-11.

Myers, B.J. 1988. Water stress integral. A link between short-term stress and long-term growth. Tree Physiol. 4:315-23.

Naor, A. 2004. The interaction of soil- and stem-water potential with crop level, fruit size and stomatal conductance of field-grown 'Black-Amber' Japanese plum. J. Hortic. Sci. Biotech. 79: 273-280.

Naor, A., I. Klein, H. Hupert, Y. Grinblat, M. Peres and A. Kaufman. 1999. Water stress and crop level interactions in relation to nectarine yield, fruit size distribution, and water potentials. J. Am. Soc. Hort. Sci. 124:189-193.

Naor, A., H. Hupert, Y. Greenblat, M. Peres, A. Kaufman and I. Klein. 2001. The response of nectarine fruit size and midday stem water potential to irrigation level in stage III and crop load. J. Am. Soc. Hort. Sci 126:140-43.

Naor, A., M. Peres, Y. Greenblat, Y.Gal and R. Ben Aire. 2004. Effects of pre-harvest irrigation regime and crop level on yield, fruit size distribution and fruit quality of field grown 'Black Amber' Japanese plum. J. Hortic. Sci. Biotech. 79:281-288.

Palmer, J.W. 1992. Effects of varying crop load on photosynthesis, dry matter production and partitioning of Crispin/M.27 apple trees. Tree Physiol. 11:19-33.

Palmer, J.W., R. Giuliani and H.M. Adams. 1997. Effect of crop load on fruiting and leaf photosynthesis of 'Braeburn'/M.26 apple trees. Tree Physiol. 17:741-746.

Saenz, J.L., T.M. DeJong and S.A. Weinbaum. 1997. Nitrogen stimulated increases in peach yields are associated with extended fruit developement period and increased fruit sink capacity. J. Am. Soc. Hort. Sci. 122:772-777.

SAS Institute. 1994. SAS/STAT user's guide. SAS Inst. Inc., Cary, N.c., USA.

Turner, N.C. 1981. Techniques and experimental approaches for the measurement of plant water status. Plant and Soil. 58:339-66.

Weinberger, J.H. 1931. The relation of leaf area to size and quality of peaches. Proc. Amer. Soc. Hort. Sci. 28:18-22.

Wünsche, J.N., A.N. Lakso and T.L. Robinson. 1995. Comparison of four methods for estimating total light interception by apple trees of varying form. HortScience. 30: 272-276.

Wünsche J.N., J. Palmer and D.H. Greer. 2000. Effects of crop load on fruiting and gas-exchange characterisitics of 'Braeburn'/M.26 apple trees at full canopy. J. Amer. Soc. Hort. Sci. 125:93-99.

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Table 1. Integrated water stress values ($\Sigma\Psi$s) and water application (mm) in the various treatments. Water savings compared to the '100' treatments (%) in parenthesis.

Treatment	Irrigation, mm	$\Sigma\Psi$s, MPa·day
100-L	159	38
100-H	159	40
-1.5MPa-L	105 (34)	53
-1.5MPa-H	118 (26)	55
St-Rec-L	112 (26)	56
St-Rec-H	117 (27)	57

Table 2. Effect of irrigation and crop load on relative trunk growth (RTG), shaded area (SA) and percentage of PAR radiation inside the canopy (RAD).

Factor	RTG, %	SA, m^2	RAD, %
Irrigation			
100	3.8	6.9	0.21
<-1.5 MPa	3.0 (0.049)[1]	6.0 (0.123)	0.27 (0.057)
St-Rec	2.9 (0.044)	5.3 (0.038)	0.31 (0.011)
Crop load			
Low	4.0	6.4	0.25
High	2.5 (0.042)	5.7 (0.093)	0.28 (0.350)
IrrigationxCrop load	0.020[2]	0. 412	0.294

[1]P value for the comparison with the respective control ('100' for irrigation and 'low' for crop load)

[2]P value for the interaction effect from ANOVA

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Table 3. Effects of crop load and irrigation on crop load, yield and adjusted fruit weight (FW).

Factor	Crop load (No, fruit/cm^2 TCSA)	Yield, kg/tree	FW, g
Irrigation			
100	5.6	45.1	97.2
<-1.5 MPa	6.3 (0.009)^1	43.1 (0.720)	87.6 (0.027)
St-Rec	6.9 (0.001)	43.7 (0.878)	85.3 (0.026)
Crop load			
Low	4.7	35.7	96.8
High	7.9 (0.001)	52.1 (0.013)	83.2 (0.008)
IrrigationxCropload	0.877^2	0.889	0.367

[1]P value for the comparison with the respective control ('100' for irrigation and 'low' for crop load)

[2]P value for the interaction effect from ANOVA

Table 4. Effects of irrigation and crop load on the percentage of fruit collected in the first pick (1FC) and on the main fruit quality parameters at harvest: total soluble solids concentration (TSS), tritable acidity (TA), dry matter fraction (DM) and flesh firmness (FF).

Factor	1FC, %	TSS, %	TA, g l^{-1}	DM, %	FF, N
Irrigation					
100	56.0	14.5	17.6	15.3	28.0
<-1.5 MPa	61.8 (0.358) [1]	15.9 (0.000)	18.0 (0.694)	16.3 (0.019)	28.6 (0.281)
St-Rec	76.7 (0.013)	15.7 (0.001)	17.9 (0.660)	17.5 (0.008)	26.8 (0.007)
Crop load					
Low	71.9	15.9	18.1	16.5	28.7
High	51.5 (0.083)	14.9 (0.000)	17.5 (0.201)	16.3 (0.395)	26.9 (0.028)
Irr.xCrop load	0.878 [2]	0.897	0.071	0.295	0.377

[1]P value for the comparison with the respective control ('100' for irrigation and 'low' for crop load)

[2]P value for the interaction effect from ANOVA

Table 5. Effects of irrigation and crop load on the fruit quality parameters after a 14 days cold storage period: total soluble solids concentration (TSS), tritable acidity (TA) and and flesh firmness (FF)).

Factor	TSS, %	TA, g l^{-1}	FF, N
Irrigation			
100	15.3	7.5	23.8
<-1.5 MPa	16.2 (0.002) [1]	8.2 (0.109)	24.2 (0.690)
St-Rec	16.6 (0.000)	8.3 (0.112)	22.8 (0.008)
Crop load			
Low	16.6	8.1	23.9
High	15.4 (0.003)	7.8 (0.245)	23.3 (0.060)
Irr.xCrop load	0.121 [2]	0.234	0.027

[1]P value for the comparison with the respective control ('100' for irrigation and 'low' for crop load)

[2]P value for the interaction effect from ANOVA

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Figures captions

Figure 1. Seasonal evolution of A) cumulative irrigation applied and rainfall, B) matric soil water potential (Ψm), C) stomatal conductance (Gs) and D) stem water potential (Ψs). Data are means and standard errors of eight granular matrix sensors for Ψm, and ten and four leaves determined at midday for Gs and Ψs, respectively. DOY day of the year, C.V. coeficient of variation.

Figure 2. Seasonal evolution of A) maximum diurnal shrinkage (MDS), B) maximum diameter reached daily by the trunk (MXTD) and C) trunk growth rate (TGR) calculated as average of 10 days. Values are averages and standard errors of six linear variable differential transformer sensors. DOY day of the year, C.V. coeficient of variation.

Figure 3. Relationship of maximum diurnal shrinkage (MDS) of the fully irrigated trees with average daily air vapour pressure deficit (VPD). Data are separated according to the two crop load levels: low (100-L) and high (100-H). Values are averages of six linear variable transformer sensors. *** significant at p<0.001.

Figure 4. Relationship between stem water potential (Ψs) and stomatal conductance (Gs) for high and low cropping trees. Values are averages of four and ten determinations for Ψs and Gs respectively, pooled over the season and irrigation treatments. *** significant at p<0.001.

Figure 5. Adjusted relative trunk growth (RTG) in the various treatments. For each crop load asterisks indicate significant effect of the irrigation treatments in comparison to the respective '100' treatments from the ANOVA at P< 0.05. Bars indicate standard error.

Figure 6. Relationship between relative tree crop load and adjusted fresh fruit weight. Data are separated in the three deficit irrigation strategies. Each data point represent a tree value. *** significant at p<0.001.
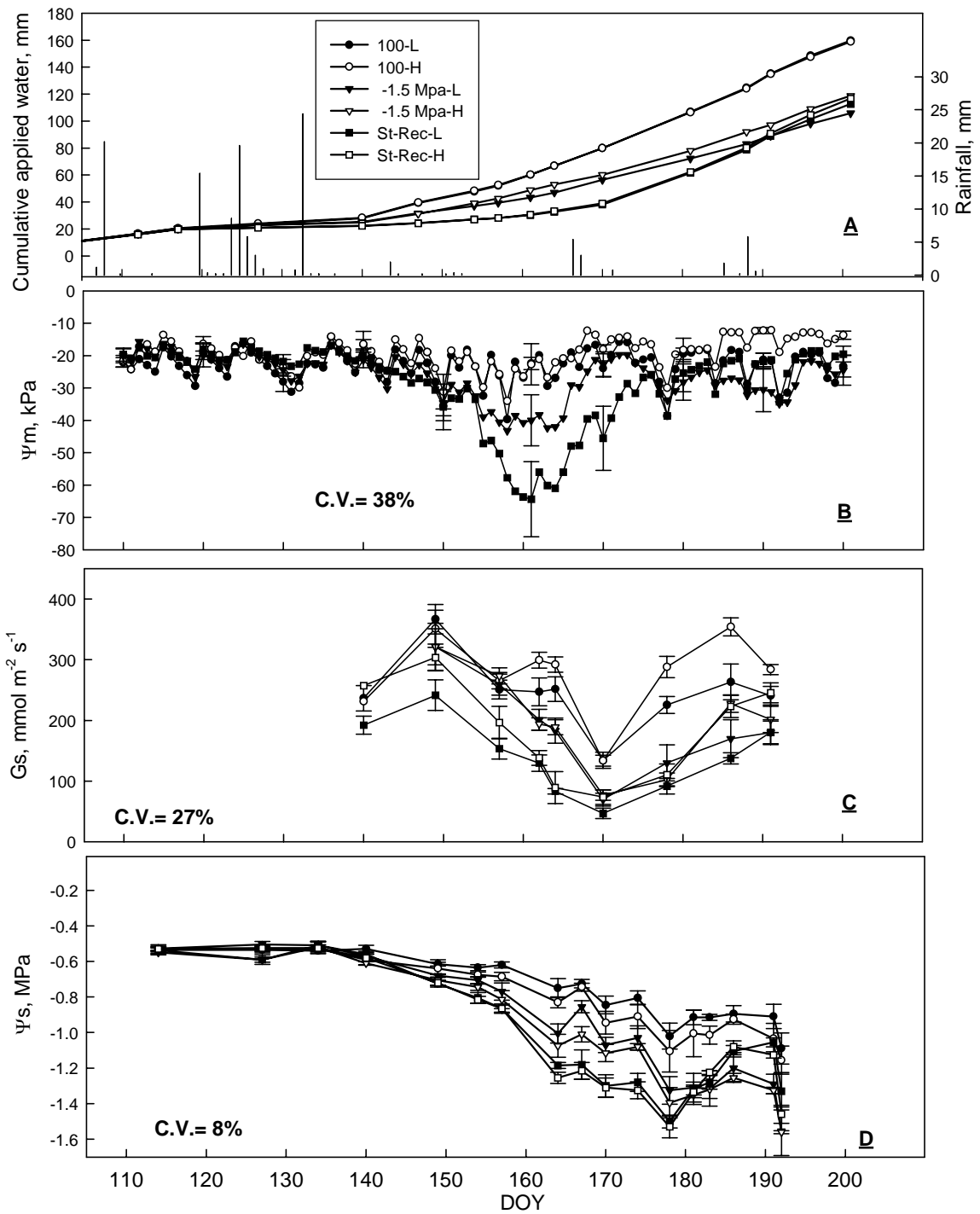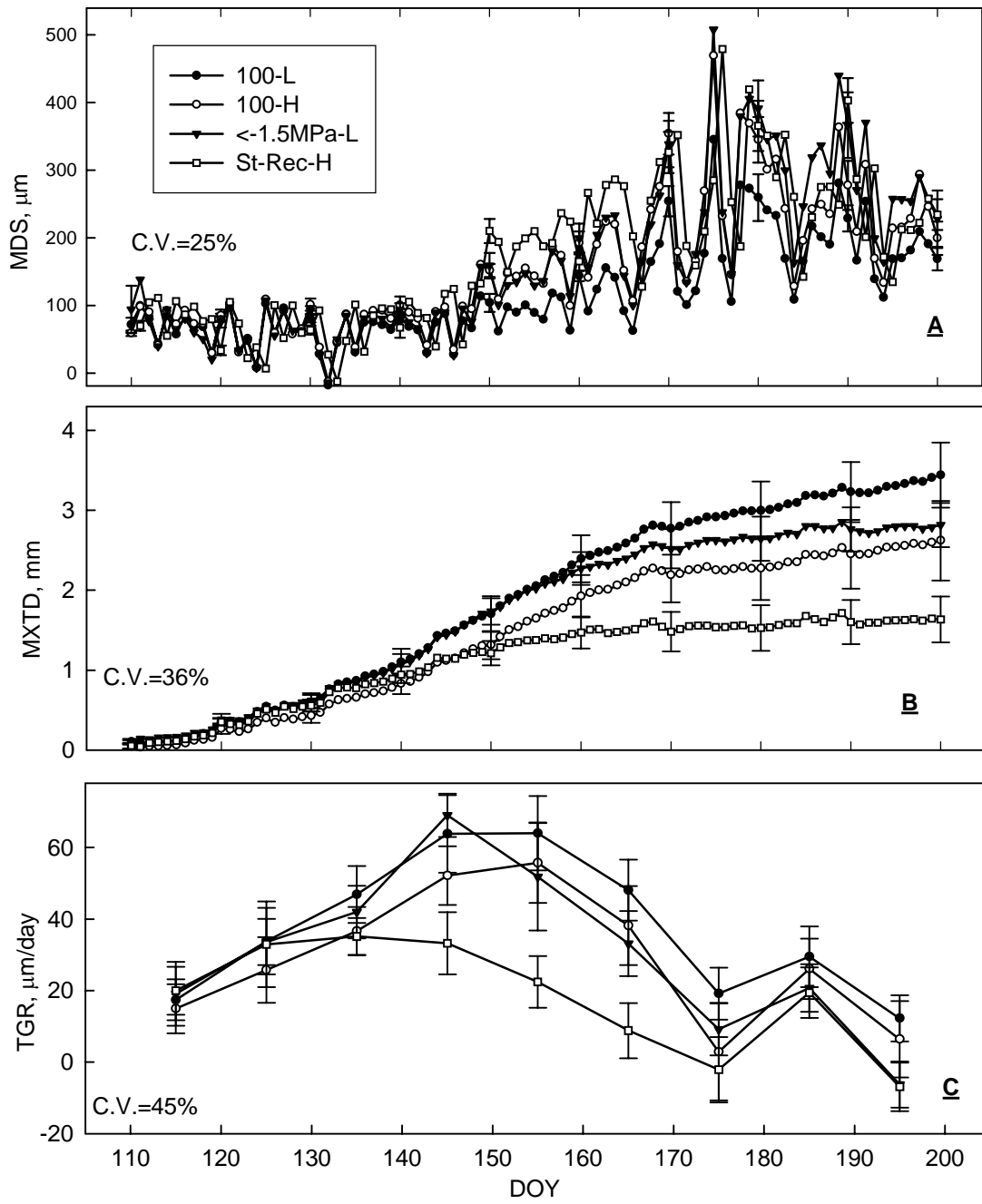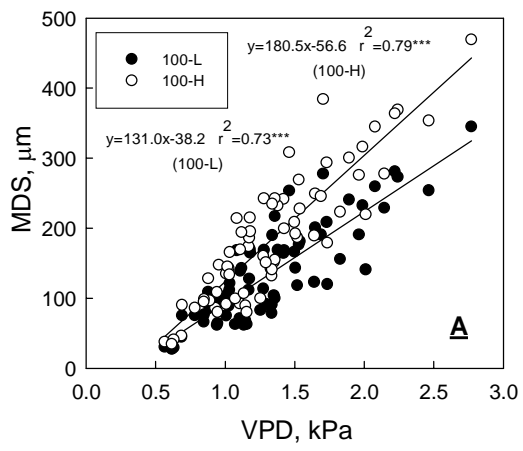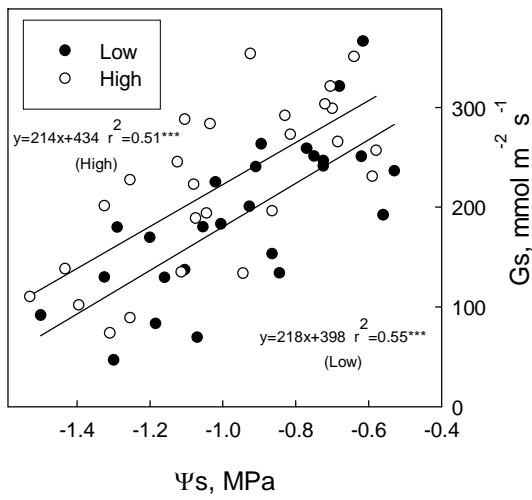
Figure 1

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Figure 2
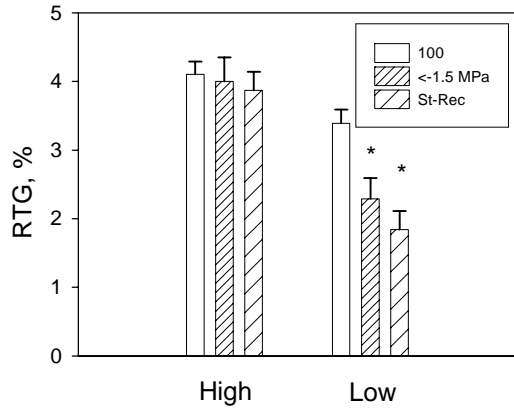
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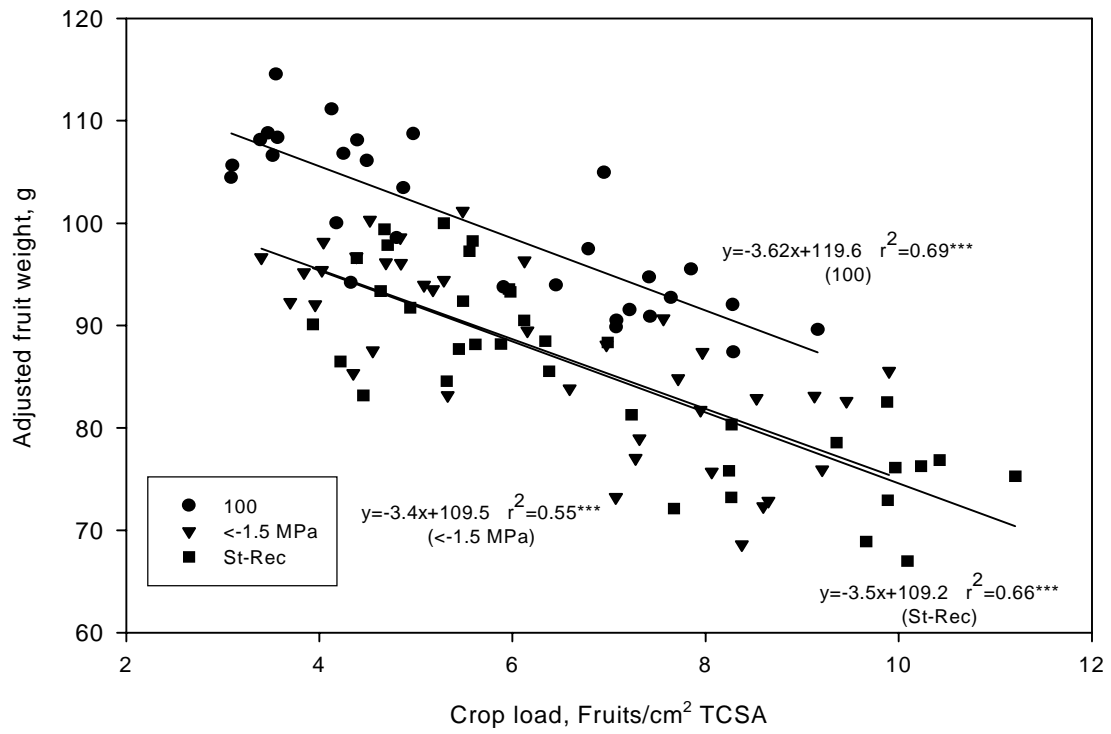
Figure 4

