UNIVERSIDAD DE CÓRDOBA

DEPARTAMENTO DE AGRONOMÍA

Programa de Doctorado

Ingeniería Agraria, Alimentaria, Forestal y del Desarrollo Rural Sostenible

TESIS DOCTORAL

Long-term effects of deficit irrigation on almond production

Efectos a largo plazo del riego deficitario en la producción del almendro

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Fecha de depósito tesis en el IdEP: 15/09/2021

Realizada en el Instituto de Agricultura Sostenible

2021

TITULO: *Long-term effects of deficit irrigation on almond production*

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TÍTULO DE LA TESIS: EFECTOS A LARGO PLAZO DEL RIEGO DEFICITARIO EN LA PRODUCCIÓN DEL ALMENDRO

DOCTORANDO/A: DAVID MOLDERO ROMERO

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

El Dr **Elías Fereres Castiel**, catedrático emérito del Departamento de Agronomía (Unidad María de Maeztu) de la Universidad de Córdoba y director de la tesis titulada “EFECTOS A LARGO PLAZO DEL RIEGO DEFICITARIO EN LA PRODUCCIÓN DEL ALMENDRO”, y el Dr. **Francisco Orgaz Rosúa**, Investigador Científico del Departamento de Agronomía del Instituto de Agricultura Sostenible del CSIC, Córdoba, y codirector de la tesis realizada por David Moldero Romero,

INFORMAN QUE:

La tesis doctoral realizada bajo nuestra supervisión por el ingeniero de montes D. David Moldero Romero constituye una aportación original muy importante en las investigaciones sobre el uso del agua en cultivos arbóreos. La investigación translacional ha sido completada con éxito, como demuestran las aportaciones realizadas en forma de conferencias al sector productivo que se indican más abajo. Todos los objetivos planteados se han cubierto muy satisfactoriamente por lo que se informa favorablemente.

Publicaciones en revista ISI elaboradas durante el periodo de tesis doctoral y directamente relacionadas con el contenido de la tesis:

Moldero D, López-Bernal A, Testi L, Lorite IJ, Fereres E, Orgaz F (2021) **Long-term almond yield response to deficit irrigation**. *Irrigation Science* 39, 409-420 https://doi.org/10.1007/s00271-021-00720-8

Moldero D, López-Bernal A, Testi L, Lorite IJ, Fereres E, Orgaz F (2021) **Almond response to a single-season of severe irrigation water restrictions** *Irrigation Science*. Aceptado

Aportaciones a congresos internacionales

Moldero D, Fereres E, Lorite IJ, González V, Testi L, Orgaz F (2019) Effects of a severe one-season water shortage on survival and yield in almond. IX International Symposium of Irrigation of Horticultural Crops (ISHS). Matera, Italia. 17-20 Junio 2019

Gonzalez-Dugo MV, **Moldero D**, López-López M, Espadafor M, Orgaz F, Testi L, Zarco-Tejada P, Fereres E (2019) Assessment of canopy transpiration from temperature: applications for almond orchards. IX International Symposium of Irrigation of Horticultural Crops (ISHS). Matera, Italia. 17-20 Junio 2019

Aportaciones a congresos nacionales

Moldero D, Fereres E, Orgaz F (2019) Riego y producción del almendro: efectos a largo plazo. Primer Taller Técnico-Científico sobre Riego de Frutales. Lleida, España. 27-28. Noviembre 2019

Conferencias invitadas

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Otras aportaciones

Agustí-Brisach, **Moldero D**, Raya MdC, Lorite IJ, Orgaz F, Trapero A (2020) Water Stress Enhances the Progression of Branch Dieback and Almond Decline under Field Conditions. *Plants* 2020, 9, 1213. https://doi.org/10.3390/plants9091213

Actividades divulgativas

Organización del stand del Campus de Investigacion Alameda del Obispo (IFAPA-IAS) en el Paseo por la Ciencia. Actividad “Médicos de las Plantas”. Córdoba, 6 de abril 2019

Mesa de investigación “¿Qué estoy comiendo? Frutos y semillas”. Ciencia y Música bajo las estrellas. Noche Europea de los Investigadores. Córdoba, 27 de septiembre 2019

Microcharla “¿Cómo regar las plantas?”. Ciencia y Música bajo las estrellas. Noche Europea de los Investigadores. Córdoba, 27 de septiembre 2019

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 15 de Septiembre de 2021

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Financiación

Esta tesis se trata de un trabajo realizado por el grupo PAIDI AGR-119 ‘Relaciones Suelo – Agua – Planta’ del Departamento de Agronomía del Instituto de Agricultura Sostenible (IAS-CSIC) en colaboración con el Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica (IFAPA) de Alameda del Obispo y el Departamento de Agronomía de la Universidad de Córdoba (DAUCO). El trabajo realizado ha sido financiado gracias a la concesión de la beca predoctoral **BES-2016-077366** en el marco del programa de “Formación de Personal Investigador” (FPI) del Ministerio de Ciencia, Innovación y Universidades (MICINN) a través del proyecto AGL2015-66141-R “**Sostenibilidad del Riego del Almendro en un Futuro de Escasez de Agua**” cofinanciado por el MICINN y fondos FEDER de la UE.

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Agradecimientos

Una tesis doctoral *per se* implica mucha cantidad de trabajo. Pero si la tesis está basada en trabajos de campo y con una finca experimental de por medio, la cantidad de trabajo se multiplica enormemente. Sólo puedo estar agradecido a todas las personas que de una u otra forma han contribuido para que esta Tesis Doctoral haya visto la luz.

En primer lugar, a mis dos directores. Francisco Orgaz y Elías Fereres, por acogerme en su grupo y transmitirme su inigualable sabiduría. De ellos me llevo el gusto por el rigor científico y la importancia de tener claros los conceptos básicos. De Elías destacaría su habilidad para ver y analizar las cosas con una perspectiva global. De Paco, su extremada capacidad analítica y su visión práctica. No he podido tener mejores directores.

También a Ignacio Lorite, la persona al frente del IFAPA en la colaboración con este grupo del IAS. Los cuales se atrevieron con la construcción de una finca experimental de almendro *ad hoc* allá por el año 2009, cuando aún no estaba "de moda" el cultivo en España. No quiero olvidarme del departamento de Agronomía del IAS por darme mi primera oportunidad laboral, creyendo más en las habilidades de una persona que en su título.

Especial mención merecen mis queridos técnicos de campo, sin ellos este trabajo simplemente no se hubiera podido ejecutar. De especial manera quisiera expresar mi gratitud a Kiki Gutiérrez, por su capacidad de perseverancia y su habilidad para medir potencial hídrico, entre otras cosas. Y a Rafa Luque, por su creatividad para solucionar problemas y su capacidad para organizar y amenizar los "peroles" del departamento. A Marcos, Ignacio Calatrava, Rafa del Río y José Luis Vázquez, por su habilidad para los trabajos de especial delicadeza y esa soberbia forma de manejar los aparatos y sensores más complejos. A Carmen Ruz, que cohesiona el departamento, y por su inestimable ayuda entre tanta burocracia. A Cristóbal Martínez, por su bondad y buen hacer. El IFAPA necesita más personas como él.

Al Almond Team. A Mónica, por iniciar esta trilogía de tesis sobre el riego del almendro y su capacidad para involucrarse y ayudar. A Manolito, nadie pudo pensar que esa inocente invitación como "resource water" terminaría siendo una decisión con tanto peso en mi vida.

A los compañeros que me han acompañado durante estos años. A los de agronomía, Omar, Ángel, Marga, Tomás, por tantos ratos de trabajo, y también de ocio. A Álvaro, el cual ha hecho de "director de tesis" en primera instancia además de compañero y amigo. A los del IAS y UCO, los cuales han hecho este viaje mucho más llevadero. Y aunque el refrán diga “mal de muchos, consuelo de tontos”, compartir las penas y las alegrías entre los becarios nos ha ayudado siempre a superar las dificultades y disfrutar más de los éxitos. No pondré el nombre de todos porque seguro que me olvidaría alguno, y eso no sería justo. Ellos saben quiénes son. A Rocío y María, dos personas que por separado son tímidas y prudentes, pero si las juntas consigues un terremoto. Así son ellas. A el “Galle”, compi de piso todoterreno donde los haya y enamorado del sur.

Dicen que, si quieres ir rápido, ve solo. Pero si quiere llegar lejos, ve acompañado. Esa es una gran verdad. Por eso quisiera agradecer especialmente a María Helena. Esa “personajilla” que entró en el IAS a finales de una primavera y que se ha convertido en mi maravillosa, estupenda y fabulosa compañera de viaje en la vida.

A mis amigos de toda la vida, los del pueblo. Porque para mí ser de pueblo sólo puede ser motivo de orgullo. Ellos siempre me han permitido mantener los pies en el suelo y darme perspectiva cuando uno se sumerge demasiado en su propia realidad.

A Juan Ángel y Lorena, los cuales siempre han estado ahí desde que empezamos la carrera. A mi familia “Punky Suomi”, que a pesar del tiempo y la distancia siempre están ahí.

A mi familia. Siempre quedaran marcados a fuego en mi memoria los recuerdos de la infancia. Comiendo tomates a “bocado limpio” mientras observaba a mi abuelo Juan como me traía unas botas de agua, más grandes que yo, para que le “ayudara” a regar el huerto. O esos ansiados días veraniegos con mi abuelo Gabriel, los cuales implicaban hacer cosas tan fascinantes para un niño como montarse en una cosechadora, gigante a mis infantiles ojos; coger almendras, vendimiar y hacer vino.

Por último, a mis padres y hermanos. Los más importantes. Creo que no existen palabras en este mundo para agradecerles su incondicional apoyo durante toda mi vida. Sin ellos yo no sería el mismo y simplemente no podría estar aquí. Gracias de corazón.

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List of Symbols

E_S	Evaporation from soil
E_{SO}	E_S from the portion of soil not wetted by the emitters
E_{SW}	E_S from the portion of soil wetted by the emitters
ET	Evapotranspiration
ET_C	Potential crop evapotranspiration
$ET_{C\ for}$	Forecasted crop evapotranspiration
ET_O	Reference evapotranspiration
ET_{WB}	Crop evapotranspiration calculated by water balance
IR	Irrigation applied
K_C	Crop coefficient
k_{sw}	Microadvective coefficient
K_T	Transpiration coefficient
P	Precipitation
P_{eff}	Effective precipitation
T	Tree transpiration
T_{for}	Forecasted tree transpiration
T_{SF}	Tree transpiration estimated by sap-flow
V_0	Volume of one tree
WP	Water productivity (general concept)
WP_{ET}	Water productivity (ET as denominator)
WP_{IR}	Water productivity (IR as denominator)
WP_T	Transpiration efficiency
Y_{DW}	Kernel yield (dry weight)
Ψ	Stem water potential

List of Abbreviations

ANOVA	Analysis of variance
AW	Applied water
CAG	Calibrated average gradient
CG	Ground cover
CHP	Compensated heat pulse
DI	Deficit irrigation
DOY	Day of the Year
DP	Deep percolation
FI	Full irrigation/fully irrigated
FW	Fruit fresh weight
IWMP	Irrigation water marginal productivity
RDI	Regulated deficit irrigation
SDI	Sustained deficit irrigation
SWC	Soil water content
SWD	Soil water depletion
SWP	Stem water potential
VPD	Vapor pressure deficit
WPF	Water production function

Summary

Introduction

The recent favourable market perspectives for almonds around the world have induced important changes in Spanish almond production systems during the last 10 years. Earlier, the production was dominated by traditional rainfed orchards in marginal areas with small trees and average yields below 300 kg ha^{-1}. Such systems have given way in some areas to an intensification of the crop with the important appearance of new irrigated plantations. These plantations have increased their area by more than 300% since 2014, and follow the Californian production standards where irrigation together with intensive mineral fertilization and phytosanitary management aim at yield objectives above 2000 kg ha^{-1}. However, the lower availability of irrigation water in Spain makes the use of deficit irrigation strategies a widely adopted practice. Furthermore, the risks of severe restrictions of water availability for agriculture caused by the recurring droughts, common in the Mediterranean basin, poses an unknown challenge with potentially devastating effects for these new almond plantations.

Research content

In 2014, López-López et al. (2018b) conducted research on almond irrigation in which they established four irrigation treatments (three deficit and one fully irrigated) to obtain the water production functions for irrigation, transpiration and evapotranspiration. In the present work, the experiment begun by López-López et al. (2018b) was continued for three more years in order to extend the period of study of the relationship between production and evapotranspiration and thus be able to generate a six-year production function. In addition, this extension allowed the study

of the productive response during this second triennium and compare it with the response obtained during the first triennia and thus be able to identify adaptation or exhaustion phenomena of the trees as a result of the continued application of deficit irrigation strategies that could have altered the yield response.

Additionally, another experiment was performed to study the effects associated with a single-season water deprivation to simulate a situation of severe water scarcity for agriculture caused by a persistent drought period. The effects on physiology and yield were measured during the season where the irrigation deficit was applied and in the subsequent seasons where irrigation was recovered to meet the ET_C needs.

Conclusions

The present work has generated an almond water production function obtained during six years. This water production function demonstrates that the evapotranspiration of an intensive adult almond plantation in southern Spain, yielding over 2.5 t ha^{-1}, can exceed 1200 mm on the average, which corresponds to an irrigation depth of about 800-900 mm under the climatic conditions of Southwestern Spain. Under average productions greater than 2500 kg ha^{-1}; deficit irrigation reduces kernel yields at a rate of 0.05 kg m^{-3} for irrigation levels close to the maximum and up to 0.35 kg m^{-3} for severe deficit irrigation (around 220 mm). These results are obtained when water stress is concentrated during the kernel-filling period, the least sensitive phenological stage of almond production to water stress. Furthermore, the data obtained suggest the non-significant appearance of adaptation or exhaustion phenomena due to the prolonged water deficits, which suggests the sustainability of the deficit irrigation strategies, at least for a six-year period under the experimental conditions. Remarkably, our experimental results simulating a single year drought, emphasised the vulnerability of irrigated almond orchards to a single-season severe irrigation deprivation. Despite the almond reputation as a drought-tolerant species, a total irrigation cut-off caused tree mortality greater than 90%. In the severe DI treatment (25% of full irrigation), negative effects on yield persisted in the two subsequent seasons, despite resuming full irrigation to restore the ET_C demand in the following seasons.

Resumen

Introducción

Las recientes buenas perspectivas económicas del mercado de la almendra a nivel mundial han inducido importantes cambios en el cultivo del almendro en España durante los últimos 10 años. Un cultivo tradicionalmente dominado por las plantaciones en secano, relegadas a zonas marginales, árboles de escaso desarrollo y producciones medias inferiores a los 300 kg ha^{-1} de pepitas. Sin embargo, este sistema ha empezado a dar paso a una intensificación del cultivo con la aparición de nuevas plantaciones en regadío. Estas plantaciones han aumentado su superficie en más de un 300% desde 2014 y son plantaciones jóvenes que siguen los cánones productivos californianos donde el riego junto a un manejo intensivo de la fertilización y fitosanitario hacen que los objetivos productivos estén por encima de 2000 kg ha^{-1}. No obstante, la baja disponibilidad hídrica de España provoca que el uso de estrategias de riego deficitario sean una actividad ampliamente adoptada. Además, el riesgo de restricciones severas de la disponibilidad hídrica para agricultura causadas por las recurrentes sequías persistentes en la Cuenca Mediterránea suponen un desafío desconocido con efectos potencialmente devastadores para estas nuevas plantaciones de almendro.