Figure 5

Figure 6

4.- Continuous measurement of plant and soil water status for irrigation scheduling in plum

ORIGINAL PAPER

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Continuous measurement of plant and soil water status for irrigation scheduling in plum

Abstract The usefulness of continuous measurement of soil and plant water status for automated irrigation scheduling was studied in a drip-irrigation experiment on plum (*Prunus salicina* Black Gold). Two levels of water restriction were imposed at different phenological periods (from pit-hardening to harvest, post-harvest) and compared with a well irrigated control treatment. Soil matrix water potential (ψ_{soil}) was measured with granular matrix sensors (Watermark); and short-period trunk diameter variation (TDV) was measured with linear variable displacement transformers. The Watermark sensor readings were in reasonable agreement with the irrigation regime and showed a good indication of plant water status across the season ($r^2 = 0.62$), although they were a better predictor of stem water potential (ψ_{stem}) in the dry range of ψ_{soil}. Nonetheless, the most important drawback in their use was the high variability of readings (typical CV of 35–50%). From TDV measurements, maximum daily shrinkage (MDS) and trunk growth rate (TGR) were calculated. Their performance was also compared with ψ_{stem}, which had the lowest variability (CV of 7%). During most of the fruit growth period, when TGR was minimum, MDS was higher in the less-irrigated treatment than in the control and correlated well ($r^2 = 0.89$) with ψ_{stem}. However, after harvest, when TGR was higher, this correlation decreased as the season progressed ($r^2 = 0.73$–0.52), as did the slope between MDS and ψ_{stem}, suggesting tissue elasticity changes. Later in the season, TGR was better related to plant water status. These observations indicate some of the difficulties in obtaining reference values useful for irrigation scheduling based exclusively on plant water status measurements.

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Introduction

To sustain agriculture, it is particularly important to optimize crop yields by minimizing inputs, mainly water and nutrient application.

Many approaches to improve water management have been developed (Fereres and Goldhamer 1990), some of which involve the use of sensors to monitor continuously either the soil water content (Hanson et al. 2000a) or the plant water status (Goldhamer and Fereres 2001).

The granular matrix sensor (GMS) is an option for indirectly estimating soil water content (Leib et al. 2003). It measures soil electrical resistance that can be converted to soil water potential (ψ_{soil}), either using a calibration formula provided in the literature for sandy soils (Irmak and Haman 2001) and silt loam soils (Eldredge et al. 1993), or calibrating them for a specific soil type.

The Watermark (Larson 1985) is a relatively low-cost GMS, which is easy to use and install and can function consistently over a range of soil water tension from −10 kPa to −200 kPa (Leib et al. 2003), which is over a larger range than tensiometers. However, there is evidence of some limitations. For example, the Watermark does not respond to changes at soil water potential higher than −10 kPa and, therefore, may not be a suitable tool in those cases where irrigation practices maintain a low soil tension (Irmak and Haman 2001; Taber et al. 2002). Moreover, the Watermark does not respond properly to rapid drying or partial rewetting of the soil, showing hysteretic behavior (McCann et al. 1992), which consequently may lead to incorrect estimation of the actual soil water status in these situations. Finally, there is also evidence that the Watermark is not suitable for accurate and reproducible measurement of ψ_{soil} or soil water content, as calibration appears to be unique for each individual sensor (Egbert et al. 1992; Hanson et al.

2000b; Leib et al. 2003). In spite of all these limitations, Watermark may be useful when a relative indication of soil wetness is needed, as indicated by reports of their successful use for irrigation scheduling in some herbaceous crops (Shock et al. 1998a, 1998b; Taber et al. 2002) and woody crops (Hanson et al. 2000a).

In contrast, recording trunk diameter variations (TDV) has been proposed in several studies as a tool for continuous estimates of plant water status, particularly stem water potential (ψ_{stem}; Goldhamer et al. 1999; Cohen et al. 2001; Moriana and Fereres 2002). However, recent findings in peach (Marsal et al. 2002) and almond (Fereres and Goldhamer 2003) show that this relationship may change during the season. Therefore, to schedule irrigation based on the information derived from TDV, the robustness of the relationship between TDV and ψ_{stem} must be established.

The objective of our study was, then, to determine the feasibility of using TDV measured with linear variable displacement transformer (LVDT) sensors and ψ_{soil} derived from GMS for irrigation scheduling in a drip-irrigated plum (*Prunus salicina* L. Black Gold) orchard, comparing different water deficits (mild, severe) with well watered plants. The advantages and limits of both techniques are discussed.

Materials and methods

The experiment was carried out during 2002 in a 5-year-old plum orchard (*P. salicina* Black Gold on Marianna GF81) planted at 5×3.5 m spacing and located at Liria (39°45′N, 0°38′W, elevation 300 m), Valencia, Spain. At the beginning of the experiment, the average tree LAI, percentage of shaded area and trunk circumference were 0.73, 29% and 0.29 m, respectively. The soil was a sandy loam with abundant stones (32% by weight) and about 80 cm of effective depth. The irrigation water had an average EC of 1.1 dS m^{-1} (at 25 °C) and an average Cl$^-$ content of 122 g m^{-3}. The fertilization applied through the irrigation system provided N, P$_2$O$_5$ and K$_2$O at 150, 75 and 175 kg ha^{-1} year^{-1}, respectively. The agricultural practices followed were those common for the area. The experiment had six treatments and three replicates in a randomized complete block design. Each experimental plot comprised three adjacent rows of eight trees per row, with the two center trees of the central row being used for measurement. To test sensor performance, only the four treatment groups described below were used:

1. Control group irrigated at 100% crop evapotranspiration (ET$_c$) during the full season
2. Group 33 I irrigated at 33% ET$_c$ from pit-hardening (14 May) to harvest (8 July) and at 100% ET$_c$ during the rest of the season
3. Group 66 I+II irrigated at 66% ET$_c$ from pit-hardening to the end of the season
4. Group 33 II irrigated at 33% ET$_c$ from harvest to the end of the season and irrigated at 100% ET$_c$ until harvest

ET$_c$ was estimated as the product of reference evapotranspiration (ET$_o$) and crop coefficient (K_c). ET$_o$ was calculated from the Penman–Monteith equation, using hourly data collected by an automated weather station situated near the orchard. K_c values were obtained from Doorenbos and Pruitt (1977) and adjusted for tree size, following Fereres and Goldhamer (1990). On a seasonal basis, the average K_c was 0.2.

. Drip-irrigation was applied with six emitters per tree (each delivering 3.85 l h^{-1}) which were located in a double-irrigation line parallel to the tree row. The reductions in the amount of water applied during the deficit periods were achieved by reducing the irrigation duration, while irrigation frequency was the same for all treatments and varied from once per week in early spring and autumn to three times per week during summer. Water meters on each replicate measured the water application.

Soil water potential was measured with eight GMS (Watermark model 200ss, Irrometer Co.) per treatment. They were all located at 30 cm depth and 25 cm distance from the vertical of a dripper situated in the west tree quadrant and at the same distance from the tree. Each of the six experimental trees per treatment had only one Watermark sensor and two trees had an additional sensor. The calibration equations used to convert the soil electrical resistance obtained with GMS (adjusted by soil temperature) to soil water potential were those reported by Allen (2000). Soil temperature was measured with a model 107 temperature probe (Campbell Scientific) installed at the same depth and distance from an emitter as the Watermarks.

TDV were measured with six LVDT (model DF-2.5, Schlumberger) per treatment. On each experimental tree, a sensor was fixed to the main trunk by an Invar frame (Invar being a metal alloy with minimal thermal expansion) located about 20 cm from the ground on the north side. Prior to installation, the transformers were individually calibrated by means of a precision micrometer (Verdtech, Spain). The typical output coefficient was about 85 mV mm^{-1} V^{-1}. The resolution of TDV, including all sources of variation (calibration, non-linearity, excitation, output voltage recording, thermal changes), was about 10 μm. From TDV, we calculated two different indexes, the maximum daily trunk diameter (MXTD) and the maximum daily shrinkage (MDS), the latter obtained as the difference between the maximum diameter reached early in the morning and the minimum reached normally during the afternoon.

All sensor data were automatically recorded every 30 s, using a model CR23X data logger (connected to an AM16/32 multiplexer for soil sensors, connected to an AM25T multiplexer for LVDT sensors) programmed to report mean values every 30 min for LVDT and every 2 h for soil sensors.

ψ_{stem} was measured with a pressure chamber, following the procedures described by Turner (1981), in four leaves per treatment (two leaves per tree on two selected trees that also had soil and plant sensors installed). Mature leaves on the north face near the trunk
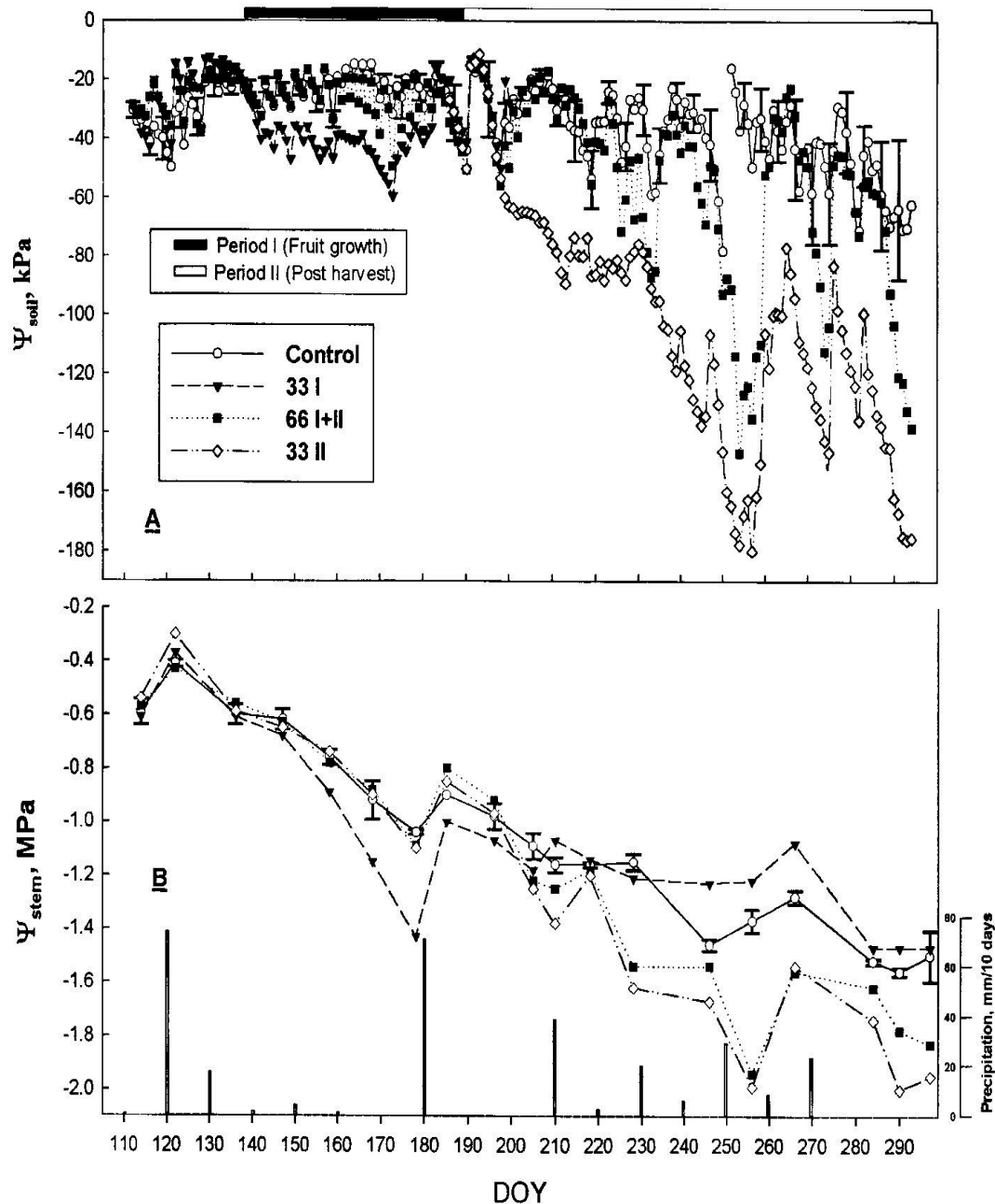
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Fig. 1A, B Seasonal patterns of water potentials. A Seasonal pattern of soil water potential (ψ_{soil}). For clarity only midday values (averages of eight sensors per treatment) are plotted. The values of the treatment groups 33 I and 33 II during the period when they had no restrictions are not shown. B Seasonal pattern of stem water potential (ψ_{stem}). Values given are means of four measurements recorded at midday (1200–1300 GMT). *DOY* Day of the year, *capped bars* standard error

were enclosed in plastic bags covered with silver foil at least 2 h prior to the measurements, which were carried out between 1200 h and 1300 h (solar time) approximately every 10 days from April to November.
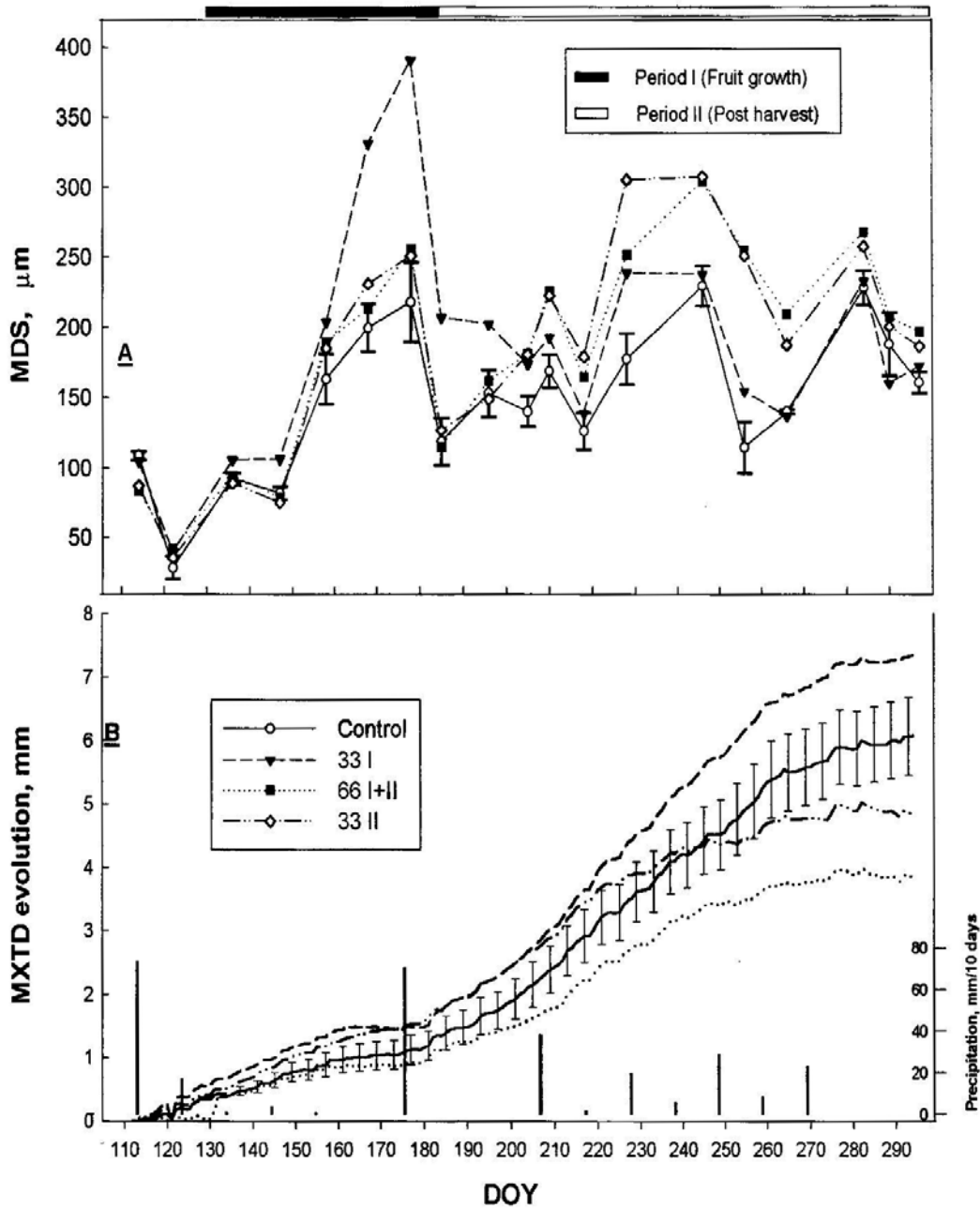
Statistical data analysis was performed with Statgraphics Plus ver. 4.1.

Results and discussion

Seasonal dynamics

Soil water potential

During the period from pit-hardening to harvest (period I), ψ_{soil} in the control treatment was nearly stable, with values of −20 kPa to −30 kPa, whereas the two

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Fig. 2A, B Seasonal patterns of shrinkage and diameter. **A** Maximum diurnal shrinkage (*MDS*). Data on MDS are presented only for those days coinciding with determinations of ψ_{stem}. **B** Maximum daily diameter (*MXTD*). Values given are averages of six linear variable displacement transformer (LVDT) sensors per treatment

restriction levels showed contrasting responses (Fig. 1A). Thus, group 33 I showed a marked tendency to decrease, reaching a minimum value of −60 kPa on

day 172. However, group 66 I + II (despite the water restriction) did not show clear differences with respect to the control trees.

During post-harvest (period II), ψ_{soil} in the control trees was less stable than previously, showing a tendency to decrease from −20 kPa just after harvest (day 189) to minimum values around −60 kPa to −70 kPa on day 280 (Fig. 1A). This reflected some underestimation of the K_c employed during this period, as the actual water applied was higher than the esti-
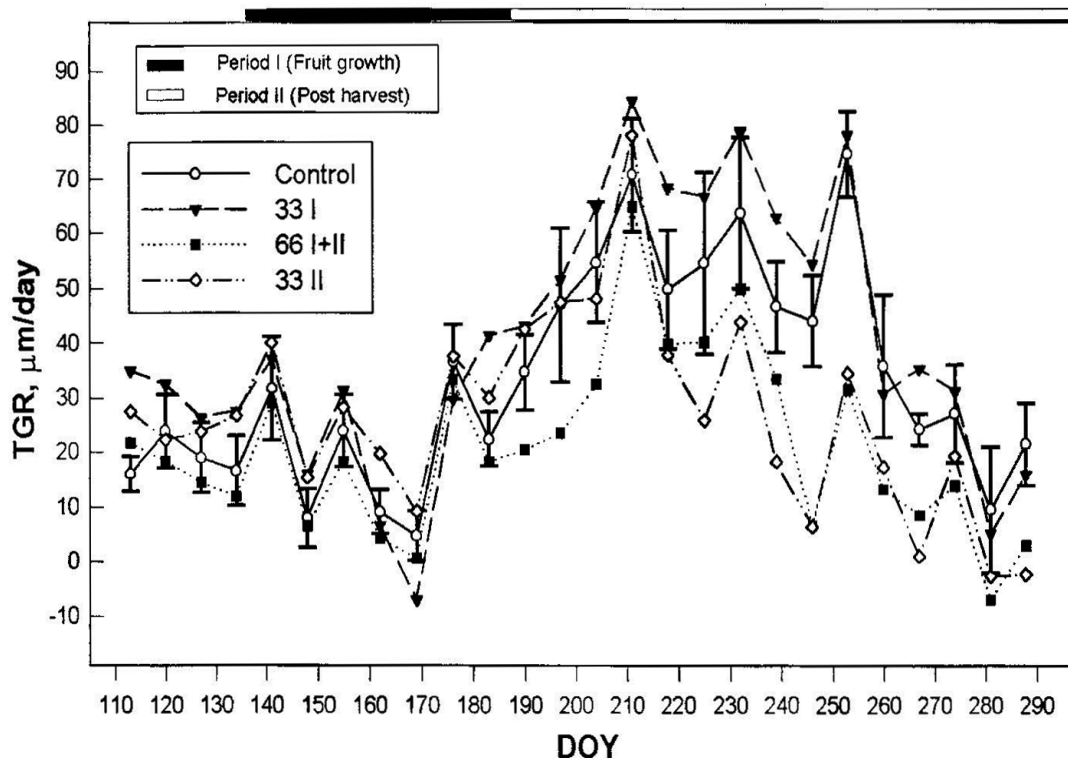
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Fig. 3 Trunk growth rate (*TGR*) in the different irrigation treatments. Values given are means of six LVDT sensors per treatment, calculated as averages for 7 days

mated ETc (data not shown). For the deficit-irrigated treatments, the less-irrigated one (group 33 II) showed, as expected, a gradual and steep decline in ψ_{soil}, reaching a minimum value of −180 kPa (after 2 months of restriction) on day 255. In contrast, group 66 I + II did not start to clearly differ from the control trees until day 255 (after 100 days of water restriction) and when its ψ_{stem} (Fig. 1B) was already lower than in the control. This indicated either that the GMS sensor had a low sensitivity to small water restrictions or that the place where the sensor was installed was not representative of the actual soil water content of this treatment.

Over all treatments and seasons, GMS responded throughout the wetting and drying cycles with a time-response to each irrigation event of about 6 h. They functioned consistently over a range of ψ_{soil} of −15 kPa to −180 kPa. A similar working range was previously found (Hanson et al. 2000a; Leib et al. 2003), confirming that GMS operate in a drier range than tensiometers but with a lower resolution at the wet end of soil water potential, as reported by Egbert et al. (1992) and Irmak and Haman (2001). This is an important limitation, especially in sandy soils or in situations where high ψ_{soil} has to be maintained. However, the most important drawback on their use for irrigation scheduling is the high variability of

readings, which precludes the detection of small treatment differences, at least under the mild restriction conditions observed here. In fact, despite attempts to minimize spatial variability in soil water content due to the drip irrigation system, by carefully installing all sensors at the same distance from selected emitters, at the same depth and at the same distance with respect to the tree, we obtained typical CV values of 35–50%, increasing at the lower ψ_{soil} range. These values are similar to those obtained in other trials where either Watermark sensors (Taber et al. 2002) or tensiometers (Hendrickx and Wierenga 1990) were employed.

Stem water potential

The evolution of ψ_{stem} (Fig. 1B) showed a decreasing trend along the season in all treatments. In fact, ψ_{stem} values for control trees decreased from an initial value of −0.6 MPa (day 112) to −1.5 MPa (day 295). This was probably due to higher evaporative demand, the increase in leaf area (over days 112–180) and a general gradual reduction in water availability towards the end of the season, even in the more irrigated (control) trees, as previously discussed (Fig. 1A).

When deficit-irrigation was first imposed by pit-hardening, only the more severe level of restriction (group 33 I) showed a marked decrease in ψ_{stem} values, which became noticeable some 15 days after the imposition of water restriction. A minimum value of −1.5 MPa was recorded in this treatment just before

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Table 1 Comparison of the sensitivity (signal to noise ratio) of the different variables (see Materials and methods) during the fruit growth and post-harvest periods. *CV* Coefficient of variation

Period	Sensitivity	ψ_{soil}	ψ_{stem}	MDS	TGR
Fruit growth	Signal	1.55	1.18	1.47	1.25
	Noise (CV)	0.43	0.07	0.17	0.25
	Ratio	3.6	16.0	8.4	4.6
Post-harvest	Signal	2.45	1.20	1.36	2.16
	Noise (CV)	0.50	0.08	0.21	0.26
	Ratio	4.9	15.0	6.5	8.3

harvest (after 50 days of restriction). However, group 66 I + II did not show any differences in ψ_{stem} values with respect to the control trees, in agreement with its soil water status as previously discussed. When irrigation returned to full dosage, the group 33 I trees recovered quickly to values similar to those of the control trees.

After harvest, differences in ψ_{stem} were evident in treatment groups 66 I + II and 33 II some 15 days after water restriction started. The differences increased during the season, reaching minimum ψ_{stem} values of −1.9 MPa and −2.0 MPa, respectively, for groups 66 I + II and 33 II by about day 258. Similar ψ_{stem} values achieved during post-harvest did not have a negative impact on the following year's production of an early-maturing plum (Johnson et al. 1994), indicating the possibility of important water savings during this period. Treatment group 33 I, which had no restriction during this period, tended to have slightly higher (i.e. more

hydrated) values than the control trees. This was probably a consequence of the reduction in vegetative growth (smaller leaf area; data not shown) which occurred during the previous period of water restriction. The time-course of ψ_{stem} in this treatment was similar to that of the control, decreasing from −1.0 MPa to −1.4 MPa during the period.

Trunk diameter variations

Although the response between species is not unique, MDS values commonly increase with water deficit, especially when water restriction is not severe (Huguet et al. 1992). During period I, treatment group 33 I (before restriction) had similar MDS values to the control trees, but they soon became higher as deficit-irrigation was imposed (Fig. 2A). As the water restriction progressed, differences increased, reaching a maximum difference of about 200 μm by day 178, just before heavy

Fig. 4 Relationship between ψ_{soil} and ψ_{stem} for all data, separated for two soil wetness ranges ($\psi_{soil} > -45$ kPa, $\psi_{soil} < -45$ kPa; *dotted lines*). Values are averages for eight sensors and four leaves, respectively. ** Significant at $P < 0.05$
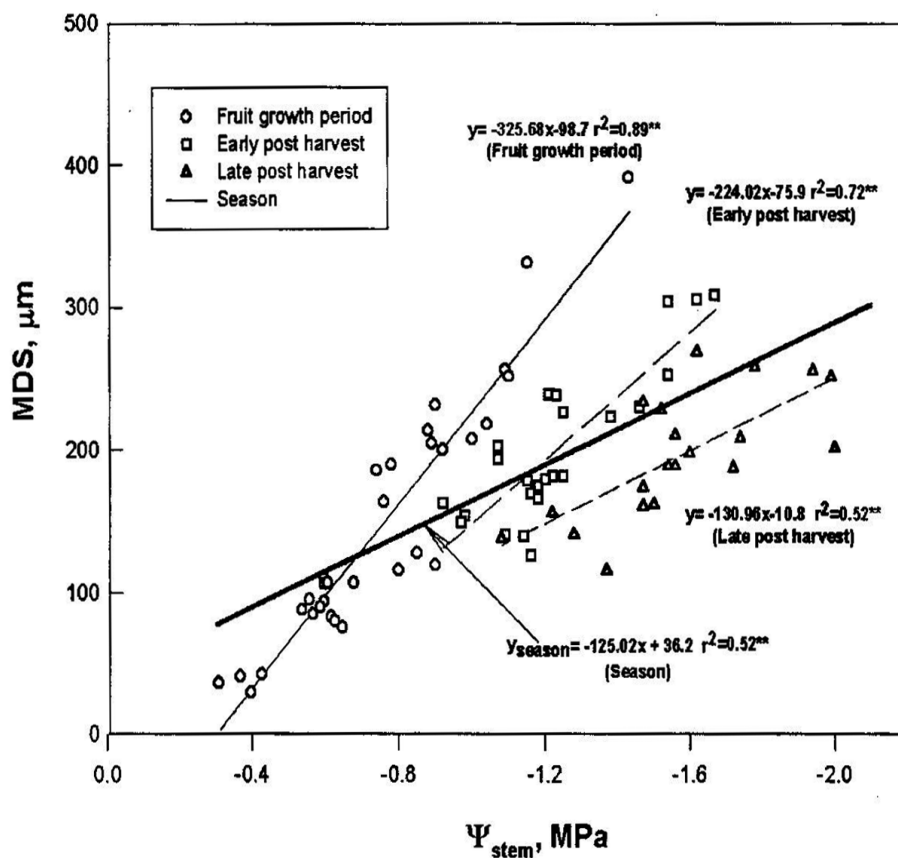

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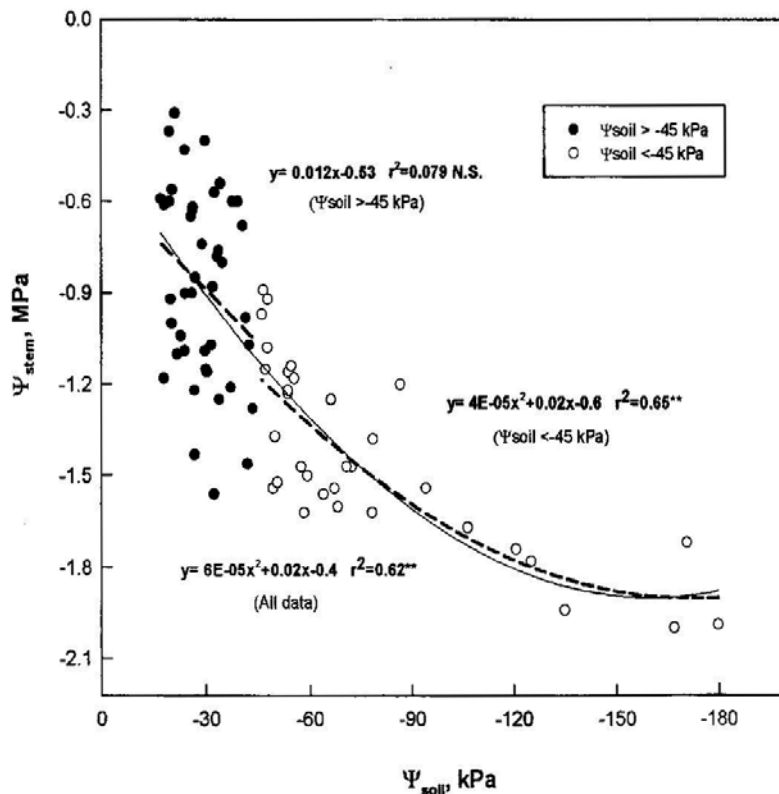
Fig. 5 Relationship between MDS and ψ_{stem} for the whole season and separated according to periods: fruit growth (from day 120 to harvest on day 188), early post-harvest (from harvest to day 215) and late post-harvest (from day 216 to day 297). Values given are averages for six sensors and four leaves, respectively

rain occurred. This was accompanied by a difference of 0.5 MPa in ψ_{stem} between those treatments. In treatment group 66 I + II, MDS values were similar to those of the control trees, in agreement with its soil and plant water status, as previously discussed.

During period II, both restriction levels (groups 66 I + II, 33 II) showed higher MDS than the control trees; and, again, differences became greater as the restriction progressed. Interestingly, treatment group 33 I (irrigated like the control trees during period II) had higher MDS than the control, but ψ_{stem} was similar or even slightly higher during this period (Fig. 1B). This suggests an adaptation of plum trees to water stress. Trees in treatment group 33 I may have a greater tissue elasticity than those in the control treatment, as a turgor maintenance response after the water stress applied during period I (Kozlowski and Pallardy 2002). This feature would lead then to higher shrinkage in this treatment with respect to the control trees for a similar plant water status.

Trunk growth rate (TGR), indicated by the evolution of MXTD, is another variable that can be used as an indicator of plant water status (Goldhamer et al. 1999; Moriana and Fereres 2002). MXTD evolution (Fig. 2B) shows a general tendency towards a very low TGR in all treatments during the fruit growth period (period I), very likely a consequence of fruit-to-vegetative growth competition (Grossman and DeJong 1994) as fruits, especially during stage III of their development, are very strong sinks and have priority for assimilates (Flore and Layne 1997). Therefore, as expected during period I, differences between treatments were small, with only group 33 I having a decreased TGR (Fig. 3) and even reaching negative values as a consequence of the reduction in water application. After harvest (days 210–255) however, TGR in control trees was relatively constant with values around 60–90 μm day^{-1}, which was higher than in the previous period, probably because of less competition for assimilates. In contrast, groups 33 II and 66 I + II had clearly lower TGR. Moreover, in these treatments, trunk growth ended 1 month earlier than in the control trees (Fig. 2B), probably as a consequence of the very low ψ_{soil} and ψ_{stem} reached (Fig. 1A, B).

A seasonal pattern of trunk growth similar to that of our control treatment was recently described for well irrigated peach trees (Marsal et al 2002), indicating the important influence of phenology on trunk growth.

Table 2 Linear regression analysis between MDS (y) and ψ_{stem} (x) and multiple linear regression analysis of MDS (y) and both ψ_{stem} (x_1) and TGR (x_2) during season. ** Statistically significant at $P < 0.05$, * significant at $P < 0.10$. Other values are non-significant

Period	Simple linear regression			Multiple linear regression			
	MDS vs ψ_{stem}			MDS vs both ψ_{stem} and TGR			
	$y = mx + b$			$y = m_1x_1 + m_2x_2 + b$			
	m	b	r^2	m_1	m_2	b	r_{adj}^2
Fruit growth	−326**	−99**	0.89**	−319**	−0.4**	−85**	0.92**
Early post-harvest	−224**	−76**	0.72**	−206**	−0.34**	−34	0.75**
Late post-harvest	−130**	−11	0.52**	−134**	0.08	−16	0.51**
Fruit growth + early post-harvest	−200**	−23*	0.67**	−210**	−0.76**	−5.5	0.81**
Whole season	−125**	+36**	0.52**	−121**	−0.13	−43.4**	0.50**

Comparison of sensitivity of the different variables

Sensitivity as defined by Fereres and Goldhamer (2003) is the average ratio between the values of a variable for the most stressed treatment and those of the control treatment (the signal) divided by the average coefficient of variation (the noise).

A comparison of the sensitivity during the two main phenological periods (fruit growth, post-harvest) among the different techniques used (Table 1) showed that ψ_{soil} had the highest signal value but the lowest sensitivity, due to its very high variability in both periods. In contrast, ψ_{stem} was the most sensitive, due to its very low CV. Finally, MDS was more sensitive than TGR during the fruit growth period, but the reverse occurred post-harvest.

Contrary to our results, Goldhamer and Fereres (2001) found MDS was more sensitive than ψ_{stem} in mature almond trees. They obtained higher signal values for MDS than in this work, while the variability was similar. This can probably be attributed to differences in the irrigation system, as theirs wetted the whole orchard floor.

Relationships between different indicators

The usefulness of the TDV-derived indexes and GMS sensors was also evaluated by regression analysis between those indexes and ψ_{stem}, commonly used as a standard measurement of plant water status.

Soil water potential was significantly related to ψ_{stem} over the full season ($r^2 = 0.62$, Fig. 4). Multiple regression analysis (including also either daily ET_o or midday air vapor pressure deficit values) only explained an extra 5% of variance (data not shown). Figure 4 indicates that Watermarks are apparently poor predictors of ψ_{stem} when the soil is wet. In fact, when data are separated on two soil wetness ranges ($\psi_{soil} < -45$ kPa, $\psi_{soil} > -45$ kPa), the correlation is clearly higher and only significant in the drier range. Nonetheless, part of the lack of agreement between both variables in the wet range can be attributed to the effects of evaporative demand on ψ_{stem}. Therefore, for irrigation of fruit trees, Watermarks would not be recommended in situations when high ψ_{soil}

has to be maintained (for instance phase III of fruit growth), but they can be a useful tool when drier soil conditions are less harmful for fruit growth (e.g. phase II). Finally, we also conducted a regression analysis for the same individual periods used later for the relationship between MDS and ψ_{stem} and found that shorter periods did not improve the correlations (data not shown). This indicates that phenology, apparently, does not influence the relationship between ψ_{stem} and ψ_{soil}.