Contenido de la investigación

En 2014, López-López et al.(2018b) comenzó un estudio en el cual estableció cuatro tratamientos de riego (tres deficitarios y uno totalmente regado) con el fin de obtener las funciones de producción para riego, transpiración y evapotranspiración. El presente trabajo continúa el trabajo de López-López et al.(2018b) durante tres años más con el objetivo de extender el periodo de estudio de las relaciones productiva y así poder construir una función de producción en respuesta al agua de seis años. Esta ampliación del estudio permitió además el estudio de la respuesta productiva durante este segundo trienio y la comparación con la respuesta obtenida durante el primer trienio con la finalidad de identificar fenómenos de adaptación o agotamiento de los árboles, fruto de la continuada aplicación de estrategias de riego deficitario y que hubieran podido alterar la respuesta productiva.

También se realizó un experimento donde se aplicó durante una temporada un recorte severo de las dotaciones de riego simulando una situación de escasez de agua de riego por una sequía con el fin de estudiar los efectos tanto en la fisiología como en la producción de dos niveles severos de recorte de riego. Posteriormente se recuperaron los tratamientos de riego para cubrir la totalidad de las necesidades hídricas y se continuó monitoreando los árboles en busca de efectos arrastrados derivados del estrés aplicado.

Conclusiones

El presente trabajo ha servido para determinar las funciones de producción en respuesta al agua en el cultivo del almendro durante un periodo de 6 años. Los datos obtenidos han demostrado que las necesidades hídricas de una plantación intensiva adulta de almendro en el sur de España pueden superar evapotranspiraciones (ETc) superiores a 1200 mm, lo que corresponde a necesidades de riego en torno 800-900 mm en las condiciones del suroeste español. Para producciones medias superiores a los 2500 kg ha^{-1}; el riego deficitario reduce las producciones a un ritmo de 0.05 kg m^{-3} cuando los valores de riego están próximos a los máximos y estas reducciones alcanzan los 0.35 kg m^{-3} para valores de riego deficitario severo (en torno a 220 mm). Estos resultados se han obtenido concentrado el estrés hídrico durante el periodo de llenado de grano, la cual es reconocida como la fase fenológica con menor sensibilidad en términos de producción al estrés. Además, los datos obtenidos sugieren la no aparición significativa de fenómenos de adaptación o agotamiento por la acumulación del estrés hídrico, lo que sugiere la sostenibilidad de las estrategias de riego deficitario, al menos para un periodo de seis años bajo las condiciones experimentales aplicadas. Es especialmente destacable la vulnerabilidad de las plantaciones de almendro en regadío a un recorte severo del riego que ha mostrado este trabajo. A pesar de la reputación de esta especie como tolerante a la sequía un recorte total del riego puede provocar una mortalidad de árboles superior al 90%. Finalmente, los efectos negativos del estrés hídrico sobre la producción pueden persistir durante las siguientes temporadas si el estrés ha sido lo suficientemente severo, incluso habiéndose restablecido el riego para cubrir la totalidad de las necesidades hídricas de los árboles.

CHAPTER 1

General Introduction

Chapter 1: General Introduction

1.1. Almond

Almond [Prunus dulcis (Mill) D.A. Web] is the most important tree nut species with a worldwide kernel production exceeding 1 368 703 t in the world during 2019-20 season (International Nut and Dried Fruit Council 2019). Their cultivation is concentrated in Mediterranean climate areas around the world, standing out in production California, Australia and Spain with 77%, 8% and 6% of the world production respectively (International Nut and Dried Fruit Council 2019). Although Spain is the third in production, it has the largest almond cultivated area with more than 700 000 ha (MAPA 2020). This is explained by the fact that most of the almond acreage in Spain is made up of traditional rainfed orchards grown in marginal agricultural areas, where the trees are sparsely planted, small in size (orchards with under 15-25% ground cover), and low-yielding (kernel yields below 300 kg ha^{-1}). By contrast, the intensive almond orchards typical of California are abundantly irrigated and have a large ground canopy cover (usually >60%) and yields over 2000 kg ha^{-1} (Almond Board of California 2019).

However, the picture is rapidly changing in Spain in the last years, as high international prices (Figure 1.1) and other factors are promoting the plantation of new intensive orchards under irrigation, which have reached 140 000 ha in 2020 (MAPA 2020) a 370% more in relation to 2013 (Figure 1.2). Irrigated orchards occupied about 15-20% (Figure 1.2) of the total almond surface in 2020 and their production is gaining more importance every year.

These recent plantations following the Californian model are principally characterized by the use of irrigation, high tree density, minimal pruning and intensive management of fertilization and control of pests and diseases. Also, these intensive plantations are mainly being planted on deep fertile soils at locations of milder climates. The two principal differences between the Spanish and the orchards of California and Australia are the lower irrigation availability in Spain and the use of different cultivars. Spanish production is based on hard-shell cultivars from the European almond breeding programs while in California and Australia the production is based on soft-shell cultivars generated from a different breeding line with 'Nonpareil' as the principal cultivar (Pérez de los Cobos et al. 2021).

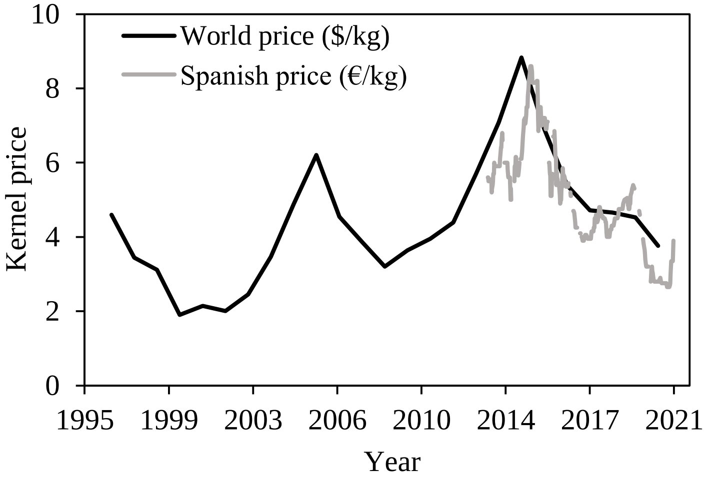

Figure 1.1 Evolution of almond kernel world price to farmer ($/kg) from December 1996 to May 2020 (Source: Almond Board of California) and the Spanish price (€/kg) according to Lonja de Reus, from September 2013 to August 2021. (Sources: http://proalmendra.com/hoja-de-precios/ and https://www.precioalmendra.es/lonja-de-reus/

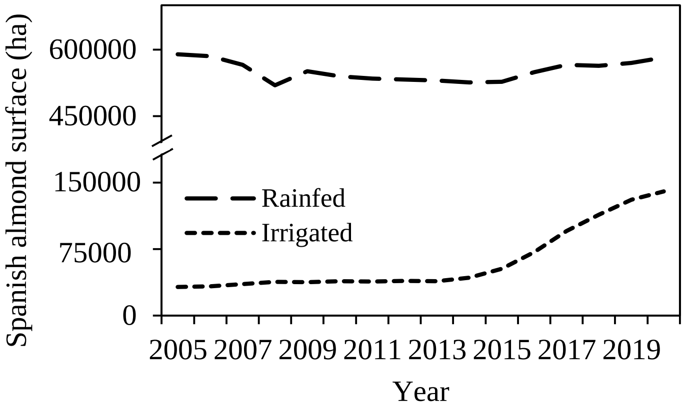

Figure 1.2 Evolution of the rainfed and irrigated almond surface in Spain from 2005 to 2020 (Source: ESYRCE, MAPA).

1.2. Water scarcity and DI strategies

Intensive and irrigated almond orchards seek kernel yields above 2000 kg ha^{-1} that could be only obtained with high levels of radiation interception and canopy ground cover (GC) that implies high crop evapotranspiration (ET_C) requirements for maximum productions under the typical climatic conditions where almonds are cultivated. Recent studies in California (Sanden et al. 2012) and Spain (Espadafor et al. 2015; López-López et al. 2018a) have determined crop coefficients (K_C) and transpiration coefficients (K_T) around 1.15 and 1.0, respectively, for intensive mature almond orchards with around 75% GC. Consequently, the annual ET_C requirements of intensive mature almond orchards in California can exceed 1300 mm for maximum production (Goldhamer and Fereres 2017), and Spanish intensive orchards can also achieve similar levels of consumptive water use (López-López et al. 2018b). Considering winter precipitations and the soil water holding capacity that levels of ET_C can be met with irrigation values around 800-900 mm (López-López et al. 2018b).

However, irrigation water restrictions are common in the majority of the almond growing areas worldwide, but especially in most parts of Spain. There, water is commonly a scarce resource and irrigation water shortage is a structural problem, with Water Authorities forced to supply irrigations quotas below the crop water requirements of fully matured orchards. Farmers are therefore impelled to adopt deficit irrigation (DI) strategies (Fereres and Soriano 2007).

DI can be defined as the deliberate application of water below ET (English 1990) to reduce water application. DI strategies are based on the greater sensitiveness of cell growth than CO_2 assimilation. in the majority of the vegetal species although it is difficult to reduce applied water (AW) with any effect on crop production because water is transpired and CO_2 is assimilated through the stomata (Tanner and Sinclair 1983; Monteith 1990; Steduto et al. 2007). In the study of the relation between water application and biomass or yield production, it should be considered the morphogenesis states, especially when yield consists in one part of a plant (Hsiao 1973) as frequently occurred in tree crops and vines (Fereres et al. 2012). Depending on the temporal patterns of water stress imposed we can distinguish between sustained deficit irrigation (SDI) (Fereres and Soriano 2007) or regulated deficit irrigation (RDI) (Chalmers et al. 1981). SDI consist of a uniform and purposely reduced amount of irrigation water along the growing season promoting a gradual development of water stress throughout the season and soil water stress is depleted (Fereres and Soriano 2007). On the contrary, RDI consist of the purposely concentration of water stress at specific developmental stages of the crop identified as less sensitive to water stress. This method was originally designed to control vegetative vigour (Chalmers et al. 1981).

Several studies have been carried out to study the effects of DI on tree growth and yield on almond. Rapid nut growth in spring [stages I and II according to Kester (1996)] and the post-harvest period were identified as the most critical stages for yield determination because water stress causes nut shedding and affects flower differentiation, respectively (Fereres et al. 1982; D.E. Kester 1996; Girona et al. 1997; Esparza et al. 2001). On the contrary, kernel filling [stage III according to Kester (1996)] is considered as a less sensitive phenological stage, thus RDI strategies concentrate water stress during that stage, even though nut weight can be reduced (Goldhamer and Viveros 2000; Girona et al. 2005; Egea et al. 2010; Goldhamer and Girona 2012). In our conditions in the Guadalquivir Basin, kernel-filling usually occurs from mid-June to August, coinciding with the period of highest atmospheric demand and when transpiration efficiency is the lowest.

1.3. Sustainability of DI strategies

DI is usually adopted on almond growing areas due to the good yield response to water deficits and to the constraints in water availability for irrigation. The interactions of water stress and yield are very complex (Hsiao 1973) and these relationships become even more complex when are considered from a long-term point of view.

One way to study the complex long-term interactions between yield and water stress is through the empirical construction and study of the water production functions over the seasons. Water production functions were defined as the relationships between crop productivity and water at any supplied level (i.e. applied water, crop evapotranspiration or transpiration) and appeared first in field crops (Stewart and Hagan 1973). Those functions are used to establish the maximum irrigation requirements and to quantify the yield reductions as a result of not reaching maximum ET_C. Developing yield-ET_C production functions in tree crops is particularly challenging both because it requires long-term experiments to account for the effects of alternate bearing and due to the difficulties in measuring ET_C in orchards. However, it is a powerful tool that allows the generalization of the relationship between crop yield and evapotranspiration for orchards differing in canopy cover, locations and years.

The yield response to ET_C might be modified by the long-term exposure to DI. On the one hand, yield potential can be limited by the cumulative effect of water stress-induced reduction in tree photosynthesis leading to a depletion of tree carbohydrates reserves. This idea was suggested by Girona et al. (2005), who observed a more detrimental almond yield response to water stress in the last biennium of a four-year experiment. Besides, continued exposure to water stress over several seasons could ultimately affect vegetative growth, canopy size and spurs population dynamics (Egea et al. 2010; Lampinen et al. 2011, 2018; Marsal et al. 2016; Tombesi et al. 2017). This would result in a decline of nut load over time as might have occurred in the three year DI experiment by Esparza et al. (2001). On the other hand, trees might exhibit positive adaptative responses to recurrent water stress through osmotic adjustment and changes in the elasticity of tissues (Castel and Fereres 1982; Kozlowski and Pallardy 2002). Also, trees under water stress can change root/shoot allocation ratios, promoting additional soil exploration and an increase in water extraction from the soil thus improving tree water status (Hsiao 1973; Sharp and Davies 1979; Bradford and Hsiao 1982; Kozlowski and Pallardy 2002; Rahman and Hasegawa 2012).

In light of all this, it becomes clear the importance of long-term experiments as a necessary prerequisite for assessing the sustainability of DI strategies. Unfortunately, such long-term studies are scarce in the literature and with data currently available, it is difficult to determine the sustainability of DI strategies over time on almond.

1.4. Severe irrigation water restrictions

Some of the Mediterranean regions like the Guadalquivir Valley in Spain are affected by chronic hydrological scarcity (Fereres and Ceña 1997). This situation is regularly exacerbated by persistent droughts and lead to severe water restrictions where irrigated agriculture has the lowest priority and irrigation allotments can be drastically reduced. This has occurred in California during the drought of 2011-2015 and in Australia in periods during 1995-2007. In the worst case, total irrigation cut-off occurred in the Guadalquivir Valley of Spain in the last year of the 1991-1995 drought. These events represent a threat to the sustainability of irrigation, due to the irrigation restriction and the uncertainty in their availability (Fereres and Soriano 2007).

The arrival of the new irrigated almond plantations to these areas gives rise to a new problem. Despite the reputation of almond as a drought-tolerant tree species (Castel and Fereres 1982; Ruíz-Sánchez et al. 1993; Torrecillas et al. 1996), the behaviour of the new irrigated plantations in a situation of severe water shortage is fraught with uncertainty.

The few studies available in the literature show the importance of the multiple effects that severe stress could have as near-complete canopy defoliation; alteration of tree carbohydrates; carry-over reductions in fruit set and fruit load even after full irrigation schedule; devaluation of nut quality and their economic value (Goldhamer and Viveros 2000; Shackel et al. 2011; Doll and Shackel 2015). Finally, extreme water stress can induce tree mortality jeopardizing the viability of plantations although the experiments carried out in California show that this is very complicated (Goldhamer and Viveros 2000; Shackel et al. 2011). As a result, severe irrigation water deprivation, even if concentrated in a single season, might result in drastic and long-lasting effects on yield reductions beyond those that could be expected from the production functions.

This uncertainty supports the need to carry out ad hoc experiments to demonstrate whether or not there are extraordinary effects for years in which irrigation endowments are severely restricted. If these extraordinary effects occur, it would be necessary to assess the risk of irreversible effects on these plantations derived from severe water deprivation and their effect on tree survival, yield and water productivity.

1.5.Objectives and outline of the thesis

The general objective of this thesis is to increase knowledge in the management of irrigation in almond plantations, especially in those where the water resource is limited as in most of the new plantations that are being carried out in Spain. Consequently, the specific objectives set were:

a) Determine a long-term production function for a representative almond orchard in Southern Spain, evaluating the long-term sustainability of DI strategies.
b) Study the effects derived from a single-season of severe irrigation water deprivation in a mature intensive almond orchard irrigated since its plantation.