The regression analysis between MDS and ψ_{stem} (Fig. 5), pooling data across the season, showed that the coefficient of determination was significant, though not very high ($r^2 = 0.52$). However, when broken into three time-periods, the correlation for individual periods clearly improved, except for late post-harvest. Moreover, we observed a general trend towards lower MDS for a given ψ_{stem} and to a reduction in the slope between both variables as the season progressed (Fig. 5). Similar behavior in this relation was also recently reported in peach and almond trees (Marsal et al. 2002; Fereres and Goldhamer 2003), suggesting that this may be a general trend, at least in deciduous fruit trees. The causes are possibly related to TGR and tissue elasticity changes during the season. After harvest, TGR is clearly higher than during the fruit growth period and theoretically (Genard et al. 2001), for a given evaporative demand and soil water potential, the trunk shrinks more when its growth rate is low. In fact, a comparison of the slope of MDS vs ψ_{stem} for the fruit growth period and for the early post-harvest period suggests that changes could be related to differences in TGR between periods. This is supported by the additional 14% of variance explained by regression that included TGR in the model of MDS vs ψ_{stem} (Table 2). However, later in the season, the MDS vs ψ_{stem} slope decreased again; and then the inclusion of TGR in the regression model did not improve the goodness of fit ($r_{adj}^2 = 0.50$; Table 2), indicating the likely involvement of factors distinct from growth. It is generally accepted that tissue age affects its elasticity, older tissues being less elastic (higher resistance to shrinkage; Tyree and Jarvis 1982). Therefore, lower MDS for a given ψ_{stem} value late in the season may be due to less elastic, older tissues.
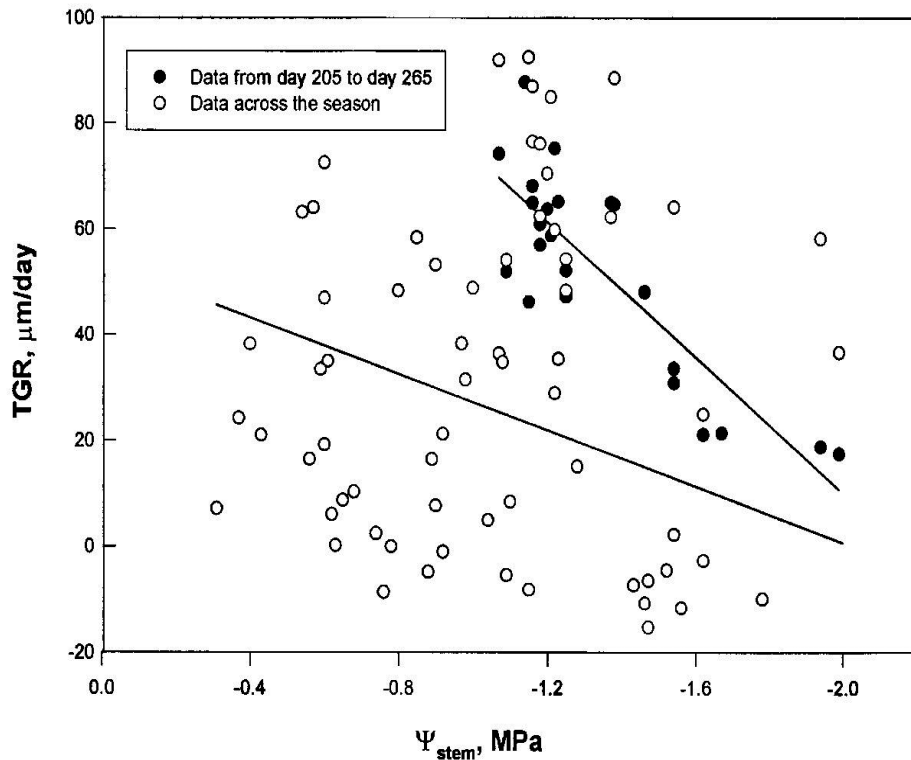
Fig. 6 Relationship between TGR and ψ_{stem}, using data across the full season and for all treatments during a period (days 205-265) of nearly constant TGR rates in the more irrigated trees. TGR values given are averages of the 7 days of the week when ψ_{stem} measurement were collected. Values given are averages of six sensors and four leaves, respectively

Another important issue is to prove the robustness of the relation between MDS and ψ_{stem} for different species. As far as we know, there are no reports of the analysis of TDV in plum or prune trees. However, on 8-year-old peach trees, Cohen et al. (2001) studied the relationship between MDS and ψ_{stem} (although only during phase III of fruit growth) and found values very similar to ours. As an example, for a ψ_{stem} of -1.0 MPa, we obtained 227 μm of contraction, while on peach the same ψ_{stem} corresponded to 230 μm. Nonetheless, more effort is required in order to check the extrapolation of this relationship among different *Prunus* species or cultivars.

Finally, the evolution of MXTD is the other TDV variable related to plant water status. As TGR was not constant during the season independently from water status, it impedes the search for a significant relation between both variables over the full season (Fig. 6). However, for a period when TGR was relatively constant and high in the more irrigated trees (days 205-265), differences were expected to be due mainly to plant water status. This is supported by the high coefficient of determination ($r^2 = 0.71$; Fig. 6) in the regression

between both variables, including data from all treatments during this period. However, in peach, Sellés and Berger (1990) found a good correlation over the full season between TGR and ψ_{stem}.

Conclusions

Our results show that ψ_{stem} was the least variable and more sensitive indicator. However, Watermark sensors can be a useful tool especially in the dry range of ψ_{soil}, as they have much higher uncertainty in the wet range. Moreover, their high variability and the reduced zone of influence imply the need for a large number of sensors per orchard. But, MDS is a very good predictor of ψ_{stem} during phases II and III of fruit growth. Therefore, especially during stage III, their use can be extremely important, as it could enable the early detection and prevention of any water stress that could reduce orchard productivity. However, it has to be taken in consideration that the relation between MDS and ψ_{stem} is not unique throughout the season. This is an important feature, as a single MDS value could lead to important deviations when evaluating plant water status, depending on the phenological period. Finally, trunk growth can also be a good plant-based water stress indicator, but the influence of phenology on its evolution impedes establishing absolute threshold values. Therefore, its use is recommended together with a reference obtained on fully irrigated "control" trees.

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References

Allen R (2000) Calibration for the Watermark 200SS soil water potential sensor to fit the 7-19-96 "calibration°3" table from Irrometer. University of Idaho, Kimberley

Cohen M, Goldhamer DA, Fereres E, Girona J, Mata M (2001) Assessment of peach tree responses to irrigation water deficits by continuous monitoring of trunk diameter changes. J Hortic Sci Biotechnol 76:55–60

Doorenbos J, Pruit WO (1977) Crop water requirements. (Irrigation and drainage, paper 24) FAO, Rome

Egbert JA, Baker S, Baker JM (1992) Calibration of Watermark soil moisture sensors for soil matrix potential and temperature. Plant Soil 143:213–217

Eldredge EP, Schock CC, Stieber T (1993) Calibration of granular matrix sensors for irrigation management. Agron J 85:1228–1232

Fereres E, Goldhamer DA (1990) Deciduous fruit and nut trees. In: Stewart BA, Nielsen DR (eds) Irrigation of agricultural crops. ASA, Madison, Wis., pp 987–1017

Fereres E, Goldhamer DA (2003) Suitability of stem diameter variations and water potential as indicators for irrigation scheduling of almond trees. J Hortic Sci Biotechnol 78:139–144

Flore JA, Layne DR (1997) Prunus. In: Zamski E, Schaffer AA (eds) Photoassimilate distribution in plants and crops: sink-source relationship. Dekker, New York

Genard M, Fishman S, Vecambre G, Huguet JC, Bussi C, Besset J, Habib R (2001) A biophysical analysis of stem and root diameter variations in woody plants. Plant Physiol 126:188–202

Goldhamer DA, Fereres E (2001) Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrig Sci 20:115–125

Goldhamer DA, Fereres E, Mata M, Girona J, Cohen M (1999) Sensitivity of continuous and discrete plant and soil water status monitoring in peach trees subjected to deficit irrigation. J Am Soc Hortic Sci 1244:437–444

Grossman YL, DeJong TM (1994) PEACH: a simulation model of reproductive and vegetative growth in peach trees. Tree Physiol 14:329–345

Hanson RB, Orloff S, Peters D (2000a) Monitoring soil moisture helps refine irrigation management. Calif Agric 54:38–42

Hanson RB, Orloff S, Peters D (2000b) Effectiveness of tensiometers and electrical resistance sensors varies with soil condition. Calif Agric 54:47–50

Hendrickx JMH, Wierenga PJ (1990) Variability of soil water tension in a trickle irrigated Chile pepper field. Irrig Sci 11:23–30

Huguet JG, Li SH, Lorendeau JY, Pelloux G (1992) Specific micromorphometric reactions of fruit trees to water stress and irrigation scheduling automation. J Hortic Sci 67:631–640

Irmak S, Haman DZ (2001) Performance of the Watermark granular matrix sensor in sandy soils. Appl Eng Agric 17:787–795

Johnson RS, Handley DF, Day KR (1994) Postharvest water stress of an early maturing plum. J Hortic Sci 69:1035–41

Kozlowski TT, Pallardy SG (2002) Acclimation and adaptive response of woody plants to environmental stresses. Bot Rev 68:270–334

Larson GF (1985) Electrical sensor for measuring moisture in landscape and agricultural soils. U.S. Patent 4531087

Leib BG, Jabro JD, Mathews GR (2003) Field evaluation and performance comparison of soil moisture sensors. Soil Sci 168:396–408

Marsal J, Gelly M, Mata M, Arbonés J, Rufat J, Girona J (2002) Phenology and drought affects the relationship between daily trunk shrinkage and midday stem water potential of peach trees. J Hortic Sci Biotechnol 77:411–417

McCann IR, Kincaid DC, Wang D (1992) Operational characteristics of the watermark model 200 soil water potential sensor for irrigation management. Appl Eng Agric 8:603–609

Moriana A, Fereres E (2002) Plant indicators for scheduling irrigation of young olive trees. Irrig Sci 21:83–90

Sellés G, Berger A (1990) Physiological indicators of plant water status as criteria for irrigation scheduling. Acta Hortic 278:87–99

Shock CC, Feibert EBG, Saunders LD (1998a) Potato yield and quality response to deficit irrigation. HortScience 33:655–659

Shock CC, Feibert EBG, Saunders LD (1998b) Onion yield and quality affected by soil water potential as irrigation threshold. HortScience 33:1188–1191

Taber HG, Lawson V, Smith B, Shogren D (2002) Scheduling microirrigation with tensiometers or Watermarks. Int Water Irrig 22:22–26

Turner NC (1981) Techniques and experimental approaches for the measurement of plant water status. Plant Soil 58:339–366

Tyree MT, Jarvis PG (1982) Water relations and carbon assimilation. In: Lange OL, Nobel PS, Osmond CB, Ziegler H (eds) Physiological plant ecology II. Springer, Berlin Heidelberg New York, pp 35–78

5.- Usefulness of diurnal trunk shrinkage as a water stress indicator in plum trees

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Running head: Trunk shrinkage as water stress indicator

Summary

The seasonal evolution of maximum diurnal trunk shrinkage (MDS) was compared with that of midday stem water potential (Ψs) during three years in drip irrigated plum tress under differing watering regimes. In well irrigated plots, day-to-day variations of Ψs and MDS were related to the evaporative demand. Reference equations were obtained to predict MDS and Ψs values for well drip irrigated trees, as function of environmental conditions. A decrease in plant water status towards the end of the season occurred even in the well irrigated trees, probably due to the reduced volume of soil wetted by the drip irrigation system. Thus, for Ψs, different reference equations have to be used at the beginning of the season (fruit growth) than at the end (after harvest). A seasonal change in the relation between MDS and Ψs was observed, which compensated the decrease in plant water status so that similar MDS values for well irrigated trees are expected before or after harvest.

The influence of tree size on the relationship between MDS and Ψs was also investigated. In a range of tree trunk diameter between 8 to 13 cm, MDS increased a 13% for each cm of increase of trunk diameter, due to the thicker phloem tissues of larger trees. This result may allow to extrapolate Ψs prediction based on empirical relations with MDS to plum trees of different sizes.

keywords: stem water potential, reference equations, tree size, phloem thickness.

Introduction

Plants integrate the effect of both, soil water availability and climatic conditions; because of that, there has been an increasing emphasis on plant water status evaluation, particularly for irrigation scheduling purposes (Jones 2004). However, the coupling of the plant with the evaporative demand makes its water status to be dynamic in response to several fluctuating environmental properties (Reicosky et al. 1975, Hincley and Bruckerhoff 1975). This means that a single measurement of plant water status may be meaningless if taken without a reference value from plants without soil water limitations.

Traditionally leaf water potential, measured with the pressure chamber (Scholander et al. 1965) and more recently, water potential of bag covered leaves (Begg and Turner 1970), named stem water potential (Ψs), has been adopted in fruit trees as a water stress indicator (Garnier and Berger 1985, McCutchan and Shackel 1992). Nowadays, research in this field is focused on evaluating trunk diameter variations as water stress indicators, because they can be easily automated in a field scale (Goldhamer and Fereres 2001).

Shrinking and swelling of tissues depend on plant water status (Kozlowski 1967), being the xylem water potential the driving force of stem shrinkage during the day (Klepper et al. 1971). During the last three decades some studies pointed out considering the influence of factors affecting phloem thickness, particularly tree size, on the absolute shrinkage rates (Molz and Klepper 1973, Parlange et al. 1975, Simonneau et al. 1993, Naor and Cohen 2003). Huguet (1985), showed that within a single tree, the absolute trunk shrinkage increased when the diameter of the branch where it was measured increased. More recently, Améglio et al. (2001) observed that the magnitude of stem shrinkage in response to freezing temperature was proportional to the organ diameter. However, to the best of our

knowledge, there are no studies describing the influence of tree size in the relationship between stem shrinkage and Ψs among trees of different size. For horticultural studies is important to define: i) whether, as expected, tree size affects the relationship between MDS and Ψs or not and ii) to quantify this influence, in order to extrapolate Ψs prediction based on MDS to different sized trees. The objectives of this work were to further asses the usefulness of MDS as a water stress indicator by: i) comparing the seasonal evolution of MDS with that of Ψs on trees under different watering regimes, ii) studying, in well irrigated plants, the influence of the aerial environment on both indicators, and iii) studying the relationship between Ψs and MDS and the influence of tree size on it.

Material and methods

Experimental plot and climatic conditions

The experiment was performed over three consecutive years (2002-2004), in a commercial Japanese plum orchard (*Prunus salicina*, 'Black Gold' grafted on 'Mariana GF81' rootstock) at Líria, Valencia, Spain, (40ºN, elevation 300m). The soil was a sandy loam 32% (w/w) stones, with an effective depth of 80 cm. The irrigation water had an average EC of 1.1 dS m^{-1} and an average Cl^- concentration of 122 mg l^{-1}. Trees were planted in 1997 at a spacing of 5 x 3.5 m. At the beginning of the experiment average tree LAI, percentage of shaded area and trunk circumference were 0.73, 29% and 0.29 m, respectively. Agricultural practices followed were those common for the area and crop load levels were about 4 to 5 fruits cm^{-2} of trunk cross sectional area.

Climatic data were recorded at an automated weather station near the orchard and daily average air vapour pressure deficit (VPD) and daily reference evapotranspiration (ETo) were calculated according to Allen et al. (1998). During the irrigation season, (March to October), annual precipitation and ETo were respectively: 406 mm and 897 mm in 2002, 387 and 912 mm in 2003 and 275 mm and 866 mm in 2004.

Irrigation treatments

The experiment had six treatments and three replicates in a randomized complete block design. Each experimental plot comprised three adjacent rows of eight trees per row, with the two center trees of the central row being used for measurement. To study the water relations only the following treatments were used: a control treatment irrigated at 100% of tree evapotranspiration (ETc) and three or two different deficit irrigation treatments. During 2002 and 2003, three deficit irrigated treatments were used; two of them irrigated at 33% of ETc either, during phases II and III of fruit growth (33-I) or during post-harvest (33-II), and a third one irrigated at 66% ETc from pit hardening to the end of the season (66-I+II). In 2004 two deficit irrigated treatments were used; one irrigated at an average of 65% of ETc during fruit growth and at 50% of ETc during post-harvest (65-I 50-II), and a second one irrigated at an average of 40 % of ETc only during post-harvest (40-II).

Crop evapotranspiration, was estimated as the product of ETo and crop coefficient (Kc). The reference evapotranspiration was calculated from the Penman-Monteith equation and Kc were obtained from Doorenbos and Pruitt (1977) and adjusted for tree size following Fereres and Goldhamer (1990).

Drip irrigation was applied with six emitters per tree, each delivering 3.85 L h^{-1}, which were located in a double irrigation line parallel to the tree row.

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Trunk diameter variations

The diameter of the trunk was measured continuously with linear variable differential transformers (LVDT, Schlumberger Mod. DF-2.5) on six representative trees per treatment. On each experimental tree a sensor was fixed to the main trunk by a metal frame of Invar (a metal alloy with a minimal thermal expansion) located about 20 cm from the ground on the north side. Prior to installation the transformers were individually calibrated by means of a precision micrometer (Verdtech SA, Spain). The typical output coefficient was about 85 mV mm^{-1} V^{-1}. The resolution of trunk diameter measurements including all sources of variation (calibration, non-linearity, excitation, output voltage recording and thermal changes) was about 10 µm. From these sensors we calculated the maximum daily shrinkage (MDS), obtained as the difference between the maximum diameter reached early in the morning and the minimum reached normally during the afternoon. Sensor data were automatically recorded every 30 s using a data logger (model CR23X connected to an AM25T multiplexer, Campbell Sci. Co.) programmed to report mean values every 30 min.

Stem water potential

Midday stem water potential (Ψs) was measured with a pressure chamber, following procedures described by Turner (1981). Two leaves per tree on two trees from each treatment, that also had an LVDT sensor installed, were determined. Mature leaves from the north face near the trunk, were enclosed in plastic bags covered with silver foil at least two hours prior to the measurements, which were carried out between 12:00 and 13:00 h solar time, approximately every ten days from May to October.

Reference equations

During the three years the fully watered control treatment was used to obtain the relationships between MDS and Ψs with average daily VDP, ETo and air temperature (Tair). Data used were collected from the beginning of May, when trees had already developed up to 70% of their total shaded area, to the end of October, before leaf fall. To make sure that fully irrigated trees had not experienced any important soil water deficit, soil water potential (Ψsoil) was measured with eight granular matrix sensors per treatment according to procedures described on Intrigliolo and Castel (2004). As an additional precaution, data from days when Ψsoil was lower than -30 kPa (e.g. during September and October of the 2002 season) were not used to obtain reference equations.

Influence of trunk diameter on the relationship between MDS and Ψs

The effect of tree size on the relationship between MDS and Ψs was studied using trees from all the irrigation treatments previously explained, except the two trees of the treatment 33-II in 2003, because their MDS was not measured during the entire season. In 2004 four additional trees were selected to increase the range of tree size. These additional trees were irrigated as the control, except in June (before harvest) and in August (after harvest) when water was withheld during 20 days. On each individual tree, the ratio MDS/Ψs was obtained from those days when Ψs was measured. The average seasonal MDS/Ψs ratio (MDS/Ψs) was then calculated and plotted against trunk diameter (TD) and trunk phloem plus bark thickness (PT). PT was measured at the end of 2003 and 2004 seasons, using a

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digital hand slide gauge (resolution 0.01 mm) on samples extracted with a core borer from the same place were the LVDT was previously installed.

Statistical analysis

Simple linear regression analysis was carried out using the 'reg' procedure of the SAS statistical package (version 8.1; SAS Institute, 1994, Cary, NC) to explore relationships between variables. Significance levels of the correlation coefficient at 5% or higher are reported. In all cases where the relationship appeared to depart from linearity, statistical tests with non linear equations were carried out. Non linear equations are shown only when they significantly improved the goodness of fit.

Results

Seasonal evolution of water stress indicators

At the beginning of each season Ψs in the control treatment was about -0.5 MPa. It then decreased towards harvest, coinciding with the increase in Tair and VPD (Figure 1). By the end of the season, at environmental conditions which were similar to those of the beginning, Ψs of the control trees had decreased to about -0.8 and -0.6 MPa in 2003 and 2004 respectively. In 2002, this drop was more noticeable and even the control treatment experienced some water deficit during the last part of this season. In fact, Ψsoil of the control treatment reached values lower than -30 kPa by the end of the 2002 season (not shown).

MDS in the control treatment had initial seasonal values of about 50 to 75 μm that increased towards harvest. After harvest there was a drop in MDS that thereafter remained around values of 150 to 200 μm (Figure 1C).

Deficit irrigated treatments had in general lower Ψs than the control that were associated with higher MDS. Ψs was much less variable than MDS, with typical values of the coefficient of variation around 8% and 23%, respectively.