Each of these objectives is addressed in one of the following chapters, which have the structure of peer-reviewed publications. Chapter 2 presents a six-year production function for a mature almond orchard in Southern Spain, which results from the continuation of the experiment started by López-López et al. (2018b) for three additional years. The experimental data obtained in this experiment enable us to compare the yield-ET functions between the two experimental triennia, assessing the occurrence of adaptation or exhaustion phenomena that could jeopardize the use of long-term DI strategies. Chapter 3 analyzes the short- and long-term effects of severe water stress originated from a single-season irrigation deprivation on tree physiology, yield and water productivity. The experiment carried out and described in this chapter try to emulate the likely constraints to water availability imposed by water authorities as a result of a persistent drought, a situation that is recurrent in many almond growing areas in the Mediterranean Basin. The main purpose of this study is the understanding the effects caused by severe water stress to support the decisions that minimize the impacts for almond productivity while saving as much water as possible in a context of severe irrigation water restrictions. Chapter 4 summarize the general conclusions taken after the elaboration of the present work.

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CHAPTER 2

Long-term Almond Yield Response to Deficit Irrigation

This chapter was published in Irrigation Science 39, 409-420

(2021)

Chapter 2: Long-term almond yield response to deficit irrigation

Summary

A substantial area of the new almond plantations in Spain are under irrigation but because of water scarcity, deficit irrigation (DI) strategies have to be adopted. This study assesses the long-term sustainability of different DI strategies over six years (2014-2019) on a mature almond [*Prunus dulcis* (Mill) D.A. Web] orchard in southern Spain. Four irrigation treatments were imposed: Full irrigation (FI); two moderate DI, (SDI_M) and (RDI_M), where applied irrigation was 65% of FI but differed in the seasonal water distribution; and a severe DI, where applied irrigation was 35% of FI. The results emphasise the key role of soil water storage and the importance to consider crop evapotranspiration (ET_C) as the principal driving variable of productivity instead of irrigation in many situations. Soil water partially buffered the irrigation reductions imposed, leading to no significant differences in yield performance between the two different moderate DI treatments. The water production functions (yield *versus* applied irrigation and yield *versu*s ET_C) did not show statistical differences when comparing the first (2014-2016) against that of the second triennia (2017-2019), suggesting the non-existence of exhaustion or adaptation phenomena that could jeopardize the longer term sustainability of DI strategies. Average annual ET_C ranged from 580 mm in the RDI_S treatment to a maximum value of 1300 mm, yielding between 1370 and 2750 kg ha^{-1} of nuts, and showed that water deficits caused yield losses ranging from 0.05 to 0.35 kg m^{-3} of irrigation water depending on the irrigation level.

2.1. Introduction

Almond [Prunus dulcis (Mill) D.A. Web] is the most important tree nut species with a worldwide kernel production exceeding 1 240 400 t in the world (International Nut and Dried Fruit Council 2018). Spain has the largest almond cultivated area with more than 700 000 ha (MAPA 2018) but is third in terms of production, well behind USA and Australia (International Nut and Dried Fruit Council 2018). This is explained by the fact that most of the almond acreage in Spain is made up of traditional rainfed orchards grown in marginal agricultural areas, where the trees are sparsely planted and small (orchards with under 15-25% ground cover) and low-yielding (kernel yields below 200 kg ha^{-1}). By contrast, the intensive almond orchards typical of California are abundantly irrigated, have ground canopy cover (usually >60%) and yield over 2000 kg ha^{-1} (Almond Board of California 2019). However, the picture is rapidly changing in Spain in the last years, as high international prices and other factors are promoting the plantation of new intensive orchards under irrigation, which have reached more than 110 000 ha in 2018 (MAPA 2018).

The annual irrigation requirements of intensive mature almond orchards in California can exceed 1300 mm (Goldhamer and Fereres 2017). Spanish intensive orchards can also achieve similar levels of consumptive water use (López-López et al. 2018a). However, irrigation water restrictions are common in the majority of the almond growing areas in Spain, where periodic droughts force the Water Authorities to supply irrigations quotas below the crop water requirements of fully matured orchards. These anticipated levels of irrigation supply varied depending on the river basin conditions, but common irrigation water supplies range between 250 and 600 mm. The effects of deficit irrigation on tree growth and yield have been the focus of several studies. Some of them have identified the rapid nut growth in spring and the post-harvest period as the most critical stages for yield determination when water shortage causes nut shedding and affects flower differentiation, respectively (Fereres et al. 1981; Girona et al. 1997; Esparza et al. 2001). On the contrary, kernel filling is recognised as a less sensitive phenological phase, thus deficit irrigation (DI) strategies are usually applied during that stage, even though nut size and weight can be reduced (Goldhamer and Viveros 2000; Girona et al. 2005; Egea et al., 2010; Goldhamer and Girona 2012).

Water production functions (WPF) define the relationships between crop productivity and water at any supply level (i.e. precipitation, irrigation, crop evapotranspiration (ET_C) or transpiration) and appeared first in field crops (Stewart and Hagan 1973). Developing yield-ET_C production functions in tree crops is particularly challenging both because it requires long-term experiments in order to account for the effects of alternate bearing and due to the difficulties in measuring ET_C in orchards. However, it is a powerful tool that allows the generalization of the relationship between crop yield and evapotranspiration for orchards differing in canopy cover, locations and years.

Long-term exposure to DI might modify the shape of the yield-ET_C production functions. On the one hand, water stress-induced reduction in tree photosynthesis can have cumulative effects leading to a depletion of carbohydrate reserves limiting yield potential. This idea was suggested by Girona et al. (2005), who observed a more detrimental almond yield response to water stress in the last biennium of a four-year experiment. Also, continued exposure to water stress over several years could ultimately affect vegetative growth, spurs positions renewal and spurs rate mortality (Egea et al. 2010; Lampinen et al. 2011, 2018; Tombesi et al. 2017). This would result in a decline of nut load over time as might have occurred in the three year DI experiment by Esparza et al. (2001). On the other hand, trees might exhibit positive adaptative responses to recurrent water stress through osmotic adjustment and changes in the elasticity of tissues (Kozlowski and Pallardy 2002). Also, trees under water stress can change root/shoot allocation ratios, promoting additional soil exploration and an increase in water extraction from the soil thus improving tree water status (Hsiao 1973; Sharp and Davies 1979; Bradford and Hsiao 1982; Kozlowski and Pallardy 2002; Rahman and Hasegawa 2012). In light of all this, it becomes clear that long-term experiments are a necessary prerequisite for assessing the sustainability of DI strategies in almond or in any other tree crops. Unfortunately, such long-term studies are scarce in the literature due to the current lack of interest in funding agencies to support long-term field research.

Egea et al. (2013) performed one of the few long-term experiments assessing the effects of DI on an almond orchard in Spain. The study covered six years, but started from orchard establishment when the canopy was not fully developed, thus there is an additional effect of water stress on tree growth, so the expected response may be different from that which will occur in the case of establishing DI in mature trees. Additionally, two productions functions for almond have been published in the last three years. The first consisted of a yield-irrigation production function obtained in a five-year experiment in California carried out by Goldhamer and Fereres (2017). The authors noted a substantial year-to-year variation in yield but without a change in the relationship between yield and applied water over time. Several issues might limit the validity of such production function for intensive almond orchards in Spain and other almond growing areas around the Mediterranean basin. First, the highest DI treatment applied 1000 mm which is much higher than the typical amounts used for irrigation in Mediterranean regions. Second, the study was conducted in the environment of the Southern San Joaquin Valley of California of very low precipitation and in a soil with low water-retention capacity where slight differences might be expected between applied irrigation and ET_C, a situation which is generally not the case in Spain. Finally, Goldhamer and Fereres (2017) used a softshell cultivar ('Nonpareil') while hardshell cultivars are the most commonly grown in Europe. The second production function was a yield-ET production function developed by López-López et al. (2018b) in Spain. The function encompasses a wide range of ET_C (648-1220 mm) and used the hardshell cultivar 'Guara', which is very common in Europe. Nevertheless, the length of the published data was only three years, clearly insufficient to observe the long-term effects of water stress previously mentioned. As a result, there is barely any reliable data regarding the long-term productive performance of almond orchards under the DI regimes that are predominant in Spain and other Mediterranean areas.

The objectives of the present study were to: (a) determine a long-term production function for a representative intensive almond orchard in Southern Spain and (b) evaluate the long-term sustainability of different DI strategies on almond. To address those goals, we continued the experiment by López-López et al. (2018b) for three additional years, enabling us to study the relationship between yield and ET over a six-year time frame.

2.2. Materials and methods

2.2.1. Experimental site

The experiment was conducted in an experimental 5.5 ha almond orchard [Prunus dulcis (Mill) Webb cv. Guara grafted onto GF-677 rootstock] planted in 2009 at the Research Centre of IFAPA-Alameda del Obispo, in Córdoba, Spain (37º 51' 3'' N, 4º 48' 38'' W). Climate is typically Mediterranean, with hot and dry summers, mild winters, and average precipitation of 600 mm, concentrated from October to April. The soil is of alluvial origin and more than 2 m depth, with a sandy loam texture. The typical upper and lower limits of plant available water are 0.23 and 0.08 cm^3 cm^{-3}, respectively.

Tree spacing was 7 x 6 m (238 trees ha^{-1}). Training was done in the first two years to 3-4 scaffolds and then no pruning was performed again. Pest and diseases control was done according to a treatment calendar-adjusted according to weather conditions. Weeds were systematically controlled by combining mowing and herbicide applications with a target of 0% weed coverage. Mineral fertilization was calculated and applied based on kernel yield and following the recommendations of the California Fertilization Guidelines for Almonds (https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Almonds.html). The irrigation system had two drip irrigation laterals per tree row, spaced 1 m away from the tree rows, with pressure compensating emitters of 4 l h^{-1}, spaced at 1 m (which makes for 12 emitters per tree). All the trees in the orchard were irrigated to satisfy their full water requirements since planting until the onset of the irrigation experiment in 2013.

During the study, meteorological data were obtained from an automated weather station installed 300 m apart from the experimental site.

2.2.2. Experimental design

The experiment was initiated in 2013 and tested four irrigation treatments including three DI treatments plus a full-irrigated control. The work by López-López et al. (2018b) describes the experimental setup and the results for the first three years (2014, 2015 and 2016); the year 2013 was cast aside because the kernel weight yield component was influenced by the previous season water status when DI was not yet applied. This study continued the experiment for three more years (2017, 2018 and 2019), maintaining the same irrigation treatments and field measurements. Briefly, the irrigation treatments were as follows.

- **Control Full Irrigation (FI)**

Trees in this treatment received the irrigation amount required to match the full pre-estimated crop water requirements ($ET_{C\ for}$) as described López-López et al. (2018b) where irrigation was calculated from the sum of transpiration (T_{for}) and evaporation from the wetted soil surface ($E_{SW\ for}$). T was calculated using the relationship between ground cover (GC) and a transpiration coefficient ($T_{for} = K_T \cdot ET_0$ where $K_T=1.2 \cdot GC$) proposed by Espadafor et al. (2015) and (López-López et al. 2018a). $E_{S\ for}$ was dynamically estimated along the season using the model of Bonachela et al. (2001). For the calculations, we assumed that the trees intercepted 70% of solar radiation (which was the average value for the FI treatment in 2017 based on measurements of GC and midday solar radiation interception) and the soil fraction wetted by emitters was estimated as a function of irrigation duration that ranged from 5% in the RDI_S during the severe deficit period to 35-40% in the FI. High percolation rates were prevented by delaying the onset of irrigation in early spring, which allowed the trees to deplete some of the water accumulated in the soil profile due to winter precipitations.

Irrigation was scheduled on a biweekly basis to match the net full pre-estimated $ET_{C\ for}$ minus effective precipitation (P_{eff}), where P_{eff} was considered to be equivalent to precipitation assuming no deep percolation and runoff using meteorological forecast data and the procedures described below.

- **Moderate Sustained Deficit Irrigation (SDI_M)**

In this treatment, the trees regularly received 65% of the irrigation supplied to FI throughout the season. This was a modification from the 75% applied to the same treatment in the Lopez-Lopez et al. (2018b) experiment, based on the anticipated level of water supply being considered by the Water Authority.

- **Moderate Regulated Deficit Irrigation (RDI_M)**

This treatment received the same total seasonal irrigation as SDI_M (i.e. 65% of that of FI) with a midsummer deficit period during the kernel-filling stage from mid-June to harvest in mid-August. Trees received 70% of the amount applied to FI in spring before kernel filling, 40% during kernel filling, and 90% during the post-harvest period.

- **Severe Regulated Deficit Irrigation (RDIS)**

The total seasonal irrigation amount was 30% of that applied to FI. Trees received 40% of FI irrigation in spring before kernel filling, 15% during kernel filling and 40% during the post-harvest period.

The experiment was designed as a randomized complete block with four replications. Each treatment plot was composed of 16 trees in four adjacent rows. The four central trees were used for experimental measurements and the rest served as guard trees. All treatments had the same numbers of emitters and were irrigated daily, differing in the duration of irrigation. Seasonal irrigations amounts are reported in López-López et al. (2018b) for the first triennium and in Table 2.1 for the second.

2.2.3. Estimating the actual ET_C from the water balance

The actual ET_C was periodically estimated from:

$$ET_C = IR + P_{eff} + \Delta\, SWC \tag{2.1}$$

Where IR is irrigation applied, P_{eff} is effective precipitation and ΔSWC is the seasonal change in soil water content. IR was monitored with water meters, installing one device per experimental plot, from which readings were taken every fortnight.

Soil water content (SWC) was measured from the surface to a depth of 210 cm with a neutron probe (NP, Campbell Pacific Nuclear Scientific, Model 503) in three tubes per experimental plot. Briefly, one tube was placed in the emitter wetted area, a second in the middle of the lane, and a third in an intermediate location. The neutron probe was calibrated. The SWC of the first 0-30 cm depth was characterized with two NP readings at 7.5 and 22.5 cm deep. Then, measurements were taken at 30 cm intervals down to 210 cm. SWC was measured every three weeks from budburst, before the onset of the irrigation season, to leaf fall (after the irrigation cut off). Deep percolation (DP) component was considered negligible based on the deeper SWC measurements.

Once ET_C was calculated, we estimated T:

$$T = ET_C - E_S \tag{2.2}$$

Where $E_{S\ obs}$ is soil evaporation, which was calculated daily as in López-López et al. (2018b). In short, Es was separated into two components for calculations, one representing evaporation from the soil wetted by emitters (E_{SW}) and the other the evaporation from the rest of the soil surface (E_{SO}) as in Orgaz et al. (2006).

E_{SW} was calculated using the model developed by Bonachela et al. (1999, 2001) considering the radiative and aerodynamic term of the Penman-FAO ET_0. Microadvective coefficient (K_{SW}) was considered 1.0 during spring and after harvest and a value of 1.2 was used during summer. The fraction of radiation reaching the soil surface was estimated considering tree canopy size and GC. Measurements of the fraction of soil wetted by the emitters were taken every time irrigation scheduling was modified.

E_{SO} was calculated as a three-stage process (Philip 1957). When the soil was completely wet, stage I, E_{SO} was calculated as described in Bonachela et al. (1999). At stage II E_{SO} was calculated using Ritchie's model (1972). E_{SO} at stage III was assumed to be 0.4 mm day^{-1} in our conditions as appear in López-López et al. (2018b).