Relationship of water stress indicators with environmental variables

Day-to-day MDS and Ψs variations in well irrigated trees were most closely related to VPD and Tair than to ETo (Figure 2 and 3 and Table 1 and 2). However, while MDS correlated better with VPD, Ψs had the best correlation with Tair (Table 1 and 2). In general, for all environmental variables, the correlations were lower for Ψs than for MDS.

When data were analysed separately by periods, on the two main phenological phases of fruit tree crops (before and after harvest), a lower Ψs for a given VPD, Tair or ETo is obtained after harvest than during fruit growth (Figure 2). The intercepts of the relationships of Ψs with Tair, VPD and ETo were all significantly ($p<0.0001$) lower after harvest than before, while the slope in all three cases did not differ significantly ($p>0.157$).

Regarding MDS, differences in the relationship with both VPD and Tair between periods (before and after harvest), were not as clear as with Ψs (Figure 3). In fact the relationships of MDS with Tair and VPD had after harvest higher ($p<0.0001$) intercepts than before harvest, but lower slopes ($p<0.0018$ for VPD and $p<0.0001$ for Tair). Prior to harvest MDS was also highly related to ETo, with an exponential relationship between both variates, although deviations from linearity were more evident only on days of high evaporative

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demand (daily ETo values > 5.5 mm). On the contrary, the correlation after harvest was much weaker and the exponential regression did not improve the goodness of fit.

Influence of tree size on the relationship between MDS and Ψs

MDS was significantly (p<0.001) related to Ψs pooling data over all the season and irrigation treatments (Figure 4). However the relation between MDS and Ψs changed across the season, with lower MDS values obtained during post-harvest for a given Ψs because of the lower slope (p<0.001) in the relationship.

The MDS/Ψs of each tree was negatively related (p<0.001) to the TD (Figure 5A). As tree size increased, there was a reduction (e.g. less negative) on MDS/Ψs, which indicates that higher MDS for a given Ψs is expected with increasing tree size. MDS/Ψs was also negatively related (p<0.001) to PT (Figure 5B). This was so as PT increased linearly with increasing trunk circumference (PT= 0.55*TD -1.22 r^2=0,79 p<0.001).

Discussion

Stem water potential is nowadays widely used as a plant water status indicator because of its reliability on reflecting soil water availability to plant, low variability and relatively good prediction of yield response to water stress (Shackel et al. 1997, Naor 2000), but its measurement cannot be easily automated. The present work explores the possibility of using MDS as a substitute of Ψs because it can be obtained automatically with LVDT sensors.

MDS appears to be a reliable water stress indicator of plum trees. In fact, during the three years, MDS of deficit irrigated treatment were consistently higher than that of well irrigated

plots in concordance with the Ψs evolution. However, similarly to reports on other fruit tree species (Fereres and Goldhamer 2003, Naor and Cohen, 2003) MDS was more variable than Ψs. Therefore, more determinations of MDS than of Ψs are needed, to estimate plant water status with similar precision.

Particularly during fruit growth, there is a good linear relation between both variables over a wide range of Ψs, up to -2.0 MPa (Figure 4). This will allow for an early detection and prevention of water stress that during this period may reduce fruit growth. However, considering a single value of MDS to predict Ψs across the whole season, may lead to an incorrect estimation of plant water status, as there is not an unique relation of MDS with Ψs valid for the whole season (Figure 4). A similar seasonal behaviour on this relationship was also found in recent horticultural studies carried out during a single season (Marsal et al. 2002, Intrigliolo and Castel 2004). Trunk growth itself affects the relationship between MDS and Ψs (McBurney and Costigan 1984), but seasonal changes in trunk growth rates, do not account for the totality of this seasonal behaviour on the MDS-Ψs relationship (Marsal at al. 2002, Intrigliolo and Castel 2004). Several theoretical models have been developed to predict stem or leaf water potential from MDS and vice versa (Molz and Klepper 1972, Parlange et al. 1975, Panterne et al. 1998) but none of them took in consideration possible seasonal changes in the relationship between Ψs and MDS. Recently, Genard et al. (2001) in a more comprehensive study, showed that trunk shrinkage was highly sensitive to changes in the tissue elastic modulus. Therefore, probably lower MDS for a given Ψs after harvest may be due to older, less elastic tissues (Tyree and Jarvis 1982). However as pointed out by Panterne et al. (1988), seasonal changes in the osmolarity of phloem tissues, due to shifts in the whole plant sink-source relations

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(Kozlowski 1992), may also influence trunk shrinkage. In *prunus* species the sugar concentration of woody tissues is normally higher after harvest, because of the absence of the fruit sink strength (Flore and Layne 1997). This should lead to lower osmotic water potential in phloem tissues and therefore to a smaller gradient of water potentials between the xylem and the phloem.

In well irrigated plants, Ψs and particularly MDS, varied with environmental conditions but similarly to findings in almond trees (Fereres and Goldhamer 2003) both VPD and Tair, had a greater effect on MDS than on Ψs (Figure 2 and 3). In fact an increase in 1ºC or 1 kPa increased MDS by 11% and 106% respectively, but only by 6% and 11% on Ψs. These features, particularly for MDS, difficult their use in absolute terms for irrigation scheduling. However, the equation here reported (Table 1 and 2) can be a useful guideline for scheduling irrigation protocols based on Ψs and MDS measurements. In our conditions, Tair may be considered as the best environmental variable to be used in a practical field approach, not only for correcting Ψs, but also for MDS. In fact, despite VPD represented slightly better day-to-day variations in MDS (Table 2); Tair can be obtained more easily and less costly than VPD.

Lower Ψs for similar environmental conditions are expected after harvest than during fruit growth (Table 1). The lower intercepts obtained in the relation with post-harvest data indicates that after harvest there is a decrease in the bulk soil water availability to plant. This is probably due to the reduced volume of soil wetted with the drip irrigation system, which implies that, particularly towards the end of the season, there is a greater proportion of roots in the dry soil portion. This explains why in horticultural studies generally lower Ψs are obtained under drip irrigation (Lampinen et al. 2001, Intrigliolo and Castel 2005)

than with furrow irrigation practices (McCutchan and Shackle 1992, Fereres and Goldhamer 2003).

Despite this decrease in plant water status by the end of the season, similar MDS for a given VPD or Tair are expected prior or after harvest (Figure 3). This is due to the seasonal change in the relationship between MDS and Ψs previously explained. The relation between MDS and VPD or Tair had after harvest higher intercepts (lower bulk soil water availability), but lower slopes because of the lower MDS/Ψs slope during post-harvest.

ETo represents MDS variations equally well as VPD, but only during the fruit growth period as during post-harvest, the relation between MDS and ETo was weak (Table 2). This may be due to a different seasonal sensitivity of stomata to air VPD. In fact, in a recent study Pretorius and Wand (2003) showed that stomata are more sensitive to the aerial environment and therefore better controlling plant water status during post harvest than during fruit growth.

To further prove the usefulness of MDS it is of importance to check for its dependence on tree size. We showed that stem shrinkage, for a given driving force, Ψs, increases with increasing phloem thickness, the tissue responsible of most of the trunk shrinkage (Molz and Klepper 1973). For a field scale approach, MDS values of different sized trees may be more easily corrected using the relation here obtained between the average ratio MDS/Ψs vs tree trunk diameter (Figure 5). In fact, in the range of trunk diameters here evaluated (8 to 14 cm), MDS increases 26 μm for each increment of 1 cm of TD and MPa of Ψs. This represents a relative increase on MDS of only a 13.3%, which seems reasonable considering that PT increased a 15.6% for each increase of 1 cm in TD. However, further studies are needed to explore the influence of tree size on trunk shrinkage, particularly in a

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range of smaller trees. In fact, there is evidence in apple (Huguet, 1985), peach (Genard et al. 2001) and almond (P. Nortes personal communication) that phloem thickness increments exponentially in a range of tree diameter lower than 7.5 cm. This feature should lead to a greater effect of tree size on MDS in trees smaller than the ones here studied.

It is also important to verify the extrapolability of the MDS-Ψs relations here obtained and of the influence of tree size on trunk shrinkage to other tree crops. More effort should be also done to gain a better knowledge of the physiological causes of the seasonal changes in MDS to Ψs. These informations are of paramount importance to use MDS in further irrigation scheduling protocols.

References

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO *Irrigation and Drainage paper* No 56. Rome, Italy, pp 15-27.

Améglio, T., H. Cochard and Ewers F.W. 2001. Stem diameter variations and cold hardiness in walnut trees. J. Exp. Bot. 52:2135-2142.

Begg, J.E. and N.C. Turner. 1970. Water potential gradients in field tobacco. Plant Physiol. 46:343-346.

Doorenbos, J. and W.O. Pruitt. 1977. Crop water requirements. FAO Irrigation and Drainage Paper 24, Rome, Italy, 49.

Fereres, E. and D.A. Goldhamer. 1990. Deciduous fruit and nut trees. *In*: Irrigation of Agricultural Crops (Stewart BA Nielsen DR Eds.) A.S.A. Madison, USA. Monograph. 30, pp 987-1017.

Fereres, E. and D.A. Goldhamer. 2003. Suitability of stem diameter variations and water potential as indicators for irrigation scheduling of almond trees. J. Hort. Sci. Biotechnol. 78:139-144.

Flore, J.A. and D.R. Layne. 1997. Prunus. *In* Photoassimilates distribution in plants and crops: sink-source relationship. Eds. E. Zamski and H. Scheffler. Marcel Dekker. Inc., New York, pp 825-849.

Garnier E. and A. Berger. 1985. Testing water potential in peach trees as an indicator of water stress. J. Hort. Sci. 60:47-56.

Génard, M., S. Fishman, G. Vercambre, J.G. Huguet, C. Bussi, J. Besset and R. Habib. 2001. A biophysical analysis of stem and root diameter variations in woody plants. Plant Physiol. 126:188-202.

Goldhamer, D.A. and E. Fereres. 2001. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrig. Sci. 20:15-125.

Hincley, T.M. and D.M. Bruckerhoff. 1975. The effect of drought on water relations and stem shrinkage of *Quercus alba*. Can. J. Bot. 53:62-72

Huguet, J.G. 1985. Appréciation de l'état hydrique d'une plante à partir des variations micrométriques de la dimension des fruits ou des tiges au cours de la journée. Agronomie. 5:733-741

Intrigliolo, D.S. and J.R. Castel. 2004. Continuous measurement of plant and soil water status for irrigation scheduling in plum. Irr. Sci. 23:93-102.

Intrigliolo, D.S. and J.R. Castel. 2005. Effects of regulated deficit irrigation on growth and yield of young Japanese plum trees. J. Hortic. Sci. Biotechnol. In press.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. J. Exp. Bot. 55:2427-2436.

Klepper, B., V. Douglas, and H.M. Taylor. 1971. Stem diameter in relation to plant water status. Plant Physiol. 48:683-685.

Kozlowski, T.T. 1967. Diurnal variation in stem diameters of small trees. Bot. Gaz. 123:60-68.

Kozlowski, T.T. 1992. Carbohydrate sources and sinks in woody plants. The Botanical Review. 58:107-232.

Lampinen, B.D., K.A. Shackel, S.M. Southwick and B. Olson. 2001. Deficit irrigation strategies using midday stem water potential in prune. Irr. Sci. 20:47-54.

Marsal, J., M. Gelly, M. Mata, J. Arbonés, J. Rufat, and J. Girona. 2002. Phenology and drought affects the relationship between daily trunk shrinkage and midday stem water potential of peach trees. J. Hortic. Sci. Biotechnol. 77: 411-417.

McBurney, T. and P.A. Costigan. 1984. The relationship between stem diameter and water potentials in stem of young cabbage plants. J. Exp. Bot. 35:1787-1793.

McCutchan, H. and K.A. Shackel. 1992. Stem water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). J. Am. Soc. Hort. Sci. 117:607-611.

Molz, F.J. and B. Klepper. 1972. Radial propagation of water potential in stems. Agron. J. 64:469-473.

Molz, F.J. and B. Klepper. 1973. On the mechanism of water-stress-induced stem deformation. Agron. J. 65:304-306.

Naor, A. 2000. Midday stem water potential as a plant water stress indicator for irrigation scheduling in fruit trees. Acta Hort. 537:447-454.

Naor, A. and S. Cohen. 2003. Sensitivity and variability of maximum trunk shrinkage, midday stem water potential and transpiration rate in response to withholding irrigation from field-grown apple trees. HortScience. 38:547-551.

Panterne, P., J. Burger and P. Cruziat. 1998. A model of the variation of water potential and diameter within a woody axis cross-section under transpiration conditions. Trees. 12:293-301.

Parlange, J.Y., N.C. Turner and P.E. Waggoner. 1975. Water uptake, diameter change, and non-linear diffusion in tree stems. Plant. Physiol. 55:247-250.

Pretorius J.J.B. and S.J.E. Wand. 2003. Late-season stomatal sensitivity to microclimate is influenced by sink strength and soil moisture stress in 'Braestar' apple trees in South Africa. Sci. Hort. 98:157-171.

Reicosky, D.C., R.B. Campbell and C.W. Doty. 1975. Diurnal fluctuation of leaf-water potential of corn as influenced by soil matric potential and microclimate. Agron. J. 67:380-385.

Sas institute. 1994. SAS/STAT *user's guide*. SAS Inst. Inc., Cary, N.c., USA.

Scholander, P.F., H.T. Hammel, E.D. Bradstreet and E.A. Hemmingsen. 1965. Sap pressure in vascular plants. Science. 148:339-346.

Shackel, K.A., H. Ahmadi, W. Biasi, R. Buchner, D. Goldhamer, S. Gurusinghe, J. Hasey, D. Kester, B. Krueger, B. Lampinen, G. McGourty, W. Micke, E. Mitcham, B. Olsen, K. Pelletrau, H. Philips, D. Ramos, L. Scheankl, S. Sibbert, R. Snyder, S. Southwick, M. Stevenson, M. Thorpe, S. Weinbaum and J. Yeager. 1997. Plant water status as an index of irrigation need in deciduous fruit trees. HortTechnol. 7: 23-29.

Simonneau, T., R. Habib, J.P. Goutouly and J.G. Huguet. 1993. Diurnal changes in stem diameter depend upon variations in water content: direct evidence in peach trees. J. Exp. Bot. 44:615-621.

Tyree, M.T. and P.G. Jarvis. 1982. Water relations and carbon assimilation. *In* Physiological Plant Ecology II. Eds. O.L. Lange, P.S. Nobel, C.B. Osmond and H. Ziegler. Springer Verlag, Berlin, pp 35-78.

Turner, N.C. 1981. Techniques and experimental approaches for the measurement of plant water status. Plant and Soil. 58:339-66.

Table 1. Values of the parameters of best fit regression equations between stem water potential (Ψs) and environmental variables for different periods. Daily reference evapotranspiration (ETo), daily average air temperature (Tair) and daily average air vapour pressure deficit (VPD). Intercept (a), slope (b), coefficient of determination (r^2) and mean square error (MSE) of the linear regression (y=a+bx) are shown.

Phenological period	a	b	r^2	MSE
Ψs vs ETo				
Fruit growth	-0.08	-0.14	0.41***	0.021
Post-harvest	-0.70	-0.09	0.51***	0.016
Whole season	-0.57	-0.07	0.11*	0.058
Ψs vs Tair				
Fruit growth	0.24	-0.05	0.67***	0.012
Post-harvest	-0.29	-0.04	0.65***	0.013
Whole season	0.17	-0.05	0.54***	0.030
Ψs vs VPD				
Fruit growth	-0.35	-0.29	0.42***	0.020
Post-harvest	-0.72	-0.23	0.57***	0.014
Whole season	-0.44	-0.30	0.39***	0.039

* and *** significant at P< 0.05 or 0.001, respectively.

Table 2. Values of the parameters of best fit regression equations between maximum diurnal shrinkage (MDS) and environmental variables for different periods. Daily reference evapotranspiration (ETo), daily average air temperature (Tair) and daily average air vapour pressure deficit (VPD). Intercept (a), slope (b), coefficient of determination (r^2) and mean square error (MSE) for linear ($y=a+bx$) or exponential regression ($y=ae^{bx}$) are shown.

Phenological period	Type of regression	a	b	r^2	MSE
MDS vs ETo					
Fruit growth	Exponential	11.2	0.51	0.73***	1588
Post-harvest	linear	79.1	25.5	0.24***	3657
Whole season	linear	21.8	31.1	0.25***	3516
MDS vs Tair					
Fruit growth	linear	-181.3	15.8	0.71***	1712
Post-harvest	linear	-46.9	9.9	0.32***	3277
Whole season	exponential	15.4	0.10	0.61***	2317
MDS vs VPD					
Fruit growth	linear	-31.6	123.8	0.72***	1568
Post-harvest	linear	37	92.2	0.54***	2198
Whole season	linear	-6.7	112.8	0.65***	2021

*** significant at $P< 0.001$.

Figures captions

Figure 1. Seasonal pattern of A) daily average air temperature (Tair) and daily average air vapour pressure deficit (VPD), B) stem water potential (Ψs) and C) maximum diurnal shrinkage (MDS). For clarity, values of the deficit irrigated treatments on periods of no water restriction are not shown. Data are means and standard errors of four determinations and of six linear variable transformer sensors, respectively. DOY day of the year.

Figure 2. Relationship of stem water potential (Ψs) of the control treatment, for the whole season (solid line) and separated by periods (dotted lines) with: A) daily reference evapotranspiration (ETo), B) average daily air temperature (Tair), C) average daily air vapour pressure deficit (DPV). Values are averages and standard errors of four determinations. * and *** significant at $p < 0.05$ and $p < 0.001$, respectively.

Figure 3. Relationship of maximum diurnal shrinkage (MDS) of the control treatment, for the whole season (solid line) and separated by periods (dotted lines) with: A) daily reference evapotranspiration (ETo), B) average daily air temperature (Tair), C) average daily air vapour pressure deficit (DPV). Values are averages and standard errors of six linear variable transformer sensors. *** significant at $p < 0.001$.

Figure 4. Relationship between MDS and Ψs for the whole season (solid line) and separated by periods (dotted lines). Values are averages and standard errors of six sensor and four determinations. *** significant at $p < 0.001$.

Figure 5. Relationship between the average MDS/Ψs ratio with A) trunk diameter (TD) and B) phloem thickness (PT). *** significant at $p < 0.001$.
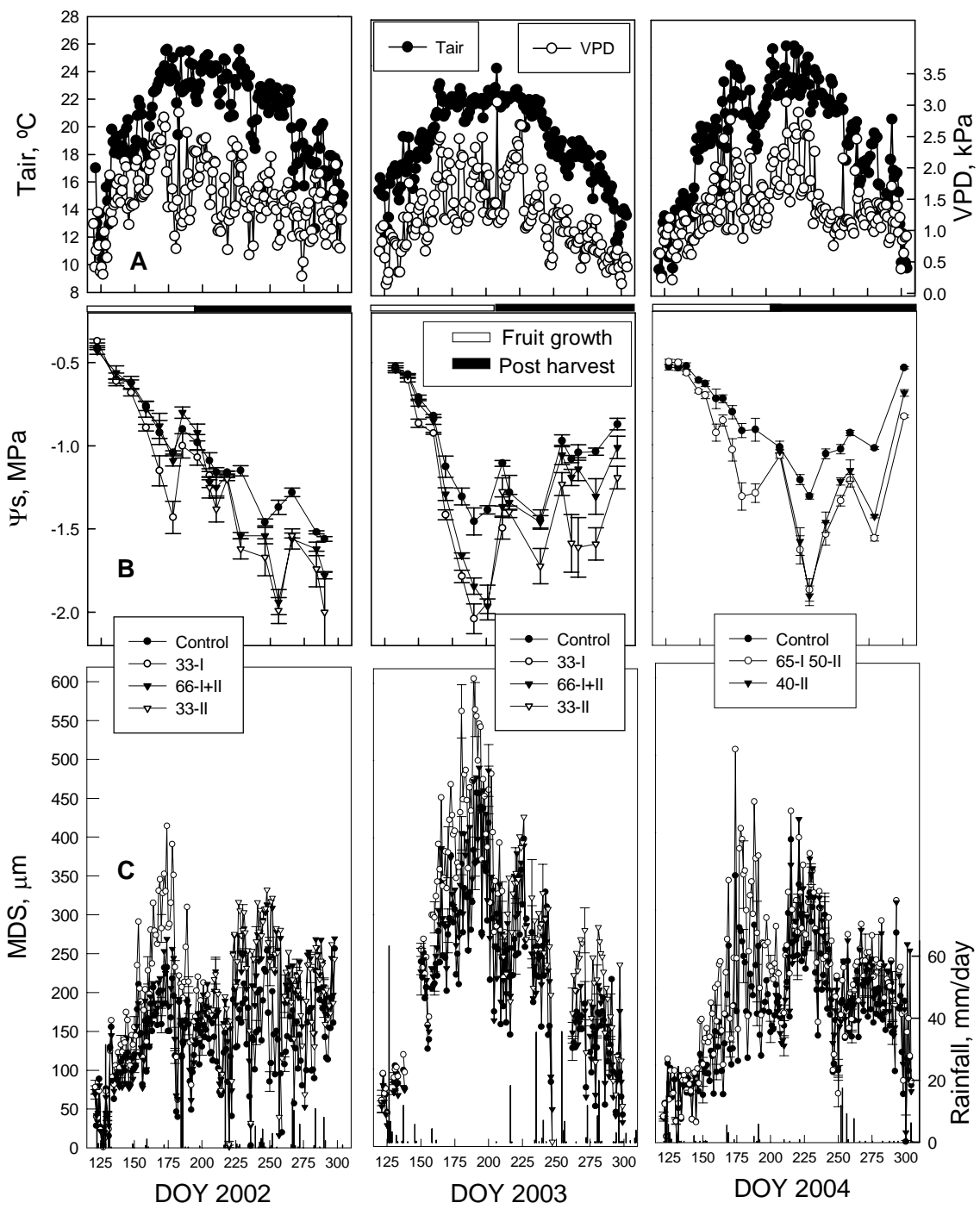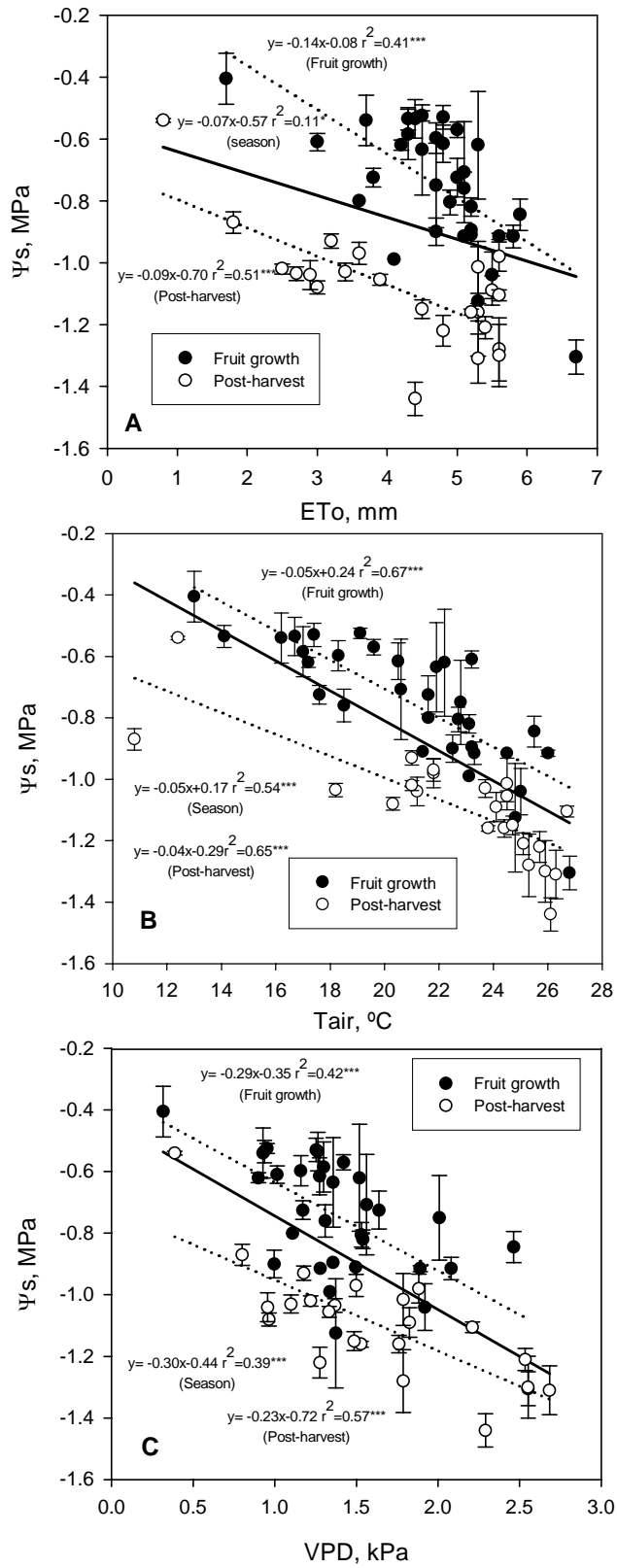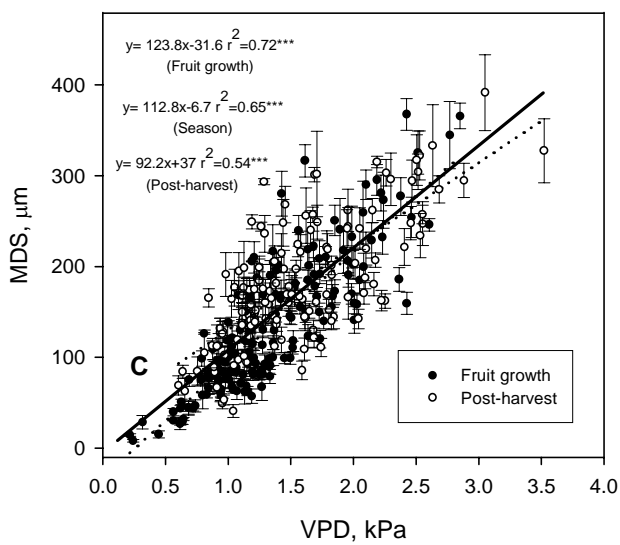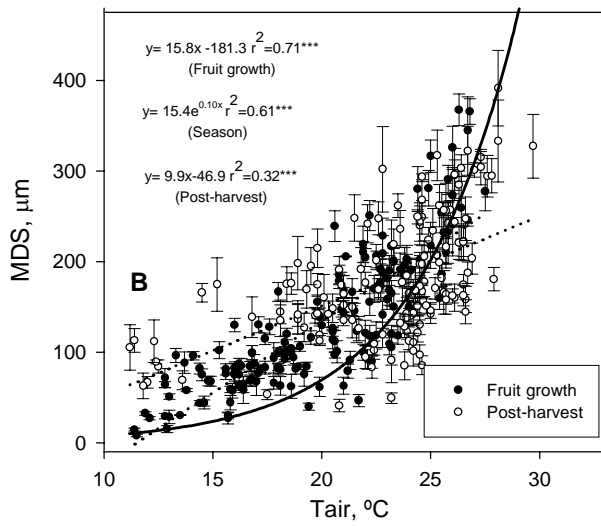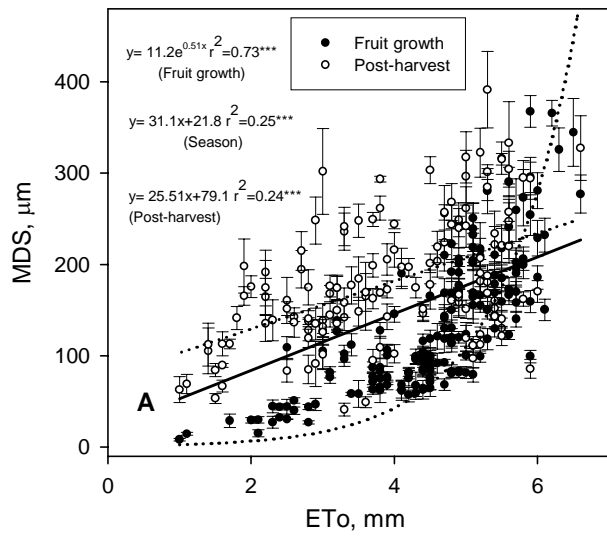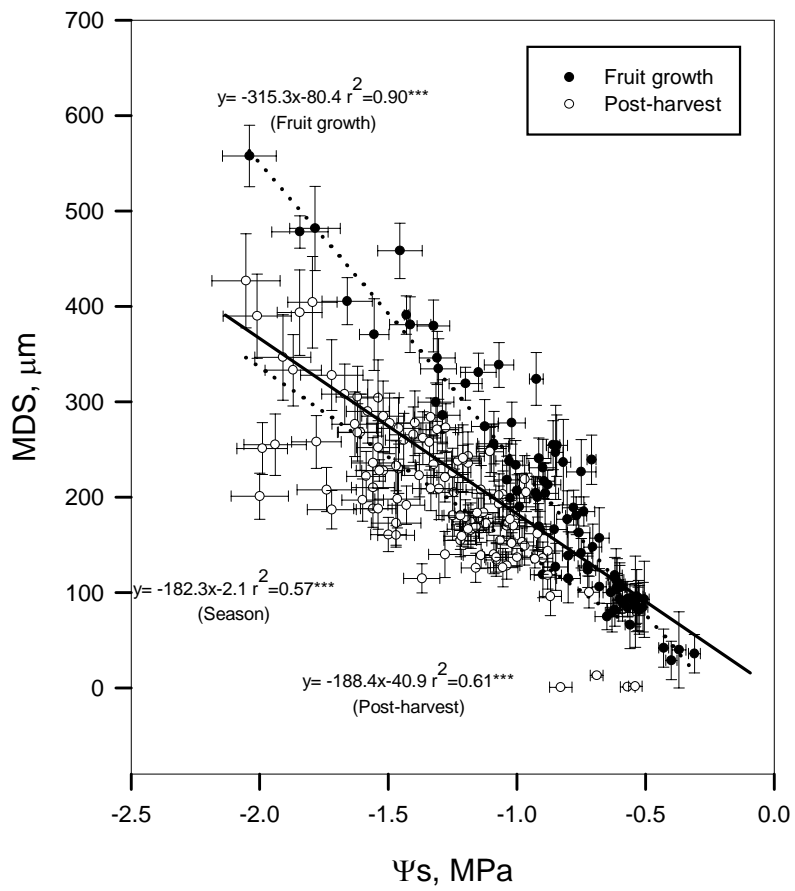
Figure1

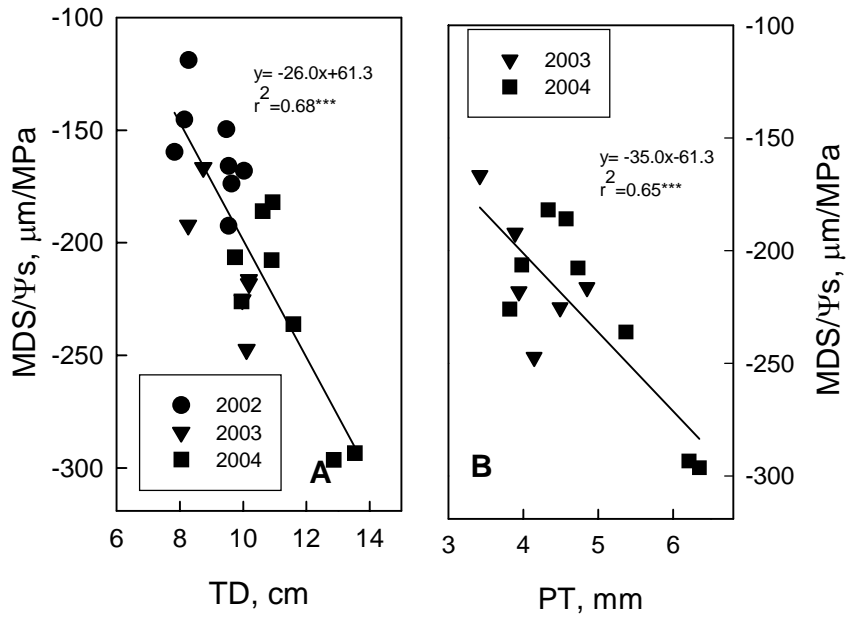Figure 2

Figure 3

Figure 4

Figure 5

6.- Discusión general

En trabajos previos en ciruelo japonés se ha estudiado el efecto del estrés hídrico aplicado durante el crecimiento del fruto (Naor et al., 2004), o en post-cosecha (Johnson et al., 1994), y el efecto de la carga (Naor, 2004; Naor et al., 2004) sobre la producción y el tamaño del fruto. Sin embargo no se prestó atención a la respuesta vegetativa del árbol a ambos factores.

Desde un enfoque agronómico global no se puede desligar el efecto de las restricciones hídricas o de la carga de cosecha sobre el crecimiento vegetativo, de los efectos sobre la producción y calidad de la cosecha. De hecho, para optimizar la productividad de una plantación joven, es preciso maximizar el crecimiento del árbol a fin de incrementar, en el menor tiempo posible, el área foliar y el número de frutos a dejar tras el aclareo, sin alterar la carga del árbol (nºfrutos/cm^2 sección tronco ó m^2 área foliar). Sin embargo, desde un punto de vista económico en fruticultura, y en particular en el ciruelo Black-Gold, puede ser de gran importancia controlar el crecimiento del árbol para reducir costes, en particular de poda y aclareo, buscando un equilibrio entre la máxima productividad y el ahorro de mano de obra.

Así, nuestros resultados han mostrado que el estrés hídrico aplicado exclusivamente en post-cosecha permitió reducir el crecimiento del árbol sin repercutir negativamente sobre la producción durante tres años al no haberse alterado el nivel de carga ni el crecimiento del fruto al año siguiente (Capítulo 2). Sin embargo, de forma similar a lo obtenido en melocotonero tardío (Girona et al., 2005), debe prestarse atención al efecto acumulado del estrés hídrico sobre el crecimiento del árbol, ya que en el tercer año, hubo una reducción de la cosecha de un 10% que, aunque no fue estadísticamente significativa (P=0.145), sí puede ser importante a nivel económico (Tabla 3 del capítulo 2). Además, en un plazo mayor del aquí evaluado, es esperable una reducción mayor de la cosecha si el estrés hídrico se prolongara durante más años.

Por ello, tampoco es conveniente reducir en exceso el crecimiento del árbol. En este sentido, tanto un estrés moderado pero de larga duración, como el del tratamiento 66-I+II (capítulo 2), como el déficit hídrico hasta cosecha con carga alta (Capítulo 3), no son recomendables agronómicamente, en particular en plantaciones jóvenes, debido a la considerable (28% y 51%, respectivamente) reducción del crecimiento del tronco observada en estos tratamientos.

El tratamiento 66-I+II (capítulo 2), a pesar de proporcionar ahorros de agua similares a los de la restricción severa del riego sólo en post-cosecha, redujo en mayor medida el crecimiento del árbol (Tabla 5 del capítulo 2), seguramente debido al efecto acumulado del estrés de larga duración. Este hecho indica la mayor conveniencia del RDC, donde el estrés hídrico se suele aplicar en un breve periodo de tiempo aunque de forma severa, frente al riego deficitario continuado.

Por otra parte, los resultados de este trabajo indican que en ciruelo Black-Gold, de forma similar a otras variedades de frutales de hueso de maduración temprana o intermedia (Torrecillas et al., 2000; Naor et al., 2004), resulta difícil reducir el crecimiento vegetativo del árbol sin afectar al crecimiento del fruto, si el estrés hídrico se aplica antes de la cosecha (Tabla 3 y Figura 1 del Capítulo 2). Esto es así ya que en estas variedades, hasta la cosecha, no existe una clara separación temporal entre el crecimiento vegetativo y el crecimiento del fruto. Este es un factor clave para el éxito de los programas de RDC (Chalmers, 1989) y sólo ocurre de forma clara durante la fase de endurecimiento del hueso en variedades tardías (DeJong y Goudrian, 1989).

Así, el estrés hídrico aplicado durante la fase III de crecimiento del fruto, redujo como era esperable su tamaño final, siendo su efecto proporcional al estrés acumulado (Capítulo 2 y 3). El fruto, al final de su crecimiento, antes de la fase de maduración, acumula gran cantidad de agua (Agustí, 2000). Por ello la reducción del tamaño del fruto, fundamentalmente debida a su menor contenido en agua, posiblemente se deba, a una reducción en la fuerza motriz de entrada de agua en el fruto, como indican Berman y DeJong (1996). Así, el menor Ψtallo observado en los árboles con restricciones hídricas sugiere un menor gradiente de potencial hídrico entre el pedúnculo y el fruto (Jonson et al.,

1992). También es esperable que el posible efecto del estrés hídrico sobre el turgor de las células del fruto (Hsiao, 1973) haya afectado a su crecimiento (Cosgrove, 1993).

En cambio, el contenido en materia seca no fue afectado por el estrés hídrico, de forma similar a lo obtenido en ciruelo para pasificación (Lampinen et al., 1995) y melocotonero (Girona et al., 1993). Estos resultados ponen de manifiesto que el estrés hídrico por si solo no suele conllevar una limitación importante de la fuente de fotoasimilados. De hecho, Berman y DeJong (1996) y Girona et al., (2004), sólo obtuvieron una reducción de la materia seca del fruto, cuando además de aplicar un estrés hídrico severo había un nivel de carga elevado.

Dado que recortar el riego durante toda la fase III del crecimiento del fruto redujo su tamaño (capítulo 2), en los experimentos descritos en el capítulo 3 se planteó una estrategia de riego deficitaria diferente definida como 'St-Rec' (Estrés y Recuperación). De este modo, se restringió el riego de forma más severa inmediatamente después de la fase exponencial de crecimiento del fruto, finalizando las restricciones unos 25 días antes de la cosecha. Por una parte se pretendía afectar más el crecimiento vegetativo del árbol, y explorar la posibilidad de un crecimiento compensatorio del fruto (Huang et al., 2000), tras la reanudación del riego a plena dosis. Sin embargo, sólo el primer objetivo pudo realizarse, pues los árboles no recuperaron su estado hídrico óptimo y por ello el fruto se quedó más pequeño que en el control. De forma similar en variedades más tardías de la aquí evaluada, un factor clave para el éxito de este tipo de estrategia de riego deficitaria, es el tiempo que tarda el árbol en recuperar su estado hídrico óptimo una vez el fruto ha comenzado su última fase de crecimiento lineal (Marsal et al., 2004). Así, si el estrés hídrico se prolonga durante la fase lineal de crecimiento del fruto, a pesar de que el riego haya vuelto al 100% de la evapotranspiración del cultivo, el tamaño final del fruto puede verse afectado (Goldhamer et al., 2002).