Also, tree transpiration was measured using sap-flow probes (T_{SF}) but data is not shown in the present work. The principal use in this study was to compare these measures to the tree transpiration estimated by water balance (T) and to identify the occurrence of deep soil water extractions. The sap-flow method used was the Compensation Heat Pulse (CHP) plus the Calibrated Average Gradient (CAG) (Testi and Villalobos 2009). The characteristics and functioning of the probes were described in López-López et al. (2018a) as well as described the process of calibration of sap-flow measurements.

Precipitation data from budburst to leaf fall were collected from the weather station near the experiment. Due to the high infiltration rate and null slope of the soil, runoff was assumed to be zero, and P_{eff} was considered 100% of precipitation as López-López et al. (2018b).

2.2.4. Tree growth

Tree growth of each experimental tree was characterised by measuring GC. A single measurement was taken each year (2017, 2018 and 2019) in May. The diameter of the horizontal projection of the canopy was measured at eight aspects using a tape measure, and GC (%) was calculated as the area of a circle of average diameter divided by the area allotted to a tree (row x tree spacing).

2.2.5. Tree water status

Stem water potential (Ψ, MPa) was generally measured every 3 weeks from April to October. Measurements started before the onset of DI treatments and finished after the irrigation season in October and were taken on two covered leaves per tree in two trees per experimental plot. A Scholander-type pressure chamber (Model 3005F01, Santa Barbara, CA, USA) was used. Leaves were selected near the trunk or a scaffold-branch and were covered with aluminium foil for at least 30 minutes before the measurement at solar noon.

2.2.6.Yield and yield components

Yield determinations were made using the same procedure as in the previous triennium (López-López et al. 2018c). Harvest took place in mid-August and each of the four central trees in every treatment plot were manually harvested. De-hulling was done mechanically in the field. Then total in-shell fruit fresh weight (FW, kg) was measured and a randomized sample of 1-2 kg of inshell nuts was taken per tree (FW_{sample}) from which the tree fruit load was estimated as:

$$Fruit\ load = \ FW \ \cdot N_{SAMPLE}/FW_{SAMPLE} \tag{2.3}$$

With N_{sample} and FW_{sample} being the number of fruits and fresh weight (kg) of the sample. Afterwards, 100 in-shell nuts were randomly chosen from the sample, oven-dried at 70°C until constant weight and de-shelled for estimating the kernel dry weight (Kernel weight, g). Kernel yield (Y_{DW}, kg ha^{-1}) was calculated as:

$$Y_{DW} = Fruit\ load \ \cdot kernel\ weight \cdot Tree\ density \tag{2.4}$$

Where Tree density was the number of trees per hectare.

2.2.7. Water productivity

Water productivity (WP, kg m^{-3}) was calculated for each experimental plot based on ETc ($WP_{ET} = Y_{DW}/ET_C$), T ($WP_T = Y_{DW}/T$) and IR ($WP_{IR} = Y_{DW}/IR$) (where ET_C, T and IR were in units of m^3 ha^{-1} (1 mm = 10 m^3 ha^{-1}).

Water production functions were constructed from three-year and six-year experimental plot averages of Y_{DW} related to their corresponding seasonal IR and ETc. Polynomial and logarithmic functions were respectively fitted to the data. Irrigation water marginal productivity (IWMP) was obtained from the derivative of the Y_{DW}-IR fit, as in Goldhamer and Fereres (2017) and López-López et al. (2018b), being IWMP expressed in kg m^{-3}.

2.2.8.Statistical analysis

The program Statistix 10 (Analytical Software, Tallahassee, USA) was used to perform the statistical analyses taking into account the randomized complete block design of the experiment with four irrigation treatments. For analysing the interactions between irrigation treatments and years we used a 'split-plot in time' design with irrigation treatments as the main-plot factor and year as subplot factor.

2.3. Results

2.3.1. Water balance

Seasonal treatment averages of IR, ΔSWC, ET_C, T and Es for the last three years of the experiment are presented in Table 2.1. The differences in IR among years were due to the differences in precipitation (Table 2.2). Less precipitation was compensated with more irrigation to meet the ET_C requirements. All treatments showed seasonal soil water extractions (ΔSWC) within the soil profile according to the measures taken at the start and the end of the season (Table 2.1 and Table 2.2). There were no significant differences in ΔSWC between treatments any year (Table 2.1). ΔSWC were lower in 2018 in comparison to 2017 and 2019 due to the most accumulated precipitation during that season.

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Table 2.1 Seasonal irrigation (IR), seasonal change in soil water content (ΔSWC), crop evapotranspiration (ET_C), soil evaporation (E_S) and transpiration (T), in mm, of the four treatments over the three years of study (2017-2019) and the percentage respect to FI of the three deficit irrigation treatments over the three years of study.

Year	Treatment	Absolute values (mm)					% of FI				
		IR	ΔSWC	ET_C	Es	T	IR	ΔSWC	ET_C	Es	T
2017	FI	764 a	230	1224 a	279 a	945 a					
	SDI_M	585 b	176	991 b	254 b	737 b	77	77	81	91	78
	RDI_M	599 b	154	983 b	251 b	732 b	78	67	80	90	77
	RDI_S	246 c	133	609 c	206 c	403 c	32	58	50	74	43
2018	FI	772 a	102	1258 a	282 a	976 a					
	SDI_M	587 b	32	1003 b	256 b	747 b	76	31	80	91	77
	RDI_M	439 b	104	927 b	247 b	680 b	57	102	74	88	70
	RDI_S	219 c	-5	598 c	204 c	394 c	28	-5	48	72	40
2019	FI	985 a	208	1293 a	285 a	1008 a					
	SDI_M	525 b	203	828 b	235 b	593 b	53	98	64	82	59
	RDI_M	533 b	189	822 b	234 b	588 b	54	91	64	82	58
	RDI_S	263 c	169	532 c	194 c	338 c	27	81	41	68	34
Average	FI	840 a	180	1258 a	282 a	976 a					
	SDI_M	566 b	137	941 b	249 b	692 b	67	76	75	88	71
	RDI_M	524 b	149	911 b	244 b	667 b	62	83	72	87	68
	RDI_S	243 c	99	580 c	202 c	378 c	29	55	46	72	39

Different letters in the same column show different homogeneous groups according to LSD test after randomized complete block ANOVA at $P \leq 0.001$

ET_C was fairly stable through the years in the FI treatment, averaging 1258 mm. The ET_C in the DI treatments was significantly lower, yielding 941, 943 and 580 mm in SDI_M, RDI_M and RDI_S, respectively. The same occurred with T and E_S. As compared to SDI_M and RDI_M, RDI_S had significantly lower average values of ET_C (580 mm), E_S (202 mm) and T (378 mm).

It is noteworthy that differences between FI and DI treatments were lower in ET_C and T than in irrigation (IR). In the SDI_M and RDI_M treatments, the applied seasonal irrigation was reduced on average 32.6% and 37.6% of that of FI, respectively, while relative reductions in ET_C and T for both treatments were ~25% and 29% in relation to FI, respectively. In RDI_S irrigation reduction was 71.1% of that applied to FI and it caused a reduction in ET_C and T of 53.9 and 61.3% relative to FI, respectively

Table 2.2 Seasonal reference evapotranspiration (ET_0) and effective precipitation (Peff), in mm, during the irrigation seasons of 2017, 2018 and 2019 and their average.

Year	P_{eff} (mm)	ET_0 (mm)
2017 (7 March-13Nov)	230	1235
2018 (15 March-11 Nov)	384	1086
2019 (12 March-8 Nov)	99.6	1181
Average 2017-19	238	1167

2.3.2.Plant Water Status

Stem water potential patterns clearly differed between FI and all DI treatments (Figure 2.1), showing differences that generally started early in the season and reached the maximum in the harvest period, during mid-August (averaged DOY 220-235 for the three seasons). In 2017 and 2018, SDI_M and RDIM exhibited significant similar Ψ patterns, reaching values greater than -1.5 MPa. However, in 2019 the patterns were slightly different, with RDIM reaching lower Ψ values in the pre-harvest period. The pattern of Ψ in RDI_S was very similar to that observed for RDI_M and SDI_M in 2018 and 2019. By contrast, the Ψ of RDI_S dropped down to -2.5 MPa in July of 2017.

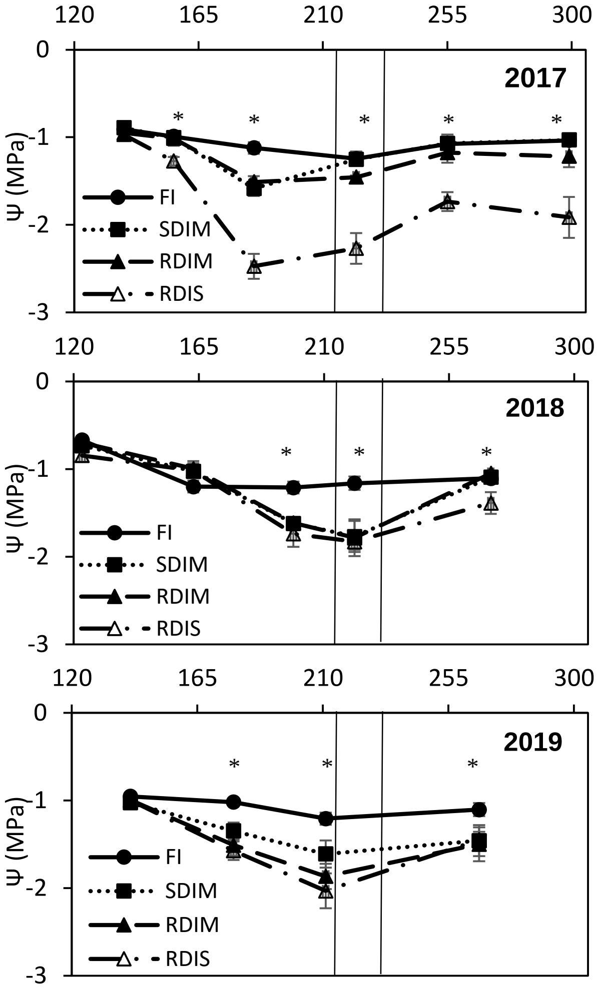

Figure 2.1 Time course of Ψ(MPa) for the three years of study. Each data point is the average of two leaves on two trees in each of the four replications of that treatment. Horizontal axes are expressed on the day of the year (DOY). Vertical solid lines showed the averaged harvest period for the three years. Vertical error bars are the standard error of the means. Asterisks denote significant differences at $P \leq 0.05$ between treatments from ANOVA.

2.3.3. Ground Cover

For all the periods of study, FI trees presented the highest GC, with an average value of 75% during the last 3 years (2017-2019). For the DI treatments, GC was ~68% for SDI_M and RDI_M and 56% for RDI_S. Nevertheless, there were no significant differences between treatments until 2017 and 2018 when GC in FI became significantly higher than that of RDI_S. In 2019 the differences in GC between treatments increased and FI trees were significantly higher than RDI_M and RDI_S trees, as shown in Figure 2.2. Besides, it is remarkable that trees under FI and moderate DI strategies grew from 2015-2016 to 2017-2019 period, where FI trees reached values over 77% of GC, whereas the most stressed trees in the RDIS treatment did not show an increase in GC.

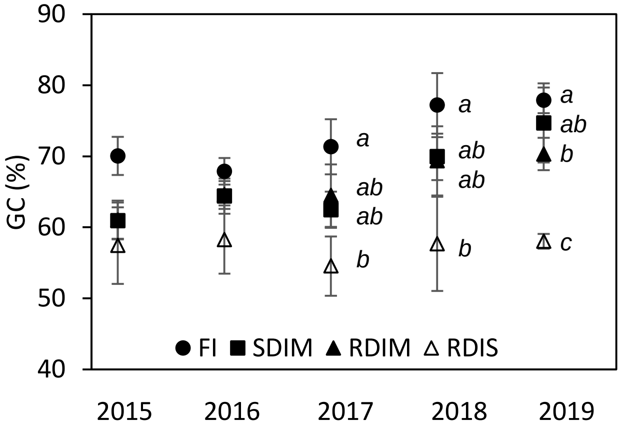

Figure 2.2 Time course of GC. Data for 2015 and 2016 were published in López-López et al. (2018b). Each point represents the average of each experimental plot. The measurements were done in May of each year. Vertical error bars are standard error of the means. Points followed by a common letter are not significantly different by the LSD test at the 5% level of significance.

2.3.4. Yield and yield components

Kernel yields and yield components were negatively affected by water stress in each of the three years (Table 2.3). There was no substantial year-to-year variation in kernel yield. Yield for FI (average of 2659 kg ha^{-1}) was significantly higher than that of DI treatments. No statistical differences were found between the SDI_M and RDI_M regimes, while RDI_S showed the lowest values.

Fruit load increased with applied water. There was no substantial year-to-year variation in any treatment. The maximum fruit load was achieved by FI (3-year average=8883 nuts $tree^{-1}$) and was significantly higher than in the other treatments. SDI_M and RDI_M had slightly but significantly lower fruit load than FI, but there were no significant differences between them. The RDI_S treatment presented a significantly lower fruit load all years, with an average reduction of 36% compared to FI.

Regarding kernel weight, FI and RDI_S presented again the highest and lowest values, respectively, during the three years (averages of 1.26 and 1.05 g per nut for FI and RDI_S). The two moderate DI presented similar values for the years 2017 and 2018 but in 2019 SDI_M achieved a slightly but significantly higher weight per nut (1.15 g nut^{-1} vs 1.03 g nut^{-1}); however, the differences in the averages of the three years were not significant.

Yield and yield components statistical analysis showed no significant interaction between year and treatment at $P > 0.05$. So statistical analysis was applied year by year.

Table 2.3 Dry weight kernel yield and yield components (fruit load and kernel weight) over the three years of study (2017-2019) and their average.

Yield and yield components	Treatment	Year 2017	Year 2018	Year 2019	Average 2017-2019
Kernel yield (kg ha^{-1})	FI	2725 a	2639 a	2613 a	2659 a
	SDI_M	2375 b	2403 b	2238 b	2339 b
	RDI_M	2318 b	2320 b	2196 b	2278 b
	RDI_S	1483 c	1505 c	1301 c	1430 c
	P-value	*0.0001*	*0.0001*	*0.0001*	*0.0001*
Fruit load (N° tree^{-1})	FI	8252 a	8844 a	9552 a	8883 a
	SDI_M	7999 a	8503 ab	8191 b	8231 b
	RDI_M	7477 b	8240 b	8972 ab	8229 b
	RDI_S	6117 c	5659 c	5463 c	5747 c
	P-value	*0.0001*	*0.0001*	*0.0001*	*0.0001*
Kernel weight (g)	FI	1.39 a	1.25 a	1.15 a	1.26 a
	SDI_M	1.25 b	1.19 a	1.15 a	1.19 ab
	RDI_M	1.30 b	1.18 a	1.03 b	1.17 b
	RDI_S	1.02 c	1.12 b	1.00 b	1.05 c
	P-value	*0.0001*	*0.0232*	*0.0010*	*0.0001*

Randomized complete block ANOVA P values are shown for each year and their 3-year average. Means followed by a common letter are not significantly different by the LSD test at the 5% level of significance.

2.3.5. Water productivity

All DI treatments showed similar values of WP_{ET} around 0.25 kg m^{-3}, whereas FI showed a significantly lower value of 0.21 kg m^{-3}. Concerning WP_T, FI and RDI_S presented the lowest value and highest WP_T values, respectively. Moderate treatments presented intermediate values (Table 2.4). All treatments presented the same behaviour in WP_{IR} that occurred in WP_T, showing FI the significantly lowest values all years, RDI_S showed the significantly highest value and both moderated DI treatments showed intermediate values (Table 2.4).

Table 2.4 Water productivity (WP_{ET}) and transpiration efficiency (WP_{T}) for the three years of study (2017-2019) and their average.

	Treatment	Year			Average
		2017	2018	2019	2017-2019
WP_{ET} (kg m^{-3})	FI	0.22	0.21	0.20 b	0.21 b
	SDI_M	0.24	0.24	0.27 a	0.25 a
	RDI_M	0.21	0.25	0.27 a	0.25 a
	RDI_S	0.24	0.25	0.24 a	0.25 a
	P-value	*0.4163*	*0.1984*	*0.0073*	*0.0016*
WP_{T} (kg m^{-3})	FI	0.29 b	0.27	0.26 b	0.27 c
	SDI_M	0.32 ab	0.32	0.38 a	0.35 ab
	RDI_M	0.29 b	0.34	0.37 a	0.34 b
	RDI_S	0.37 a	0.38	0.38 a	0.38 a
	P-value	*0.0378*	*0.0625*	*0.0061*	*0.0001*
WP_{IR} (kg m^{-3})	FI	0.36 b	0.34 d	0.27 c	0.32 c
	SDI_M	0.41 b	0.41 c	0.43 b	0.41 b
	RDI_M	0.39 b	0.53 b	0.41 b	0.43 b
	RDI_S	0.60 a	0.69 a	0.49 a	0.59 a
	P-value	*0.0004*	*< 0.0001*	*< 0.0001*	*< 0.0001*

Means followed by a common letter are not significantly different by the LSD test at the 5% level of significance.

Water productivity functions for kernel yield versus both applied irrigation (Y_{DW}-IR) and evapotranspiration (Y_{DW}-ET) for the three years of study (2017-2019) are shown in Figure 2.3. Yields ranged from ~1400 kg ha^{-1} at 220 mm of irrigation, 580 mm of ET_C and 400 mm of transpiration (RDI_S treatment) to 2750 kg ha^{-1} at 870 mm of irrigation, 1300 mm of ET_C and 1050 mm of transpiration (FI treatment). This figure also presents the mean yield response to irrigation and evapotranspiration corresponding to the three years preceding this study (2014-2016) and shown in López-López et al. (2018b). The statistical analysis of Y_{DW}-IR

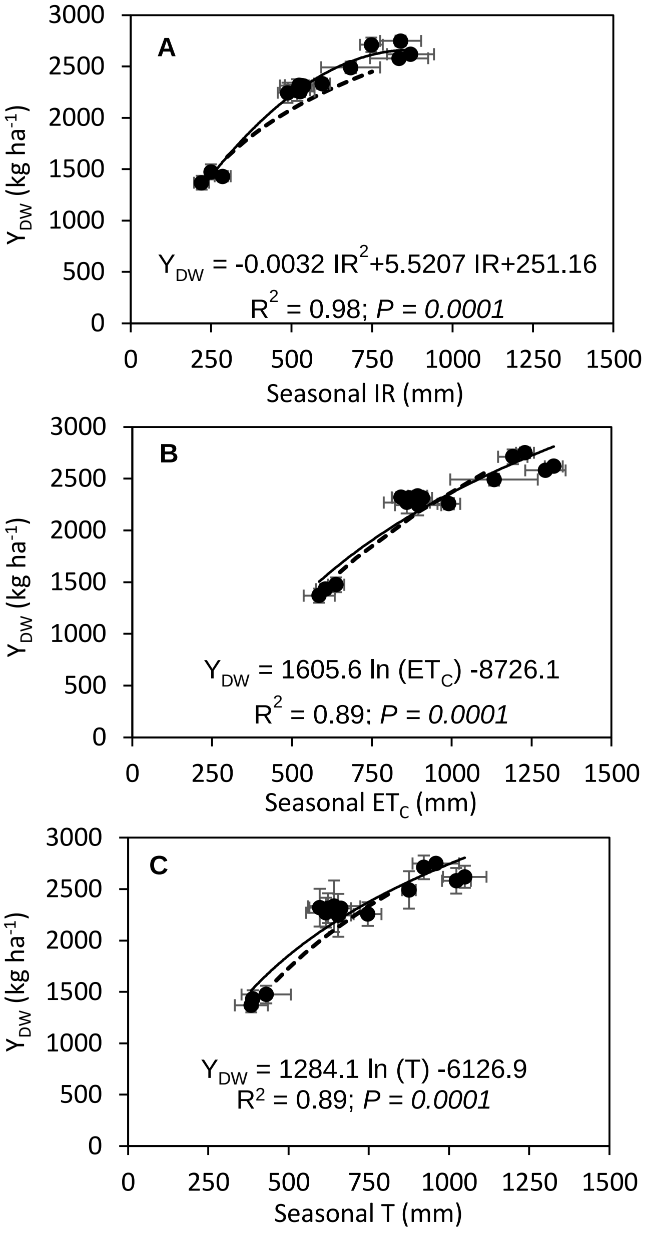

Figure 2.3 Mean annual kernel yields expressed as dry weight (Y_{DW}) against seasonal irrigation (IR) (A), crop evapotranspiration (ET_C) (B) and transpiration (T) (C). Data points are the average of three years (2017-2019) for each treatment plot. Errors bars are standard errors of the means among the three years, if not visible are smaller than the data point symbol. Solid lines show the best-fit expression for the period 2017-2019. The dotted lines show the best-fit expression for the period 2014-2016 (published in López-López et al., 2018b).

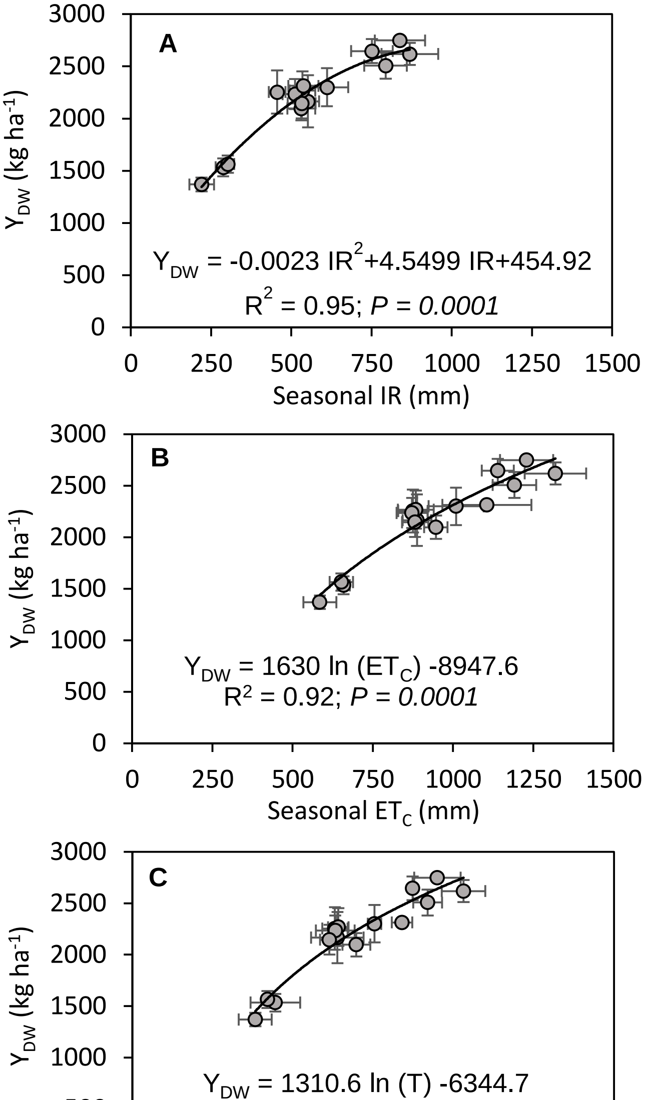

Figure 2.4 Mean annual kernel yields expressed as dry weight (Y_{DW}) against seasonal irrigation (IR) (A), crop evapotranspiration (ET_C) (B) and transpiration (T) (C). Data points are the average of six years (2014-2019) of each replication. Errors bars are standard errors of the means among the six years, if not visible are smaller than the data point symbol. Solid lines show the best-fit expression for the period 2014-2019.

regressions for the two different periods (2014-2016 *vs*. 2017-2019) showed no significant differences at $P > 0.05$. The same occurred for the analysis of the Y_{DW}-ET and Y_{DW}-T functions.

Figure 2.4 shows the production function for Y_{DW} versus IR (Y_{DW}-IR), ET_C (Y_{DW}-ET_C) and T (Y_{DW}-T) for the six years of study (2014-2019).

As no statistical differences were found when comparing the production functions of IR, ET_C and T between the two triennia (2014-2016 versus 2017-2019), no significant differences were noticed for the IWMP functions either. The IWMP derived from the six-year (2014-2019) fit of Y_{DW}-IR resulted in a linear function with a negative slope that varied from 0.35 kg m^{-3}, in RDI_S, to 0.05 kg m^{-3}, in FI, for the range of IR applied in the experiment (Figure 2.5).

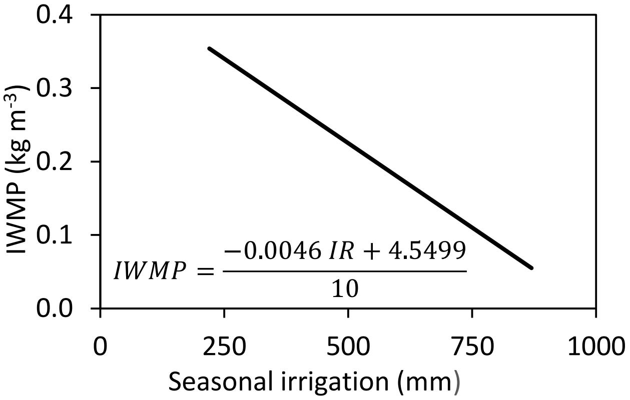

Figure 2.5 Irrigation water marginal productivity (IWMP, kg m^{-3}) calculated as the derivate of Y_{DW}-IR for the six-year study.

2.4. Discussion

2.4.1. Irrigation requirements, soil water storage and water stress effects on growth and yield

Firstly, this study demonstrates that ET_C requirements of a mature and intensive almond orchard in Southern Spain can exceed 1200 mm, as shown by López-López et al. (2018b), reaching 1300 mm for the year 2019, similar requirements to those obtained in almond orchards in California (Goldhamer and Fereres 2017). On average, 840 mm of irrigation were required in our experiment to meet those ET_C levels. The large differences between ET_C and IR requirements for full productivity highlight the importance of considering ET_C instead IR as the driving variable in conditions of high water-holding soil capacity and/or considerable in-season precipitation as mentioned by López-López et al. (2018b). Also, soil water extraction can partially buffer the expected effects of water restrictions applied in the irrigation treatments. In fact, the imposed reduction in irrigation on DI treatments were translated into reductions in measured T and ET_C, and these differences increased proportionally with the severity of the treatment. For example, in RDI_S the average reduction in irrigation, compared to FI treatment, was 71.1% whereas the reductions in T and ET_C were 61.3% and 53.9%, respectively.

Our soil water content measurements suggest that the water extraction was concentrated within the 2.1 m soil depth. Nevertheless, given that we did not measure below 2.1 m depth, we cannot rule out additional soil water extraction below that depth. However, we believe that such additional extraction was of little magnitude, given the independent tree transpiration sap flow measurements that were taken as in López-López et al. (2018a). Our estimates of additional tree T beyond the 2.1 m depth is between 20-30 mm, which represents only 2% of the ET_C of the FI treatment.

FI had the highest average yield, 2659 kg ha^{-1}, and significantly higher yield components compared to the other treatments. This yield was higher than the previously reported by López-López et al. (2018b) for the first triennium (2508 kg ha^{-1}) due to a higher canopy size of the second triennium compared with the previous triennium, GC of 75% and 65% respectively (Figure 2.2), that could allow a higher fruit load and maintenance of high nut unit weight. Our study showed that yield and its components were negatively affected by water reductions, in line with the majority of works (Goldhamer et al. 2006; Egea et al. 2013). In the RDI$_S$ treatment, fruit load was more affected by water availability than kernel weight, which contrasts with the general assumption of kernel weight being the most sensitive yield component to water deficit (Goldhamer and Viveros 2000; Goldhamer et al. 2006). An explanation for this behaviour resides in the substantial irrigation reduction in this treatment compared to the evapotranspiration capacity of the trees. Even where irrigation was concentrated in the post-harvest period (in the RDI treatments), it was not sufficient to improve tree status; stem water potential was significantly lower in the DI compared to the FI trees for the three years and below a threshold that would avoid a reduction in fruit load the following season. In contrast, kernel weight was less impacted because stored soil water partially alleviated stress earlier during kernel filling.

The large contribution of soil water storage to ET$_C$ also appears to explain the non-significant differences in yield and growth between SDI$_M$ and RDI$_M$ in this three-year study and in the earlier observations by López-López et al. (2018b). Soil water storage appeared to alleviate the impacts of the drastic irrigation reduction during kernel-filling stage in both moderate DI treatments reducing the impact of the stress on kernel weight. Moreover, the reduction of the evaporative demand in late September together with the first precipitations after the dry summers in the area, alleviated water stress of SDI_M trees above a critical threshold to produce a more substantial carry-over effect on crop load (Fereres et al. 1982; Goldhamer et al. 2006). This hypothesis is supported by the similar stem water potential time course of both treatments for the three years (Figure 2.1). In summary, under these conditions, neither of the two strategies seemed to perform better than the other for the moderate level of irrigation used here.

GC data showed that long-term water stress tended to have a cumulative effect on tree growth and correlated with the severity of the treatment. During the first triennium (2014-2016), no significant differences were noticed among treatments (López-López et al. 2018c). The first statistical GC differences between FI and RDI_S (i.e. the most severe treatment) appeared in 2017. Those differences continued to increase until the end of the experiment in 2019. Our results suggest that the long-term exposure to severe DI strategies resulted in reductions in canopy size in comparison to FI conditions, which would limit potential yield, as occurred on Japanese plum after three years of DI (Intrigliolo and Castel 2010) and on almond after three years of DI (Esparza et al. 2001).

2.4.2. Long-term water productivity

The six-year ET_C production function (Figure 2.4B) covers a wide range of ET_C, from fully irrigated trees with ETc >1300 mm down to the most water stressed trees with ETc <600 mm. By contrast, the production function published by Goldhamer and Fereres (2017) ranged between 1000 and 1350 mm of irrigation wherein their conditions of very low P_{eff} and very low soil water-retention capacity, IR was very similar to ET_C. A mature almond orchard in our conditions can reach average productions over 2700 kg ha^{-1} when irrigation fully meets ET_C requirements. This yield is higher than the rest of the experiments conducted to date in Spain

(Romero et al. 2004; Girona et al. 2005; García-Tejero et al. 2011; Egea et al. 2013) but is lower than that obtained in California for the same levels of ET_C (Figure S1). It is likely that the reproductive effort in both types of varieties is similar but the differences in shell weight account for the higher yields of soft-shell varieties. In fact, the ratio of kernel to fruit weight of the cv. Guara reported here is approximately 0.4, while the ratio exceeds 0.6 in the cv. Nonpareil. Additionally, López-López et al. (2018b) hypothesized the possibility of a lower maximum kernel yield capacity of hardshell varieties compared to softshell varieties due to lower fruit load capacity, but more data is necessary to compare yield behaviour between both groups of varieties. The difference between the Y_{DW}-ETc and the Y_{DW}-T relations was due to the evaporation from the soil, which ranged from about 220 mm in the DI treatments to 280 mm in the FI treatment, confirming the values obtained by Lopez-Lopez et al. (2018b), where some of the implications related to water conservation are discussed.