De todos modos la ligera reducción del tamaño del fruto observada en el 'St-Rec' pudiera ser compensada económicamente por el adelanto en la maduración del fruto que esta estrategia de riego provocó (Tablas 3 y 4 del capítulo 3). En particular en zonas de cultivo tempranas, donde llegar primero a los mercados es uno de los principales objetivos agronómicos, pudiera ser de interés adelantar la maduración del fruto. En el futuro, se

deberá mejorar el momento de comienzo y final de las restricciones, a fin de favorecer la recuperación de los árboles antes de la cosecha, además de reducir la integral de estrés para que no supere el umbral aquí determinado (40-45 MPa·día). En este sentido, en melocotonero, Marsal et al., (2004) proponen que durante el periodo de recorte del agua el estrés máximo al que debe someterse la planta debe ser inferior a un Ψtallo de -1.5 MPa.

En el capítulo 3 se muestra que la carga, como era esperable, también redujo el tamaño del fruto. Pero este efecto es en gran parte independiente de las relaciones hídricas del árbol. De hecho, mientras los tratamientos '-1.5 MPa-L' y 'St-Rec-L' tuvieron valores de Ψtallo sensiblemente menores a los del '100-H' (Figura 1 del capítulo 3), en este último, la reducción del tamaño del fruto debida a la carga alta, fue similar o incluso ligeramente mayor a la causada por el déficit hídrico con carga baja (Figura 6 del capítulo 3).

Más probablemente, la reducción del crecimiento del fruto cuando la carga es alta se deba a la mayor competencia entre frutos. Evidencias indirectas de este efecto de competencia son, tanto el retraso de la maduración del fruto en la carga alta, como su menor firmeza, aún estando menos maduro, posiblemente debido a su menor densidad celular (Tabla 4 del capítulo 3).

La carga alta no aumentó la sensibilidad del crecimiento del fruto al estrés hídrico (Figura 6 del capítulo 3), quizás porque los árboles con carga alta se mantuvieron al mismo estado hídrico que los de carga baja (Figura 1 del capítulo 3). Sin embargo, la combinación de ambos efectos provocó una reducción muy importante (25%) en el tamaño del fruto en comparación con los árboles bien regados y con carga baja. Por ello, a escala comercial en caso de escasez de recursos hídricos, sería más recomendable reducir la carga a fin de reducir poco el tamaño final del fruto. Ahora bien, en árboles con carga baja el crecimiento vegetativo es mayor y por lo tanto mayor es la superficie transpirante, lo que podría conllevar un mayor consumo de agua. En este caso podría retrasarse el momento del aclareo o escalonarlo, para reducir la competencia entre frutos, sin aumentar en exceso la brotación del árbol.

En fruticultura y en particular en el ciruelo, es imprescindible reducir los costes de aclareo. Para ello una técnica cada vez más empleada es la inhibición de la floración mediante la aplicación del ácido giberélico (Southwick et al., 1995; Baviera et al., 2002),

que además de reducir los tiempos de aclareo, favorece el crecimiento del fruto al reducir la competencia entre frutos en las primeras etapas de su crecimiento. Así podría ser de gran interés inhibir la floración y reducir la competencia, en particular en programas de RDC a fin de minimizar los posibles efectos negativos del estrés hídrico.

Por otra parte, se ha demostrado la utilidad del Ψtallo como indicador del estado hídrico de los árboles (Capítulo 2 y 4), confirmando los resultados obtenidos por diversos autores (Shackel et al., 1997; Naor, 2000).

En el futuro, para generalizar el empleo de este indicador en fruticultura, debe estudiarse la posible extrapolación de los umbrales de estrés y ecuaciones de referencias obtenidas en este y otros trabajos, a distintas situaciones de cultivo, por ejemplo: otras variedades o conjuntos portainjerto/variedad, otras especies del genero *Prunus,* distintas características edáficas y climáticas y niveles de carga de cosecha. Si los valores de Ψtallo fueran dependientes de las características particulares de cada explotación, obligaría a obtener previamente los umbrales en cada situación de cultivo, lo que restaría utilidad práctica a este indicador. En este sentido en un trabajo reciente, Basile et al., (2003), han demostrado que el portainjerto puede tener gran influencia sobre los valores de Ψtallo de la variedad injertada sobre él.

En este trabajo, se ha puesto de manifiesto, además, que el sistema de riego empleado puede influir sobre el nivel de hidratación de los árboles. En particular hacia el final del ciclo del cultivo (después de la cosecha), en condiciones de riego localizado, los árboles tienden a tener un menor estado hídrico. Así, las ecuaciones de referencia obtenidas en el capítulo 5 predicen valores de Ψtallo menores (en un 12-14% antes de la cosecha y en un 44-48% después de cosecha) que las obtenidas anteriormente en ciruelo (McCutchan y Shackel, 1992) y almendro (Fereres y Goldhamer, 2003) con sistemas de riego que mojaban toda la superficie del suelo.

También se ha evaluado en el capítulo 3 el efecto de la carga de cosecha sobre el Ψtallo y el MDC. Así, mientras en árboles bien regados el Ψtallo no fue diferente entre niveles de carga, diferencias notables se observaron para el MDC (Figuras 1, 2 y 3 del capítulo 3), lo que indica que el nivel de carga debe de ser tenido en cuenta a la hora de emplear el MDC como indicador del estado hídrico de los árboles para la programación del riego.

Otras incertidumbres surgen para el MDC a la hora de generalizar el empleo de este indicador. En primer lugar, por lo menos en el genero *Prunus*, no existe una única relación entre el MDC y el Ψtallo a lo largo de todo el ciclo de cultivo. Los resultados aquí obtenidos durante tres años (capítulo 5) confirman los obtenidos en ensayos de un año en melocotonero (Marsal et al., 2002) y almendro (Fereres y Goldhamer, 2003).

Mientras en el año 2002 se observó una disminución de la pendiente MDC-Ψtallo a lo largo del post-cosecha (Figura 5 del Capítulo 4), lo que nos llevó a separar el análisis durante este periodo de una forma un poco arbitraria, entre "early post-harvest" y "late-post-harvest", en los dos años siguientes, no se observó tal diferencia (Figura 4 del Capítulo 5). Así en el 2003 y 2004 a lo largo de todo el periodo post-cosecha, la relación observada entre MDC-Ψtallo fue muy similar a la obtenida en el "early post-harvest" del 2002. Esto posiblemente se debió a que en el 2002 los árboles al final del periodo post-cosecha, incluso en el tratamiento control, sufrieron mayor estrés acumulado. Así pues, durante el "late post-harvest", el MDC pudo haber disminuido, a medida que los árboles acumularon el efecto del estrés hídrico, de una forma similar a lo observado en cítricos (Ortuño et al., 2004).

Tras una reelaboración de los datos de los tres años, se observa que no sólo tras la cosecha hay un cambio en la relación MDC-Ψtallo. Incluso durante el periodo de maduración del fruto, una vez el fruto ha enverado y hasta cosecha, la pendiente de la relación MDC-Ψtallo es ligera, aunque significativamente menor (p<0.05), con respecto al periodo en el cual el fruto estaba en pleno crecimiento (Figura 1).

De forma similar en vid (Intrigliolo et al., 2004), tras el envero, también se observa un cambio en la relación MDC-Ψtallo. En esta especie se ha demostrado (Greenspan et al., 1996) que después del envero hay una disfunción de los vasos xilemáticos del racimo que lo aísla del resto del sistema conductor apoplástico de la planta, lo que quizás pueda afectar a la relación MDC-Ψtallo.
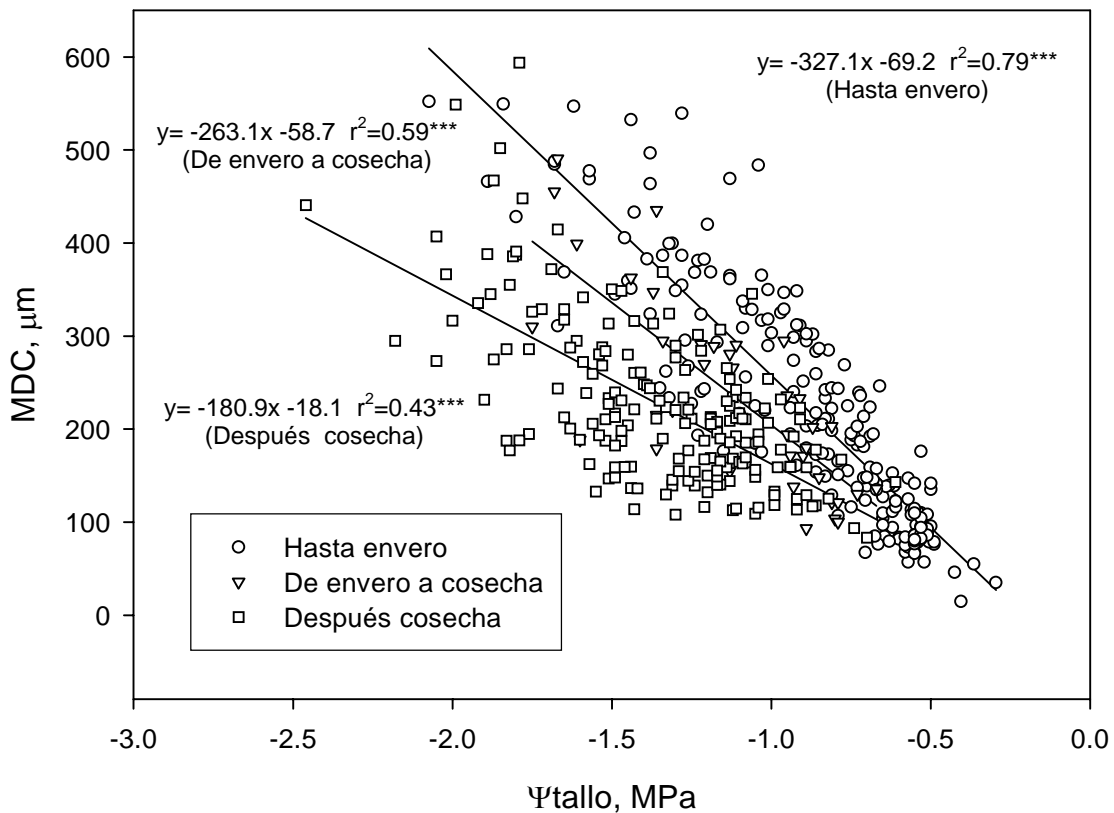
Figura 1: Relación entre MDC y Ψtallo separada en 3 periodos fenológicos: i) hasta el envero del fruto, ii) desde el envero hasta la cosecha y iii) después de la cosecha. Los datos son valores individuales de cada árbol del conjunto de tres años (2002-2004). *** indica que la relación entre las variables es significativa a P<0.001.

Así, nuestros resultados apuntan a que la relación MDC-Ψtallo puede evolucionar a medida que el fruto se desconecta del xilema del resto de la planta, con una cambio brusco en esta relación tras la eliminación del fruto con la cosecha. Así pues, este resultado sugiere que también en ciruelo, aunque no ha sido estudiado, como ocurre en vid y tomate (Ho et al., 1987) pueda producirse esta disfunción xilemática de los tejidos conductores del fruto durante la época de maduración del mismo. En el futuro, habrá que estudiar este aspecto con más detalle, interpretando las variaciones en el diámetro del tronco, no sólo en base a la relaciones hídricas y los flujos hídricos dentro del árbol, sino también teniendo en cuenta el

transporte de fotoasimilados ente los órganos de la planta a lo largo de su ciclo anual, como así lo indican los ensayos de Daudet et al., (2005).

Algunos autores (Naor y Cohen, 2003) han postulado que los valores umbrales de MDC obtenidos para árboles de una determinada edad, y por lo tanto tamaño, podían no ser extrapolables a otras edades del cultivo. Por ello, el Ψtallo sería preferible al MDC, como indicador del estado hídrico de la planta debido a su independencia del tamaño de los árboles.

En este trabajo, además de mostrar que el MDC depende del espesor del floema donde se mida y por lo tanto del diámetro del tronco de los árboles (Figura 5 del capítulo 5), como se había especulado, aunque no demostrado claramente en numerosos trabajos (Parlange et al., 1975; Simonneau et al., 1993), se ha hecho, por primera vez, un esfuerzo para cuantificar dicho efecto a fin de poder extrapolar los umbrales de contracción propuestos a otros tamaños de los árboles y por lo tanto edades futuras del cultivo.

Los resultados de este trabajo indican que, por lo menos en ciruelo, y en el rango de diámetros de tronco aquí evaluado, el incremento del MDC en función del tamaño de los árboles es, en términos porcentuales, muy parecido al aumento de espesor del floema según el diámetro del tronco. Este hecho, además de validar los resultados obtenidos, apunta a la posibilidad de que puedan corregirse directamente los valores de MDC en función del tamaño de los árboles simplemente estudiando la relación existente entre diámetro del tronco y espesor de floema. A pesar de ello, deben hacerse más ensayos para cuantificar la influencia del tamaño de los árboles en otras especies, y confirmar que lo obtenido en este trabajo pueda ser una tónica general.

En este trabajo se ha evaluado la utilidad de los sensores Watermark® para estimar el estado hídrico del suelo y cuantificar el efecto de las restricciones del riego. Su elección se debió a su bajo costo y facilidad de manejo pensando por ello que su uso podría extenderse en fruticultura.

Los resultados muestran que su respuesta a las restricciones del riego fue razonablemente clara ante restricciones severas, pero no tanto cuando el recorte del riego fue moderado

(Figura 1 del capítulo 3 y 4). Por ello no es del todo aconsejable su empleo en aquellos periodos fenológicos más sensibles al estrés hídrico.

Así pues, los sensores pueden ser de utilidad para describir tendencias en el contenido de humedad del suelo, más que para obtener una estimación en términos absolutos del potencial mátrico del suelo. De este modo podrían servir como herramienta complementaria a la programación del riego en base a la información climática, para ajustar con más precisión las dosis de riego, observando la evolución de sus lecturas. De este modo, no se requeriría un calibrado previo de los sensores, agilizando su empleo, y además, se limitaría el problema de su alta variabilidad.

7.- Conclusiones generales

La sensibilidad del ciruelo japonés cv. Black-Gold al déficit hídrico depende de la etapa fenológica en el que se lleve a cabo.

En post-cosecha las restricciones hídricas no afectaron la intensidad de floración ni el cuajado ni el crecimiento del fruto del año siguiente y permitieron ahorros de agua de hasta un 29%. Sin embargo, a medio-largo plazo, el estrés hídrico aplicado en post-cosecha, puede reducir la producción de la plantación debido al efecto acumulado de las restricciones hídricas sobre el crecimiento del árbol. Esta pérdida de producción pudiera ser compensada por los importantes ahorros de costes, en particular poda y aclareo, que podrían conseguirse.

El estrés hídrico durante las fases II y III del crecimiento del fruto, redujo su tamaño de forma proporcional a la integral de estrés, además de reducir el crecimiento del árbol cuando el estrés fue severo o cuando iba asociado a una carga alta. En cambio, la restricción severa del riego, exclusivamente durante la fase II y el principio de la fase III, aunque redujo en un 12% el tamaño del fruto, permitió reducir el desarrollo del área foliar del árbol en un 23% y seguramente por ello adelantar la maduración del fruto.

La restricción del riego moderada, pero de larga duración, aunque permitió ahorrar hasta un 30% de agua, provocó una reducción demasiado severa en el crecimiento del árbol además de afectar al crecimiento del fruto cuando el estrés acumulado durante este periodo supera el umbral de 45 MPa·día.

La reducción del tamaño del fruto debida al déficit hídrico durante su crecimiento se relacionó mejor con la intensidad y duración del estrés (integral de estrés), que con un máximo nivel de estrés alcanzado.

Incrementar el nivel de carga de 4-5 frutos/cm^2 de sección de tronco, a 7-8 frutos/cm^2, permite, a corto plazo, incrementar la cosecha en un 47% ya que el peso medio del fruto se redujo sólo en un 16%.

La carga alta también redujo el crecimiento vegetativo del árbol, aunque con mayores efectos sobre el crecimiento del tronco que sobre el desarrollo del área foliar.

No se observó interacción entre carga alta y riego deficitario moderado sobre el crecimiento del fruto, ya que la reducción del tamaño del fruto debida al estrés hídrico fue similar con carga baja que alta. En cambio, el crecimiento del tronco fue únicamente afectado, por el estrés hídrico moderado cuando la carga era alta.

El nivel de carga también afectó a las relaciones hídricas del árbol. En árboles bien regados la carga alta incrementó en un 15% la conductancia estomática de las hojas, siendo su efecto más pronunciado hacia el final del periodo del crecimiento del fruto. A pesar de ello, la reducción del Ψtallo debido a la carga fue solo de un 6%. En cambio, el efecto de la carga fue más notable sobre las variaciones del diámetro del tronco, incrementando en un 28% el MDC y reduciendo el CT en un 29%.

Tanto el Ψtallo como el MDC pueden ser herramientas útiles para estimar el estado hídrico de los árboles. Sin embargo, se ha demostrado que el Ψtallo es mejor indicador que el MDC, debido a su mayor sensibilidad, la cual deriva de su menor variabilidad, coeficiente de variación medio (CV) del 7%, frente a CV del 19% del MCD (Tabla 1 del Capítulo 4).

El Ψtallo depende en menor medida que el MDC de la demanda evaporativa. Por ello, sería posible emplear el Ψtallo en términos absolutos, mientras que el MDC debe de corregirse mediante una ecuación de referencia obtenida en árboles bien regados.

Se han obtenido ecuaciones de referencia que permiten predecir el valor esperado tanto de MDC como de Ψtallo en función de las condiciones ambientales, que podrán ser empleadas en protocolos de riego basados en la medida del estado hídrico de los árboles.

Debido al restringido volumen de suelo mojado con el riego localizado, menor es el estado hídrico de los árboles hacia final del ciclo de cultivo (post-cosecha). Por ello, para el Ψtallo habrán de utilizarse distintas ecuaciones de referencia, una a principios del ciclo anual de cultivo (antes cosecha) y otra después de la cosecha. Sin embargo, una misma ecuación de referencia podría emplearse para el MDC a lo largo de todo el ciclo anual de cultivo. Esto se debe a un cambio estacional en la relación MDC-Ψtallo, que conlleva menores MDC para un mismo Ψtallo durante el periodo post-cosecha y por lo tanto compensa la reducción del estado hídrico de los árboles.

Para el MDC diferentes ecuaciones de referencia deberán usarse en función del nivel de carga de los árboles.

Para un mismo estado hídrico del árbol el valor absoluto del MDC depende del diámetro de los árboles, ya que los árboles más grandes tienen mayor espesor de floema. Así, en un rango de diámetro de tronco de entre 8 y 14 cm, el MDC incrementa un 13% por cada incremento de 1 cm en el diámetro del tronco.