IWMP for the period 2014-2019 (Figure 2.5) has a constant negative slope from 0.35 kg m^{-3} to 0.05 kg m^{-3} within the limits of the experiment. This result implies that when applying irrigation close to the full irrigation requirements, a given reduction or increase in water supply has a minimal impact on yield, while imposing the same change in water supply in a DI context will cause higher yield reductions. That result is similar to the obtained by López-López et al. (2018b) for the previous triennium and it has also been reported for other tree crops such as olive (Moriana et al. 2003).

The equations developed (Y_{DW}-IR; Y_{DW}-ET_C; Y_{DW}-T; IWMP) in this study are only valid within the limits where they have been tested in these experiments. The results cannot be extrapolated to determine the productive response to lower amounts of irrigation than those applied here. Nevertheless, the Y_{DW}-IR relationship intercepts the y-axis at a kernel yield of 450 kg ha^{-1}, a value similar to those observed in the rainfed orchards of Southern Spain. Also, the derivate of this mathematical expressions showed an IWMP close to 0 kg m^{-3} (IR ~990 mm), which approaches the maximum IR applied in this work, that showed the nearest of an inflexion point in Y_{DW}-IR as it occurred in Goldhamer and Fereres (2017) who observed even a decline in kernel yield in the most irrigated treatments, that could be the result of overwatering (Fereres et al. 2012).

2.4.3. Sustainability of DI treatments on almond

In the current framework of increasing water scarcity, it is essential to study the multiple long-term effects and adaptations that can occur in almond plantations subjected to DI as their life cycle can exceed 20 years. The short-term effects of water stress on almond yield are widely known with fruit load being the most important parameter that determines yield on almond (Lampinen et al. 2011). Nevertheless, long-term effects of water stress are not clearly known because of the difficulties in conducting long-term experiments. Some authors have suggested the occurrence of depletion phenomenons that could jeopardize the long-term use of DI strategies (Esparza et al. 2001; Girona et al. 2005). The lack of significant differences in the water production functions between the two experimental triennia (Figure 2.3) of the experiment (i.e. 2014-2017 versus 2017-2019) suggests the non-existence of exhaustion or adaptation phenomena or the compensation between them, at least during the first six years of the experiment. These results are in concordance with the works of Egea et al. (2013) and Goldhamer and Fereres (2017). By contrast, Girona et al. (2005) hypothesised the possibility that long-term water stress has a cumulative effect on carbohydrate reserves producing a more damaging response over time on almond. Furthermore, the results of Esparza et al. (2001), showed reductions in yield after two successive years of irrigation deprivation during the harvest period associated with reduced annual growth and renewal of fruiting positions. Here, the reasons for the lack of significant differences between trienniums might be explained by the combined effect of: (i) the absence of water stress in all treatments ($\Psi > -1.0$ MPa) during spring, due to substantial winter and spring precipitations that filled the soil profile, allowing some vegetative growth that guaranteed the necessary spurs renewal (Lampinen, 2018); and (ii) late summer precipitations combined with a reduction in evaporative demand that allowed an improvement in Ψ after-harvest, varying between -2.0 and -1.5 MPa, which apparently was not severe enough to cause a cumulative effect on reserves that would affect yield over time. This hypothesis is strengthened by the similar values of Ψ in spring and post-harvest stages obtained in other studies that showed no changes in the relationship between yield and applied water over time (Egea et al. 2013; Goldhamer and Fereres 2017). It may be that the post harvest values of Ψ observed in the RDI_S can serve as a first approximation of a Ψ threshold to maintain long-term sustainability, but more work is needed to confirm our results.

The use of RDI strategies that concentrate water stress during kernel filling appears to be better than SDI strategies where water stress is sustained for the season. However, our six-year data showed similar performance between both strategies. This could be due to the buffering effect of the soil water storage on the applied water deficits, as previously discussed. Data obtained in this work and the data obtained by López-López et al. (2018b) suggest the possibility to maintain deficit irrigation strategies on almond over time without changes in the relationship between yield and ET_C. This is contrary to the response in Spain of other fruit tree species such as peach, where the reduction in fruit growth hampers the long-term adoption of DI strategies due to the economic impact on sustainability (Marsal et al. 2016). However, the long-term sustainability of DI could be location dependent. Under other edaphoclimatic conditions, where winter and spring rainfalls were insufficient to fill the soil profile or in soils with low water holding capacity, DI may cause chronic water stress patterns that induce harmful processes such as the exhaustion of reserves (Girona et al. 2005) or a depletion in spur population. As a result, yields would decline with time due to the combined effect of water stress on reducing spur renewal, by the reduction of vegetative growth in spring, and increasing spur mortality (Esparza et al. 2001; Lampinen et al. 2011; Tombesi et al. 2017)

The present study is the result of more than 10 years of work in a plantation expressly designed for this research. Even though the difficulties in measuring ET_C are high, there is a need for long-term experiments, that take more time than the habitual duration of most scientific projects nowadays. We believe that the production function approach used here is a powerful tool to assist water management stakeholders, such as growers, technicians, and water authorities in the decision-making process.

The long-term sustainability of DI has been studied here, but there are still gaps in knowledge such as the possible differences in response to water stress of different almond cultivars and in their own Ψ thresholds for long-term sustainability. Also, the extension of the production function to a lower range of IR and ET_C is recommended in order to provide more data to support the decision-making process in situations of very low irrigation water availability.

Acknowledgements

This research was partially funded by the Spanish Ministry of Science, Innovation and Universities (MICINN), project AGL2015-66141-R, co-financed by the European Union FEDER Funds, project INNOVA-Clima (PR.AVA.AVA2019.051) funded by the European Regional Development Fund (FEDER) and project PCI2019-103621 by the MICINN. D.M. is a holder of a pre-doctoral fellowship funded by MICINN. ÁL-B was supported by a postdoctoral fellowship of the 'Juan de la Cierva-Formación' program (FJCI-2015-24109, Spanish Ministry of Economy and Competitiveness). We acknowledge the support of K. Gutierrez, R. Luque, M. Orgaz, I. Calatrava, R. del Río and C. Martínez in the fieldwork.

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CHAPTER 3

Almond Responses to a Single-season of Severe Irrigation Water Restrictions

This chapter is accepted in Irrigation Science

Chapter 3: Almond responses to a single-season of severe irrigation water restrictions

Summary

A substantial area of the new almond plantations in Spain are under irrigation but due to recurring severe droughts, the irrigation water allocation for agriculture can be drastically reduced eventually. This study assesses the physiological and yield effects of a single-season water deprivation (2017) over three seasons (2017-2019) on a previously well-irrigated mature almond [*Prunus dulcis* (Mill) D.A. Web, cv. Guara] orchard in southern Spain. Three irrigation treatments were imposed during 2017: full irrigation, applying the amount required to match maximum crop evapotranspiration (FI); sustained deficit irrigation applying 25% of FI (DI); and rainfed which received no irrigation at all (RF). During 2018 and 2019 all treatments were irrigated as FI. The results documents the vulnerability of irrigated almond orchards to severe water stress, as the rainfed treatment resulted in 92% tree mortality. In relation to FI, yield and quality were reduced in RF and DI by the negative impact of water stress on kernel weight and the formation of hull tights in the season of water deprivation. In the two following years, the negative impact on yields persisted due to reductions in fruit load (carry-over effects) even though trees in DI and RF were restored to full-irrigation levels. The three-year average yields of DI and RF treatments were less than what could be predicted from an almond production function obtained in the same orchard. This highlights the long-term negative impacts that severe water stress resulting from suspending or reducing drastically irrigation in a single season has on almond trees.

3.1. Introduction

Almond cultivation is concentrated in Mediterranean climate areas around the world, with California, Australia and Spain producing 77%, 8% and 6 % of the world production respectively (International Nut and Dried Fruit Council 2019). In California and Australia, where irrigation water availability is commonly higher than in Spain, most of the orchards are irrigated to meet their maximum evapotranspiration (ET_C), with kernel yields above 2000 kg ha^{-1} (Almond Board of California 2019) and irrigation water requirements that can exceed 1300 mm (Goldhamer and Fereres 2017). By contrast, the acreage devoted to almond orchards in Spain has been traditionally dominated by low-yielding (c.a. 200 kg ha^{-1}) rainfed orchards located in marginal areas and characterised by low planting densities and canopy cover. However, a number of factors affecting almond world markets, including the recent California drought, has led to the expansion of intensive almond orchards under irrigation in Spain in the last decade. Irrigated almond plantations in Spain have been growing rapidly, reaching almost 140 000 ha in 2020, 326% more than in 2014 (MAPA 2020). The production model adopted in Spain also targets average kernel yields above 2000 kg ha^{-1} and is based on the use of new varieties and rootstocks from European breeding programs; higher tree density on good quality soils; intensive fertilization and tree health measures; minimal pruning; and irrigation programs similar to those used in USA and Australia. The amounts of irrigation needed to meet ET_C can exceed 900 mm in Southern Spain (López-López et al. 2018a, b) but the use of deficit irrigation (DI) strategies are common in many areas limited by irrigation water availability (Moldero et al. 2021).

In most almond growing regions, but particularly in many areas of Spain, water is a scarce resource and irrigation water shortage is a chronic problem, so that deficit irrigation strategies (Fereres and Soriano 2007) must be applied. Tree water relations have been deeply studied in almond and it is well known that water stress affects stomatal conductance and CO_2 assimilation (Castel and Fereres 1982; Romero et al. 2004). Furthermore, the effects of water stress on tree growth and yield are also known. In this regard, yield is considered to be particularly sensitive to water stress in the periods of flowering, rapid vegetative growth in spring (Goldhamer and Smith 1995) and post-harvest (Goldhamer and Viveros 2000), while the kernel filling phase seems to be less sensitive (Romero et al. 2004; Girona et al. 2005; Goldhamer and Girona 2012). Based on this knowledge, DI strategies have been tested in almond by reducing irrigation applications from 30 to 60% of ET_C (Romero et al. 2004; Girona et al. 2005; Egea et al. 2010, 2013; López-López et al. 2018b; Moldero et al. 2021).

An important problem arises when these regions are impacted by severe and persistent drought events that can cause substantial deprivations in irrigation water for agriculture. Irrigation water allotments can be drastically reduced to 20-30% of the historical levels for almond as it occurred in California during 2011-2016 (Doll and Shackel 2015) and in Australia during 1995-2007, or, in the worst case, reaching total cut-off, as it happened in Spain during the 1991-1995 drought. In severe drought situations growers have reacted with a number of measures including procuring additional irrigation water by purchasing water rights from other growers, extracting more groundwater or reducing demand by removing the older and/or less productive blocks of the orchard. Other practices such as reduction of evaporation losses (decreasing irrigation frequency) and severe pruning have been used as well. However, severe pruning has been shown to be ineffective as it leads to long-lasting effects of yield (Proebsting et al. 1981; Shackel et al. 2011).

Scientific literature only shows two studies where almond trees were subjected to severe water stress to investigate the effects of a severe water shortage due to a drought. First, Goldhamer and Smith (1995) imposed a single-season irrigation water deprivation on a mature ‘Nonpareil’ almond orchard in California. Treatments consisted of a control (FI) and four deficit irrigation strategies (406 mm; 36% of FI) differing in the temporal distribution of the deficits. Although there were no direct measurements of tree water status, the severe water stress suffered by trees caused a significative reduction in quality and yield during the season of the irrigation deprivation and the negative impact on yields remained until two seasons after the irrigation deprivation. These carry-over effects were particularly accentuated in the treatments in which irrigation was concentrated early in the season. A conference report by Shackel et al., 2011, also on the cv. Nonpareil, described an experiment conducted in the Sacramento Valley of California which applied a control FI (983 mm), two DI treatments (127 mm and 254 mm) and a rainfed treatment, all distributed along the season. That work confirmed the results obtained by Goldhamer and Smith (1995) regarding the negative impact of severe water stress on kernel yield and its carry over effects in subsequent seasons. Shackel et al. (2011) reported that their rainfed treatment reached stem water potential (SWP) values between -2.9 and -6.3 MPa with an important increase of canopy dieback.

Several issues might limit the validity and applicability of the results obtained in the previous studies for the conditions of other Mediterranean-type regions. First, the study of Goldhamer and Smith (1995) applied in all the irrigation deprivation treatments an irrigation water of 406 mm plus 107 mm in pre-season, a water depth which is higher than even the usual amounts used for irrigation in other Mediterranean-type regions, and much higher than the water allocation supplied during severe droughts.

Furthermore, both studies (Goldhamer and Smith 1995; Shackel et al. 2011) were conducted using Nonpareil, a soft-shell cultivar widely used in USA and Australia, while almond orchards in Spain and other Mediterranean countries are planted with hard-shell cultivars, coming from a different breeding line (Pérez de los Cobos et al. 2021). Given the prospects for severe water scarcity in the Mediterranean region, it would be desirable to characterize the response of irrigated almond orchards to a single season of severe water deprivation in the event of a drought. We hypothesise that, although almond has been considered a drought-tolerant species in the past (Castel and Fereres 1982; Ruíz-Sánchez et al. 1993; Torrecillas et al. 1996), sudden irrigation deprivation for a season in previously well-watered almond orchards can produce severe water stress conditions jeopardizing the economic viability of the orchardss and even tree survival. The objectives of the present study were to (a) investigate the physiological responses and (b) tree survival to different water stress levels imposed during a single-season of severe irrigation water deprivation and, (c) determine their short- (in the season of the stress) and long-term (subsequent seasons) effects on yield.

3.2.Materials and methods

3.2.1. Experimental site

The experiment was performed in an experimental 5.5-ha almond orchard [Prunus dulcis (Mill) Webb cv. Guara grafted onto GF-677 rootstock] planted in 2009 at the Research Centre of IFAPA-Alameda del Obispo, in Cordoba, Spain (37º 51’ 3’’N, 4º 48’ 38’’ W). Climate is the typical Mediterranean, with hot and dry summers, mild winters, and rainfall averaging 600 mm, concentrated from October to April. The soil is of alluvial origin, with a sandy loam texture and more than 2 m deep. The upper and lower limits of soil water storage are 0.23 and 0.08 cm^3 cm^{-3}, respectively. Tree spacing was 7 x 6 m (238 trees ha^{-1}). Training was done in the first two years to 3-4 scaffolds and then no pruning was performed again. Pest and diseases control was done according to a treatment-calendar adjusted according to weather conditions. Weeds were controlled by combining mowing and herbicide applications. Mineral fertilization was calculated and applied following the recommendations of the California Fertilization Guidelines for Almonds (https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Almonds.html). The irrigation system consisted of two drip irrigation laterals, spaced 1 m from the tree rows, with pressure compensating emitters of 4 l h^{-1}, spaced at 1 m (which makes for 12 emitters per tree). All the trees in the orchard were irrigated to satisfy their full water requirements since planting until the experiment in 2017.

During the study, meteorological data were obtained from an automated weather station installed 300 m apart from the experimental site.

3.2.2.Experimental design

The experiment was initiated in 2017 and tested three differential irrigation treatments, including a rainfed (RF) and a deficit (DI) treatments, plus a full-irrigated control. After that, in 2018 and 2019 full irrigation was restored to all treatments. Briefly, the irrigation treatments were as follows.

- **Control Full Irrigation (FI)**

Trees in this treatment received the irrigation amount required to match the full orchard water requirements (ET_C) as described by López-López et al. (2018b) and following the procedure used in the FI treatment of Moldero et al. (2021). Therein, irrigation was calculated as the sum of transpiration (T) and evaporation from the wetted soil surface (E_{SW}). T was calculated using the relationship between ground cover (GC) and a transpiration coefficient ($T = K_T \cdot ET0$ where $K_T = 1.2 \cdot GC$) proposed by Espadafor et al. (2015) and used in López-López et al. (2018c). Evaporation from soil (ES) was dynamically estimated along the season using the model of Bonachela et al. (2001). For the calculations, we assumed that trees intercepted 70% of solar radiation, which was the average value for the FI treatment in 2017 based on measurements of GC and midday solar radiation interception. The soil fraction wetted by emitters was estimated as a function of irrigation duration, and it ranged from 10% under low evaporative demand to 40% in the high evaporative demand period. Deep percolation was minimized by delaying the onset of irrigation in early spring, which allowed the trees to deplete some of the subsoil water accumulated due to winter precipitations.

Irrigation was scheduled on a biweekly basis to match the balance between ET_C minus effective precipitation (P_{eff}), where P_{eff} was considered to be equivalent to precipitation, assuming no runoff and negligible deep percolation.

- **Deficit Irrigation (DI)**

In this treatment, trees regularly received 25% of the irrigation supplied to FI throughout the 2017 season. To do so, the original irrigation system, with two irrigation laterals with pressure compensating emitters of 4 l h^{-1} spaced at 1m, was replaced by one irrigation lateral with pressure compensating emitters of 2 l h^{-1} before starting the 2017 irrigation season. There are two options to reduce applied water in drip irrigation: either reduce the number of emitters or reduce irrigation time. When the restriction is severe (25% of control), reducing irrigation time with the same number of emitters would lead to high direct evaporation losses which would be excessive for the low application level, as predicted by

Bonachela et al., (2001) model. Therefore, we decreased the number of emitters by using one drip lateral instead of two to achieve the 25% application level. In 2018 the original irrigation system was restored and during 2018 and 2019 the irrigation program was the same as in the FI treatment.

- **Rainfed (RF)**

This treatment did not receive any irrigation water during the 2017 season. In 2018 the original irrigation system was restored and during 2018 and 2019 the irrigation program was the same as in FI treatment.

Table 3.1 presents the values for irrigation (IR), effective precipitation (P_{eff}) and potential evapotranspiration (ET_0), for each treatment and year, all three computed for each growing season. Effective precipitation was considered equivalent to the total precipitation from bud break to leaf fall, due to the high soil infiltration and the null slope. Losses due to deep percolation were subtracted considering the neutron probe measurements and also were subtracted the soil evaporation (Allen et al. 1998). P_{eff} since bud break to total defoliation of RF trees was around 100 mm. Annual rainfall during 2016 and 2017 (January to December) was 675 and 416 mm, respectively.

Table 3.1 Seasonal irrigation (IR), effective precipitation (P_{eff}) and seasonal reference evapotranspiration (ET_0), in mm, during the irrigation seasons of 2017, 2018 and 2019.

Year	Treatment	IR	P_{eff}	ET_0
2017 (7 March - 13 Nov)	FI	764	230	1235
	DI	191		
	RF	0		
2018 (15 March - 11 Nov)	FI	772	384	1086
	DI	772		
	RF	772		
2019 (12 March - 8 Nov)	FI	985	99.6	1181
	DI	985		
	RF	985		

The experiment had a completely randomized design with 7 replications per treatment. Each replication consists of an experimental plot, composed of three rows and three or four trees per row. Only the central trees, named experimental trees, in each plot (one or two trees per plot, depending on plot size), were used for experimental measurements and the rest served as guard trees. Summing up, FI was composed of 13 experimental trees while DI and RF were composed of 11 and 13 experimental trees respectively.

3.2.3.Ground cover

Growth of each experimental tree was determineded by measuring ground cover (GC; %). A single measurement was taken each year (2017 and 2018) in May. The diameter of the canopy horizontal projection was measured at eight different radii (R_{1-8}), 45° apart, using a tape measure in order to document the variability due to the irregular shape of the canopy horizontal projection. GC was calculated as the area of the circle determined by the average of the eight radii divided by the area allocated to each tree with the following equation.

$$GC\ (\%) = \frac{\pi \cdot (\bar{R}_{1-8})^2}{row \cdot tree\ spacing} \cdot 100 \qquad (3.5)$$

3.2.4. Tree water status

Stem water potential (Ψ, MPa) was generally measured every week from April to October during 2017 and once a month in 2018 and 2019. Measurements covered the whole irrigation season and were taken on two covered leaves per tree in all central trees per experimental plot. A pressure chamber (Soilmoisture Equipment Corp, Model 3005F01, Santa Barbara, CA, USA) was used. Leaves were selected near the trunk or a scaffold-branch and were covered with aluminium foil for at least 30 minutes before the measurement was taken around solar noon.

3.2.5. Defoliation

During 2017, the canopy defoliation was monitored over time by periodical evaluations from June to October (seven evaluations in total). Defoliation (D) was assessed by estimating the percentage of the defoliated surface of the tree canopy using a 0-4 rating scale. The equivalences between the values of the scale and the percentage of tree canopy defoliation were approximately: 0 < 20%; 1 = 21-40%; 2 = 41-60%; 3 = 61-80%; 4 ≥80%.

3.2.6. Mortality

Trees that did not sprout during spring 2018 were considered dead.

3.2.7. Yield and yield components

Yield determinations were made using the same procedure as in López-López et al. (2018b). Harvest took place around the mid August and each experimental tree in every treatment plot was manually harvested. De-hulling was done mechanically in the field. Then total in-shell fresh weight (FW, kg) was measured and a randomized sample of 1-2 kg of in-shell nuts was taken per tree (FW_{sample}) from which the tree fruit load, equivalent to number of nuts per tree, was estimated as:

$$Fruit\ load = FW \cdot N_{SAMPLE}/FW_{SAMPLE} \tag{3.2}$$

Where N_{sample} and FW_{sample} being the number of fruits and fresh weight of the sample. Afterwards, 100 in-shell nuts were randomly chosen from the sample and oven-dried at 70°C until constant weight for estimating the averaged kernel dry weight (kernel weight, g). Kernel yield (Y_{DW}, kg ha^{-1}) was calculated as:

$$Y_{DW} = Fruit\ load \cdot averaged\ kernel\ weight \cdot Tree\ density \tag{3.3}$$

Where the Tree density is the number of trees per hectare.

Hull tight determination was made by counting the number of hull tight nuts ($N_{HULL\ TIGHT\ SAMPLE}$), considered as nuts with suture unsplit, within the randomized sample of 1-2 kg of in-shell nuts taken per tree. Hull tight (hull tight; %) was calculated as:

$$Hull\ tight\ (\%) = N_{HULL\ TIGHT\ SAMPLE}/N_{SAMPLE} \cdot 100 \qquad (3.4)$$

3.2.8. Statistical analysis

The program Statistix 10 (Analytical Software, Tallahassee, USA) was used to perform the statistical analyses considering the completely randomized design of the experiment. The trees that died as a result of the water stress imposed in 2017 were excluded from the statistical analysis in 2018 and 2019.

3.3. Results

3.3.1. On year irrigation restrictions effects (2017)

At the start of the study in May 2017 FI trees were slightly smaller than DI and RF trees. These differences were determined by the random choice of the treatments and were small and far from the statistical significance (Figure 3.1).

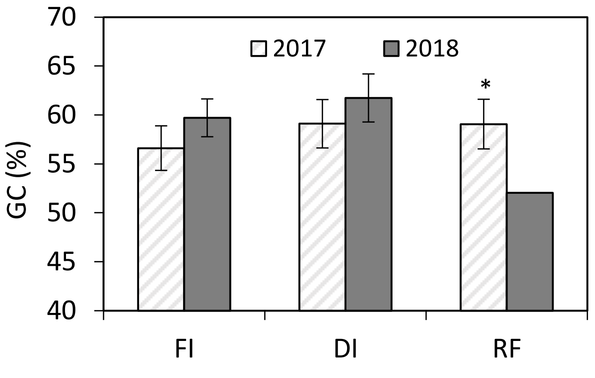

Figure 3.1 GC for 2017 and 2018. The measurements were done in May of each year. Vertical error bars are the standard error of the means. The asterisk shows the GC of the only RF tree survivor after 2017.

Although the no significant differences between treatments in tree size (~60% of GC) at the start of the experiment (Figure 3.1), the different irrigation amounts applied to FI (764 mm), DI (191 mm) and RF (0 mm) induced very different Ψ patterns among treatments along 2017 (Figure 3.2). Ψ differences started early in the season and reached the maximum at the end of July. FI treatment had Ψ around -1.0 MPa for most of the season, only reaching lower values (-1.47 MPa) during the harvest period when irrigation was briefly interrupted to facilitate mechanical harvest. In the DI treatment, Ψ measurements gave similar levels to those of FI until mid-May, but then Ψ decreased rapidly reaching values of -3.3 MPa at the end of July. After that, Ψ partially recovered to around -2.0 MPa by the first two weeks of August, coinciding with a period of defoliation (Figure 3.3), and remained at a similar level for the rest of the season. Regarding RF trees, Ψ values were similar to those measured for DI and FI until mid-May and then decreased sharply, reaching -4.0 MPa at the end of July. At that time, RF trees were completely defoliated which hampered subsequent Ψ measurements. Indeed, we were only able to measure Ψ in two trees that retained a few leaves (open triangles in Figure 3.2). Overall, FI showed significantly higher values of Ψ as compared to DI and RF when the measurements were averaged for the pre-harvest or post-harvest periods, or for the whole measurement campaign. Statistical differences were also found between DI and RF for the same periods, the latter exhibiting the lowest values (Table 3.2).

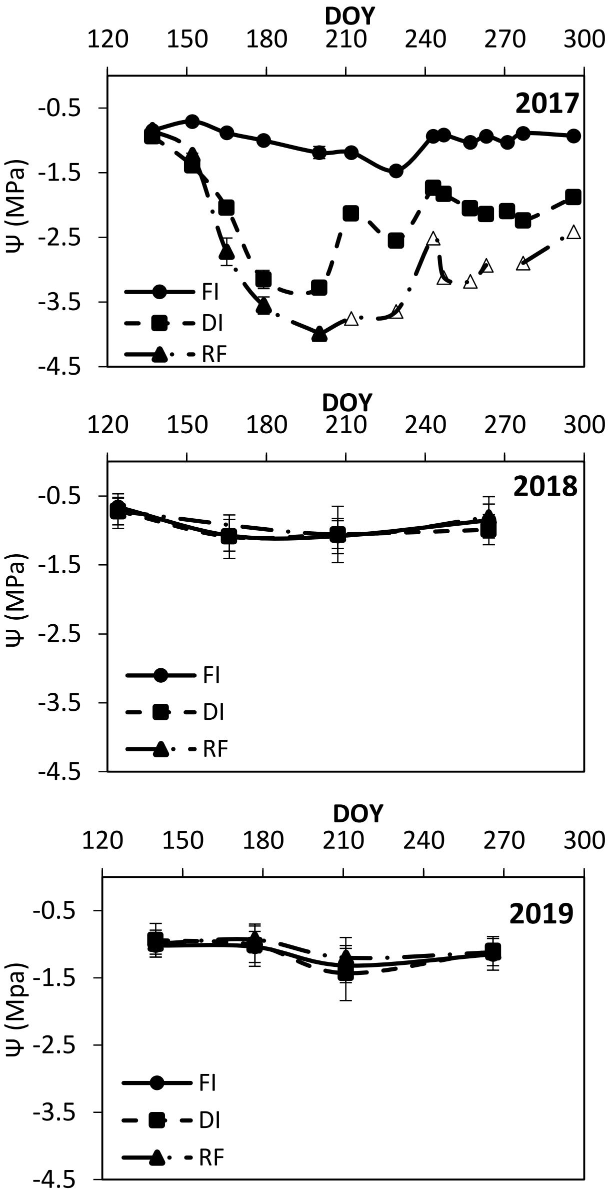

Figure 3.2 Time course of Ψ (MPa) for 2017, 2018 and 2019 seasons. Each data point is the average of two leaves on all experimental trees in each treatment. Open triangles showed Ψ of the only two RF trees that maintained some leaves after DOY 200. Vertical error bars are the standard error of the means.

Table 3.2 Average Ψ (MPa) of the three treatments for the season 2017 divided into periods: pre-harvest (DOY 137-212); post-harvest (DOY 229-296); season (DOY 137-296). Each value represents the average of all the measurements taken in each period.

Treatment	Pre-harvest	Post-harvest	Season
FI	-0.93 a	-1.02 a	-0.98 a
DI	-2.17 b	-2.07 b	-2.10 b
RF	-2.60 c	-2.96 c	-2.76 c
P	*<0.001*	*<0.001*	*<0.001*

Completely randomized ANOVA P values are shown for each period and treatment. Means followed by a common letter are not significantly different by the LSD test at the 5% of significance.

The sharp Ψ decrease observed in DI and RF resulted in the partial or total tree defoliation (Figure 3.3). Leaf shedding in RF trees occurred rapidly after the start of the season, reaching defoliation scores around 4 (i.e. >80%) by the second fortnight of July and complete defoliation by the middle of August. Only one experimental plot formed by two trees exhibited a slower pattern of defoliation, even though they also reached severe defoliation levels of over 75% by the end of the season in mid-October. DI also induced considerable leaf fall, but to a lesser extent than in RF. In the DI treatment, maximum defoliation scores were around 1.5 (i.e. ~50%), in the middle of September after which a slight recovery was noted due to tree resprouting in early autumn. On the other hand, defoliation scores for FI trees were always 0, implying negligible leaf shedding until the season ended in autumn.

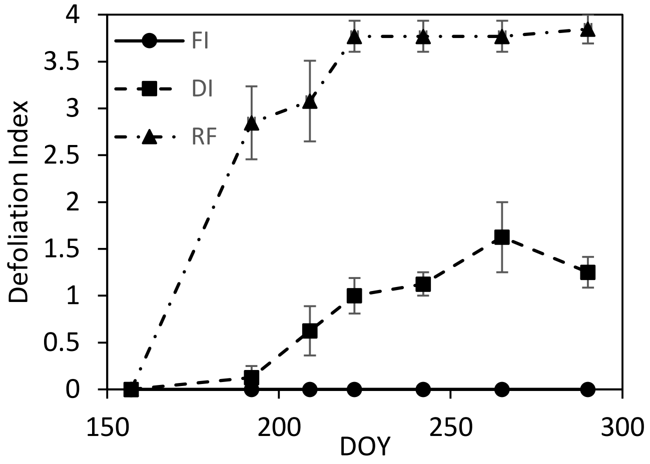

Figure 3.3 Time course of Defoliation index during 2017 in the three treatments. Vertical error bars are the standard error of the means.

Table 3.4 reports that kernel yield for the FI treatment in 2017 was 2244 kg ha^{-1}, while yield values were 33.5% and 35.8% lower for DI and RF, respectively. These lower kernel yields were directly related to significant reductions in kernel weight in DI and RF, as there were no significant differences in fruit load among treatments (Table 3.4). Water stress during 2017 also caused a devaluation of the harvest in DI and RF, as many fruits were hull tights (Goldhamer and Smith 1995). Almost all the RF (97%), and most of the DI (74%) production was formed by hull tights, while no hull tights were observed in the FI trees. The fraction of hull tight almonds was related to the level of water stress during the kernel-filling period. A strong sigmoidal relationship between such a fraction and Ψ was found according to which Ψ values below -2.0 MPa lead to a dramatic increase in the proportion of hull tights (Figure 3.4).