El CT puede ser un indicador útil del estado hídrico de los árboles, en particular después de la cosecha, cuando el crecimiento del tronco es más acusado que durante la fase final del crecimiento del fruto. Sin embargo, el CT responde a la falta de agua en el suelo mas lentamente que el MCD o el Ψtallo. Además su variabilidad es mayor que la del MCD.

Para emplear el CT como indicador del estado hídrico de los árboles deben de tenerse en cuenta los cambios en las relaciones fuente-sumidero a lo largo del ciclo anual de cultivo. Por ello, aunque no se ha demostrado que la evolución de este indicador pueda depender de las condiciones ambientales, su uso debe de ser acompañado por una referencia obtenida en árboles sin limitación de agua en el suelo.

Los sensores Watermark a pesar del pequeño volumen del suelo explorado y de su alta variabilidad, permiten tener una razonable estima del estado hídrico de los árboles, en particular en condiciones de suelo seco (Ψm < -40 kPa). En suelo húmedo (-20 kPa<Ψm< -10 kPa) su sensibilidad es menor, por lo que su empleo no es aconsejable en aquellos periodos fenológicos más sensibles al estrés hídrico.

8.- Bibliografía general

Agustí, M. 2000. Crecimiento y maduración del fruto. En: Fundamentos de Fisiología vegetal. J. Azcón-Bieto y M. Talón (Eds), McGraw-Hill Interamericana de España SAU y Ed. Univ. Barcelona, Madrid, España, pp. 419-433.

Agustí, M. 2004. Desarrollo del fruto. En: Fruticultura. Ediciones Mundi-Prensa, Madrid, España, pp. 127-147.

Alarcón, J.J., R. Domingo, S.R. Green, E. Nicolás and A. Torrecillas. 2003. Estimation of hydraulic conductance within field-grown apricot using sap flow measurements. *Plant and Soil*. 251:125-135.

Basile, B., J. Marsal and T.M. DeJong. 2003. Daily shoot extension growth of peach trees growing on rootstocks that reduce scion growth is related to daily dynamics of stem water potential. *Tree Physiology*. 23:695-704.

Baviera, B., M. Juan, V. Almela, N. Gariglio y M. Agustí. 2002. La inhibición de la floración en el melocotonero (*Prunus persica* L. Bastch), como técnica indirecta de aclareo de frutos. *Fruticultura profesional*. 125:15-28.

Behboudian, M.H. and T.M. Mills. 1997. Deficit irrigation in deciduous orchards. *Horticultural Reviews*. 21:125-131.

Berman, M.E. and T.M. DeJong. 1996. Water stress and crop load effects on fruit fresh and dry weights in peach (*Prunus persica*). *Tree Physiology*. 16:859-864.

Berman, M.E. and T.M. DeJong. 2003. Seasonal patterns of vegetative growth and competition with reproductive sinks in peach (*Prunus pesica*). *Journal of Horticultural Science and Biotechnology*. 78:303-309.

Blanco, A., A. Pequerul, J. Val, E. Monge and J. Gomez Aparisi. 1995. Crop-load effects on vegetative growth, mineral nutrient concentration and leaf water potential in 'Catherine' peach. *Journal of Horticultural Science and Biotechnology*. 70:623-629.

Chalmers, D.J. 1989. A physiological examination of regulated deficit irrigation. *New Zeland Journal of Agricultural Science*. 4:44-48.

Chalmers, D.J., P.D. Mitchell and J. Van Heek. 1981. Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. *Journal of the American Society for Horticultural Science*. 106:307-312.

Chalmers, O. and B. van den Ende. 1974. Productivity of peach trees: factor affecting dry–weight distribution during tree growth. *Annals of Botany*. 41:707-714.

Cohen, M., D.A. Goldhamer, E. Fereres, J. Girona and M. Mata. 2001. Assessment of peach tree responses to irrigation water deficit by continuous monitoring of trunk diameter changes. *Journal of Horticultural Science and Biotechnology*. 761:55-60.

Cosgrove, D.J. 1993. How do plant cell walls extend?. *Plant Physiology*. 102:1-6.

Daudet, F.A., T. Améglio, H. Cochard, O. Archilla and A. Lacointe. 2005. Experimental analysis of the role of water and carbon in tree stem diameter variations. *Journal of Exerimental Botany*. 56:135-144.

DeJong, T.M., J.F. Doyle and K.R. Day. 1987. Seasonal patters of reproductive and vegetative sink activity in early and late maturing peach (*Prunus persica*) cultivars. *Physiologia Plantarum*. 71:83-88.

DeJong, T.M. and J. Goudrian. 1989. Modelling peach fruit growth and carbohydrate requirements: reevaluation of the double-sigmoid growth pattern. *Journal of the American Society for Horticultural Science*. 114: 800-804.

Dichio, B., C. Xiloyannis, V. Nuzzo, G. Montanaro e A.M. Palese. 2004. Risparmio di acqua nella peschicoltura precoce con la tecnica dello stress idrico controllato. *Frutticoltura*. 7:53-57.

Ebel, R.C., E.L. Proebsting and R.G. Evans. 1995. Deficit irrigation to control vegetative growth in apple and monitoring fruit growth to schedule irrigation. *HortScience*. 30:1229-1232.

FAO. 2003. Agricultura 21; Enfoques; Revista Gestión Moderna del Riego. Departamento de Agricultura. FAO, Roma.

Faust, M. 1989a. Photosynthetic productivity. En: Physiology of Temperate Zone Fruit Trees. Wiley-Interscience Publication, New York, USA, pp 1-51.

Faust, M. 1989b. Fruiting. En: Physiology of Temperate Zone Fruit Trees. Wiley-Interscience Publication, New York, USA, pp 169-188.

Fereres, E. and D.A. Goldhamer. 2003. Suitability of stem diameter variations and water potential as indicators for irrigation scheduling of almond trees. *Journal of Horticultural Science and Biotechnology*. 78:139-144.

Fereres, E., D.A. Goldhamer and L.A. Parsons. 2003. Irrigation water management of horticultural crops. *HortScience*. 38:1036-1042.

Flore, J.A. 1994. Stone fruit. En: Handbook of environmental physiology. Volume 1: temperate fruits. CRC Press, Boca Raton, Florida, USA, pp 233-270.

Freeman, B.M., T.H. Lee and T. Turkington. 1979. Interaction of irrigation and pruning level on growth and yield of shiraz vines. *American Journal of Enology and Viticulture*. 30:218-223.

Ginestar, C. and J.R. Castel. 1996. Use of stem dendrometers as indicators of water stress in drip-irrigated citrus trees. *Acta Horticulturae*. 421:209-219.

Girona, J. 1989. Physiological growth and production responses of late maturing peach (*Prunus persica* L. Batsch) to controlled deficit irrigation. MS Thesis, Dept. Pomology, Univ. California, Davis.

Girona, J., M. Mata, D.A. Goldhmaer, R.S. Johnson and T.M. DeJong. 1993. Patterns of soil and tree water status and leaf functioning during regulated deficit irrigation scheduling in peach. *Journal of the American Society for Horticultural Science*. 118: 580-586.

Girona, J., M. Mata, A. Arbonés, S. Alegre, J. Rufat and J. Marsal. 2003. Peach tree response to single and combined regulated deficit irrigation regimes under shallow soils. *Journal of the American Society for Horticultural Science*. 128: 432-440.

Girona, J., J. Marsal, M. Mata, A. Arbonés and T.M. DeJong. 2004. A comparison of the combined effect of water stress and crop load on fruit growth during different phenological stages in young peach trees. *Journal of Horticultural Science and Biotechnology*. 79:308-315.

Girona J., M. Gelly, M. Mata, A. Arbonés, J. Rufat and J. Marsal. 2005. Peach tree response to single and combined deficit irrigation regimes in deep soil. *Agricultural Water Management*. 72:97-108.

Greenspan, M.D., H.R. Schultz and M.A. Matthews. 1996. Field evaluation of water transport in grape berries during water deficits. *Physiologia Plantarum*. 97:55-62.

Goldhamer, D.A., E. Fereres, M. Mata, J. Girona and M. Cohen. 1999. Sensitivity of continuous and dicrete plant and soil water status monitoring in peach trees subjected to deficit irrigation. *Journal of the American Society for Horticultural Science*. 124:437-444.

Goldhamer, D.A. and E. Fereres. 2001. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. *Irrigation Science*. 20:115-125.

Goldhamer, D.A., M. Salinas, M. Soler, M. Anaya and M. Elvira. 2001. Peach trees perform similarly despite different irrigation methods. *California Agriculturae*. 55:25-29.

Goldhamer, D.A., M. Salinas, C. Crisosto, K.R. Day, M. Soler and A. Moriana. 2002. Effects of regulated deficit irrigation and partial root zone drying on late harvest peach tree performance. *Acta Horticulturae*. 592:343-350.

Goldhamer, D.A. and E. Fereres. 2004. Irrigation scheduling of almond trees with trunk diameter sensors. *Irrigation Science*. 23:11-19.

Goode, J.E., K.H. Higgs and K.J. Hyrycz. 1978. Nitrogen and water effects on the nutrition, growth, crop yield and fruit quality of orchard-grown Cox's orange pippin apple trees. *Journal of Horticultural Science*. 53:295-306.

Ho, L.C., R.I. Grange and A.J. Picken. 1987. An analysis of the accumulation of water and dry matter in tomato fruit. *Plant Cell Environment*. 10:157-162.

Hsiao, T.C. 1973. Plant responses to water stress. *Annual Review Plant Physiology*. 24:519-570.

Huang, X.M., H.B. Huang and F.F. Gao. 2000. The growth potential generated in citrus fruit under water stress and its relevant mechanism. *Scientia Horticulturae*. 83:227-240.

Idso, S.B., R.D. Jackson, P.J. Pinter, R.J. Reginato and J.L. Hatfield. 1981. Normalizing the stress-degree-day parameter for environmental variability. *Agricultural Meteorology*. 24:45-55.

Inglese, P., T. Caruso, G. Gugliuzza and I.S. Pace. 2002. Crop load and rootstock influence on dry matter partitioning in trees of early and late ripening peach cultivar. *Journal of the American Society for Horticultural Science*. 127:825-830.

Intrigliolo, D.S., D. Perez and J.R. Castel. 2005. Water relations of field grown drip irrigated "Tempranillo" grapevines in Requena, Spain. *Acta Horticulturae*. (En prensa).

Intrigliolo, D.S., S. Pedrón y J.R. Castel. 2004. Efecto del riego: dosis y sistema de aplicación (PRD) en las relaciones hídricas y la producción de la vid cv. Tempranillo en

Requena. *Actas de la Reunión Anual del Grupo Experimentación en Viticultura y Enología*. Orense.

Jackson, R.D. 1982. Canopy temperature as a drought stress indicator. *Advances Irrigation Research*. 1:43-85.

Johnson, R.W., M.A. Dixon and D.R. Lee. 1992. Water relations of the tomato during fruit growth. *Plant Cell Environment*. 15:947-953.

Johnson, R.S., D.F. Handley and K.R. Day. 1994. Postharvest water stress of an early maturing plum. *Journal of Horticultural Science*. 69:1035-1041.

Jones, H.G. Irrigation scheduling: advantages and pitfalls of plant based methods. *Journal of Experimental Botany*. 55: 2421-2436.

Klein, I. 1983. Drip irrigation based on soil matric potential conserves water in peach and grape. *HortScience*. 18:942-944.

Lampinen, B.D., K.A. Shackel, S. M. Southwick and B. Olsson. 1995. Sensitivity of yield and fruit quality of French prune to water deprivation at different fruit growth stages. *Journal of the American Society for Horticultural Science*. 111:607-611.

Lampinen, B.D., K.A. Shackel, S.M. Southwick and B. Olson. 2001. Deficit irrigation strategies using midday stem water potential in prune. *Irrigation Science*. 20:47-54.

Li, S.H., J.G. Huguet, P.G. Schoch and P. Orlando. 1989a. Responses of peach tree growth and cropping to soil water deficit at various phenological stages of fruit development. *Journal of Horticultural Science*. 64:541-552.

Li, S.H., J.G. Huguet and C. Bussi. 1989b. Irrigation scheduling in a mature peach orchard using tensiometer and dendrometer. *Irrigation and Drainage Systems*. 3:1-12.

McBurney, T. and P.A. Costigan. 1984. The relationship between stem diameter and water potentials in stem of young cabbage plants. *Journal of Experimental Botany*. 35:1787-1793.

McCutchan, H. and K.A. Shackel. 1992. Stem water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). *Journal of the American Society for Horticultural Science*. 117:607-611.

Marsal, J., M. Gelly, M. Mata, J. Arbonés, J. Rufat, and J. Girona. 2002. Phenology and drought affects the relationship between daily trunk shrinkage and midday stem water potential of peach trees. *Journal of Horticultural Science and Biotechnology*. 77:411-417.

Marsal, J., G. Lopez., M. Mata, A. Arbonés and J. Girona. 2004. Recomendations for water conservation in peach orchards in mediterranean climate zones using combined regulated deficit irrigation. *Acta Horticulturae*. 664:391-397.

Mitchell, D. and D.J. Chalmers. 1982. The effect of reduced water supply on peach tree growth and yields. *Journal of the American Society for Horticultural Science*. 107:853-856.

Molz, F.J. and B. Klepper. 1973. On the mechanism of water-stress-induced stem deformation. *Agronomy Journal*. 65:304-306.

Moriana, A. and E. Fereres. 2002. Plant indicators for scheduling irrigation of young olive trees. *Irrigation Science*. 21:83-90.

Moriana, A. and E. Fereres. 2004. Establishing reference values of trunk diameter fluctuations and stem water potential for irrigation scheduling of olive trees. *Acta Horticulturae*. 664:407-412.

Myburg, P.A. 1996. Response of *Vitis vinifera L.* cv. Barlinka/Ramsey to soil water depletion levels with particular reference to trunk growth parameters. *South African Journal of Enology and Viticulture*. 17:3-14.

Naor, A. 2000. Midday stem water potential as a plant water stress indicator for irrigation scheduling in fruit trees. *Acta Horticulturae*. 537:447-454.

Naor, A. 2004. The interaction of soil- and stem-water potential with crop level, fruit size and stomatal conductance of field-grown 'Black-Amber' Japanese plum. *Journal of Horticultural Science and Biotechnology*. 79: 273-280.

Naor A., I. Klein and I. Doron. 1995. Stem water potential and apple size. *Journal of the American Society for Horticultural Science*. 120:577-582.

Naor, A., H. Hupert, Y. Greenblat, M. Peres, A. Kaufman and I. Klein. 2001. The response of nectarine fruit size and midday stem water potential to irrigation level in stage III and crop load. *Journal of the American Society for Horticultural Science*. 126:140-143.

Naor, A. and S. Cohen. 2003. Senitivity and variability of maximum trunk shrinkage, midday stem water potential, and transpiration rate in response to withholding irrigation from field-grown apple trees. *HortScience*. 38:547-551.

Naor, A., M. Peres, Y. Greenblat, Y. Gal and R. Ben Aire. 2004. Effects of pre-harvest irrigation regime and crop level on yield, fruit size distribution and fruit quality of field

grown 'Black Amber' Japanese plum. *Journal of Horticultural Science and Biotechnology*. 79:281-288.

Oliveira, C.M. and C.A. Priestley. 1988. Carbohydrate reserves in deciduous fruit trees. *Horticultural reviews*. 10:403-430.

Ortuño, M.F., J.J. Alarcón, E. Nicolás and A. Torrecillas. 2004. Interpreting trunk diameter changes in young lemon trees under deficit irrigation. *Plant Science*. 167: 275-280.

Palmer, J.W. 1992. Effects of varying crop load on photosynthesis, dry matter production and partitioning of Crispin/M.27 apple trees. *Tree Physiology*. 11:19-33.

Parlange, J.Y., N.C. Turner and P.E. Waggoner. 1975. Water uptake, diameter change, and non-linear diffusion in tree stems. *Plant Physiology*. 55:247-250.

Pavel, E.W. and T.M. DeJong. 1993. Source- and sink-limited growth periods of developing peach fruits indicated by relative growth rate analysis. *Journal of the American Society for Horticultural Science*. 118:820-824.

Russo, D. and E. Bresler. 1982. Soil hydraulic properties as a stochastic processes: II. Error of estimates in a heterogenenous field. *Soil Science Society of American Journal*. 46:20-26.

Schmitz, M. and H. Sourell. 2000. Variability in soil moisture measurement. *Irrigation Science*. 19:147-151.

Shackel, K.A., H. Ahmadi, W. Biasi, R. Buchner, D. Goldhamer, S. Gurusinghe, J. Hasey, D. Kester, B. Krueger, B. Lampinen, G. McGourty, W. Micke, E. Mitcham, B. Olsen, K. Pelletrau, H. Philips, D. Ramos, L. Scheankl, S. Sibbert, R. Snyder, S. Southwick, M. Stevenson, M. Thorpe, S. Weinbaum and J. Yeager. 1997. Plant water status as an index of irrigation need in deciduous fruit trees. *HortTechnology*. 7: 23-29.

Shock C.C., E.B.G. Feibert y L.D. Saunders. 1998a. Potato yield and quality in response to deficit irrigation. *HortScience*. 33:655-659.

Shock C.C., E.B.G. Feibert and L.D. Saunders. 1998b. Onion yield and quality affected by soil water potential as irrigation threshold. *HortScience*. 33:1188-1191.

Simonneau, T., R. Habib, J.P. Goutouly and J.G. Huguet. 1993. Diurnal changes in stem diameter depend upon variations in water content: direct evidence in peach trees. *Journal of Experimental Botany*. 44:615-621.

Smith, D.S. and S.J. Allen 1996. Measurement of sap flow in plant stems. *Journal of Experimental Botany*. 47:1833-1844.

Southwick, S.M., K.G. Weis, J.T. Yeager and H. Zhou. 1995. Controlling cropping in "loadel" cling peach using gibberellin: effects on flower density, fruit distribution, fruit firmness, fruit thinning and yield. *Journal of the American Society for Horticultural Science*. 120:1087-1095.

Torrecillas**,** A., R. Domingo, R.. Galego and M.C. Ruíz-Sánchez. 2000. Apricot tree response to withholding irrigation at different phenological periods. *Scientia Horticulturae*. 85: 201-215.

Velez, J.E., D.S. Intrigliolo y J.R. Castel. 2005. Programación de riego en cítricos en base a sensores de medida del estado hídrico del suelo y de la planta. *Ingeniería del Agua*. (Enviado a publicar).

Warrick, A.W. and D.R. Nielsen. 1980. Spatial variability of soil physical properties in the field. In: Applications of soil physics. D.Hillel (Eds.). Academic Press, New York, USA, pp. 319-344.

Webster, D.H. and G.L. Brown. 1980 Trunk growth of apple tree as affected by crop load. *Canadian Journal of Plant Science*. 60:1383-1391.

Zreik, C.H., P. González-Altozano y J.R. Castel. 2000. Sap flow determination in plum and mandarin trees by the compensated heat pulse method. *Proceedings of the 5th International Workshop on Plant Water Relations and Sap Flux Measurement*. 93-101.