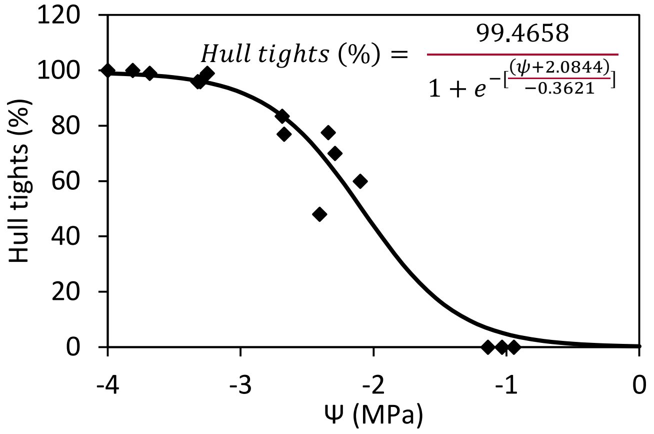

Figure 3.4 Hull tight nuts (%) against average Ψ measured during kernel-filling stage (DOY 165-225). Each point corresponds to the average values of each experimental tree during the year of stress (2017). The solid line shows the best-fit expression (R^2=0.96; P < 0.0001).

Finally, the total irrigation cut-off performed in the RF during 2017 caused the mortality of 92% of the trees under this treatment, as they did not regrow in 2018. None of the FI and DI trees died during the three experimental years (Table 3.3).

Table 3.3 Number of experimental trees, number of trees alive and dead after the 2017 season and their mortality rate for each treatment.

Treatment	n	Alive	Dead	Mortality rate (%)
FI	13	13	0	0
DI	11	11	0	0
RF	13	1	12	92

3.3.2. Long-term irrigation restrictions effects (Carry-over effects)

GC measures taken in 2018 revealed slightly higher values (without statistical significance to those determined for each treatment in the spring of the previous season for both FI and DI treatments. Despite water stress, the vegetative growth of DI trees during 2017 was not affected because water stress developed after the main growth flush, which normally occurs during spring in almond. In addition, water stress did not cause branch losses as in RF treatment. For that reason, DI trees again maintained their largest size compared to FI during 2018, but again the differences between them were not statistically significant. By contrast, the only RF tree surviving the irrigation cut-off applied in 2017, showed lower GC values in 2018 (52%) than in 2017 (63%) (Figure 3.1) due to branch losses resulting from severe stress.

The full irrigation applications to meet ET_C in all treatments resulted in no statistical differences in Ψ among them in 2018 and 2019. In 2018 and 2019, all treatments showed Ψ values ranging from -0.7 MPa to -1.06 MPa (Figure 3.2).

In 2018, kernel yield in the DI treatment was 14% lower than in FI, but such a difference was not significant. The only tree survivor of the RF treatment only produced 32 kg ha^{-1}, by far the lowest kernel yield among the three treatments. Contrary to 2017, there were no differences between treatments in kernel weight and yield reductions were mostly caused by a lower number of fruits. In 2019, no statistical differences between FI and DI yields were found. Regarding the only survivor of the RF treatment, kernel yield in 2019 was still far below the values observed for FI and DI for the second successive season (Table 3.4). Kernel weight was similar for FI and DI treatments, 1.24 and 1.18 g respectively, while RF had a much lower value of 0.76 g. The number of fruits increased in the RF tree in 2019 (4852 fruits $tree^{-1}$) in relation to the previous season (186 fruits $tree^{-1}$), but it was still far behind the crop load recorded for the same tree in 2017 or for FI and DI, regardless of the season (>7000 fruits $tree^{-1}$). It should be pointed out that during 2018 and 2019, the number of hull tights was negligible in all treatments.

Table 3.4 Dry weight kernel yield and yield components (fruit load and kernel weight) over the three years of study (2017-2019) and their average. Data showed for the years 2018, 2019 and the average for Rainfed treatment was calculated with the data corresponding to the only tree survivor.

Yield and yield components	Treatment	Year			Average
		2017	2018	2019	
Kernel yield (kg ha^{-1})	FI	2244 a	2430 a	2318 a	2331 a
	DI	1493 b	2083 a	2124 a	1900 b
	Rainfed	1440 b	*32	*1303	*925
	P-value	*<0.0001*	*0.1659*	*0.2915*	*0.0004*
Kernel weight (g)	FI	1.32 a	1.24 a	1.15 b	1.20 a
	DI	0.88 b	1.18 a	1.29 a	1.07 b
	Rainfed	0.78 b	*0.76	*1.13	*0.89
	P-value	*<0.0001*	*0.2986*	*0.0439*	*0.0016*
Fruit Load (Nº tree^{-1})	FI	7220	8430 a	8499 a	8049 a
	DI	7234	7355 a	7020 a	7203 b
	Rainfed	7786	*186	*4852	*4275
	P-value	*0.5682*	*0.3212*	*0.0883*	*0.0312*
Hull tights (%)	FI	0 a	0	1	0 a
	DI	74 b	0	1	25 b
	Rainfed	97 c	*0	*0	*32
	P-value	*<0.0001*		*0.6637*	*0.0011*

Completely randomized ANOVA P values are shown for each year and their 3-year average. Means followed by a common letter are not significantly different by the LSD test at the 5% level of significance. *Data reported for the only tree that survived in the Rainfed treatment.

Averaging the three years, FI showed the highest kernel yields, followed by DI and RF. Statistical tests revealed that the differences among treatments were always significant, regardless of the pair compared. Kernel weight and fruit load showed the same pattern as kernel yield with significantly higher and lower values for FI and RF, respectively.

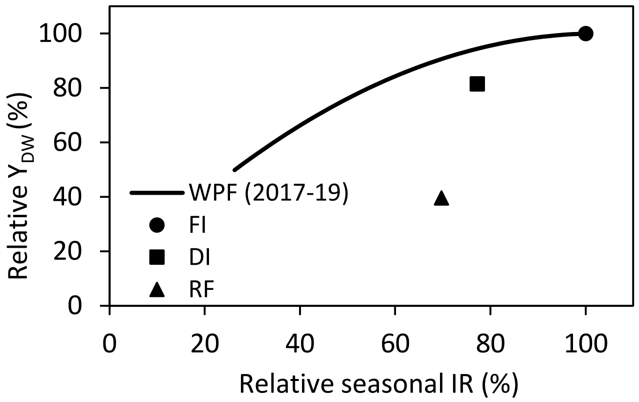

Figure 3.5 Mean annual kernel yields expressed as dry weight (Y_{DW}) against seasonal irrigation (IR) for FI, DI and RF treatments) and the water production function (WPF) for 2017-2019 (Moldero et al. 2021) represented by the solid line. Data points are the average of three years (2017-2019) of each treatment. All data are presented in relative terms (Rel Y_{DW}-Rel IR).

3.4.Discussion

3.4.1. Tree survival

The most remarkable result of the present study is that, despite of the reputation of almond as drought resistant (Castel and Fereres 1982; Ruíz-Sánchez et al. 1993; Torrecillas et al. 1996), total irrigation cut off during one season resulted in the mortality of 92% of trees of a mature almond orchard (cv. Guara) that had been previously cultivated under ample irrigation supply. Risk of almond tree death is a threat that may occur under severe irrigation water restrictions in the event of a drought if water authorities cannot supply even a small fraction of seasonal water requirements. . Such a grim scenario is recurrent in southern Spain as a consequence of the water scarcity and the severe and persistent droughts that occur in the region with some periodicity.

The high tree mortality observed in RF was unexpected because of both the presumed water stress resistance of almond and the relatively high depth and water holding capacity of the soil where the study was performed. While soil water content was not measured in this experiment, root zone available water at the beginning of the 2017 season was more than 200 mm, according to neutron probe measurements performed in another block of the same experimental orchard (Moldero et al. 2021). Effective precipitation before the total defoliation of trees was estimated as 100 mm, which implies that RF trees had around 300 mm at their disposal to uptake and use as ET (~25% of seasonal ET_C of a fully irrigated orchard). Such an ET_C estimate is clearly above the 150-200 mm (~15% of seasonal ET_C) suggested by Shackel et al. (2011) as the almond ET survival threshold in their work performed in California with the cv. Nonpareil. The differences between Shackel et al. (2011) findings and those of the present study may be attributed to several factors. For instance, our Ψ measurements in RF trees revealed a very fast decline in tree water status, contrary to the gradual development of water stress observed by Shackel et al. (2011). The rate of development of water stress during the season might be critical for the survival of trees, as the lack of the necessary time may have prevented our trees to acclimate to the severe water stress conditions (Fereres et al. 1982; Goldhamer and Smith 1995). By contrast, the DI trees in our experiment received sufficient water to survive, shedding part of the leaves to avoid excessive dehydration levels, as shown in its seasonal Ψ trajectory (Figure 3.2). One important consideration is that the experimental trees had developed large canopies in previous years under localized irrigation and had never experienced moderate to severe water stress in previous seasons. In that situation, we have observed (Espadafor et al. 2018) a positive response to increased wetted soil volume, suggesting that the drip irrigation system used in the orchard kept the root system relatively confined, and this, together with the large tree size, might explain the fast rate of water stress development, leading to tree death. Additional factors could be the severe evapotranspiration conditions of the 2017 summer and the predisposition of severe water-stressed trees to biotics factors such as bark beetle attacks which could favour tree mortality. As a final remark, cultivar differences in the response to severe water stress may explain the contrasting results reported in Shackel et al. (2011). In our study, cv. 'Guara' was totally defoliated at -4.0 MPa and trees were not able to re-sprout in the next season. By contrast, cv. Nonpareil survived after undergoing Ψ of -6.0 MPa (Goldhamer and Viveros 2000; Shackel et al. 2011), performing better than 'Carmel' and 'Monterrey' cultivars as reported in Shackel et al (2011). It appears that there is genetic variability among almond cultivars in their responses to severe water stress, a topic which deserves further research.

3.4.2. In season effects of water stress on yield

The deprivation of irrigation in RF and DI in 2017 resulted in yield reductions in proportion to the severity of water deficits. No differences in fruit load existed among treatments, so the decrease in yield observed for DI and RF was exclusively caused by reductions in kernel weight. This was the consequence of the occurrence of water stress during the kernel-filling stage as previously reported in other studies (Goldhamer and Viveros 2000; Girona et al. 2005; Egea et al. 2010). Fruit load had been determined during the post-harvest period of the previous season when all treatments were subjected to the same irrigation schedule (Hutmacher et al. 1994; Goldhamer and Viveros 2000; Esparza et al. 2001; Girona et al. 2005; Egea et al. 2010). Nut shedding was not observed in 2017 in any of the treatments, probably because water stress was developed after the initial and more critical stage of rapid growth (Fereres et al. 1982; Girona et al. 1997; Esparza et al. 2001). In the case of the DI treatment, there could have been effects on the root system of the change from two drip lines to one as a result of imposing the severe DI regime (25% of control).

Under our conditions of substantial winter rainfall and deep soils, the root system of drip-irrigated orchards evolve from having a generalized root water uptake pattern to concentrate the water uptake preferentially in the wetted volumes of the emitters, as the rest of the soil dries.Unfortunately, we do not have information on root system dynamics to speculate what could have been the specific impact of the drip system change.

All in all, our results have implications for the assessment of the impact of severe water deficits on almond production in the future. Firstly, the experiments should encompass various seasons in order to capture the long-term responses following the severe water deprivation. In this regard, even the RF trees that died in our study produced a rather high amount of nuts in the year of the irrigation cut off. Second, fruit load in almond is influenced by the water status during the previous season, so it would seem advisable in some cases to discard the data obtained during the first year of application of the experiments because they are not totally attributable to the treatments applied (López-López et al. 2018b).

Additionally, we observed in-season negative effects of water stress on yield quality due to the formation of hull tights. Our data suggest a sudden increase in the proportion of hull tights in cv. Guara when the average Ψ remain below -2.0 MPa during the kernel-filling period. Even if the kernel-filling stage was identified as being less sensitive to water stress (Goldhamer and Smith 1995; Goldhamer and Viveros 2000; Goldhamer et al. 2006; Goldhamer and Girona 2012), our analysis suggest that deficit irrigation strategies should avoid excessive water stress during that period to obtain good kernel quality and subsequent profits.

3.4.3. Carry-over effects of water stress on yield

Our results indicate that the impacts of severe water stress on yield were extended beyond the season where the irrigation cut-off is applied, even if irrigation is re-established, which is in agreement with previous reports (Goldhamer and Smith 1995; Goldhamer and Viveros 2000). The carry-over effects on the productivity of the DI and RF treatments were principally attributed to the decline in fruit load caused by the negative effects of water stress on spur differentiation during the post-harvest period (Fereres 1981; Girona 1997, Esparza 2001), and to a possible increase of premature spur mortality. The intensity and durability of the carry-over effects seem to be directly related to the severity of water stress. Our Ψ measurements in the only tree which survived in the RF treatment indicate that the occurrence of persistently low Ψ values (below -3.5 MPa) can produce long-lasting effects on yield that may be attributed to a massive spur mortality induced by desiccation during such period of severe water stress. Slight carry-over effects were also noted in the DI treatment, but the impact of the water stress imposed in 2017 (seasonal average Ψ of -2.0 MPa) was not sufficient to induce a significant yield reduction in subsequent seasons in relation to FI. In this case, the decline in spur population presumably induced by water stress might have been partly compensated by an increase in fruit set in 2018 and 2019, although this compensatory mechanism is limited (Kester and Griggs 1959; Tombesi et al. 2017).

Another striking observation which needs to be confirmed was the considerable lower kernel weight in 2018 of the RF survivor tree relative to FI and DI, despite the fact that its fruit load was negligible and irrigation was not limited. One could speculate that severe water stress during spurs differentiation may have affected flower bud differentiation, limiting the potential ovary size and hence the future kernel weight. On the other hand, the limited ovary size may be due to the competition with vegetative growth for the scarce tree carbohydrate reserves after a season where photosynthesis was severely limited by water stress.

3.4.4. Cumulative effects on yield

In a previous work performed in another block of the same orchard used in the present study, Moldero et al. (2021) obtained the irrigation water production function from data collected in the same years (2017-2019). When plotting the three-year average yield responses in relative terms for the irrigation treatments applied in the present study, the data corresponding to the FI shown in Table 4 fitted very well the relationship found by Moldero et al. (2021). By contrast, the average yields of DI and RF were far below (24% and 61%, respectively) what would be expected from the production function (Figure 5). A severe restriction followed by two years of ample supply had a lower yield response than if the same total allocation was evenly distributed over the three years (Figure 5). The different yield responses in the two experiments show that cumulative yields over three years do not depend only on the total cumulative irrigation applied, but also on its distribution over the years, with the concentration of water stress in specific years resulting in large reductions in water productivity. This remarkable finding highlights the great importance of timing of occurrence and temporal distribution of water stress and indicates its multiple implications in agricultural water management.

3.4.5.Concluding remarks

This study demonstrates that a complete irrigation cut-off for one season can have devastating effects on the productive capacity of irrigated almond orchards even affecting tree survival. Tree mortality of up to 92% was reached when trees were not irrigated during one season.

Additionally, significant carry-over effects on yield were documented two seasons after the resuming of full irrigation.

The differences in yield responses between the production function obtained by Moldero et al. (2021) and the results of the present study highlight the importance of the temporal distribution of water stress, showing large reductions in water productivity caused by the ocurrence of water stress in one-crop season. This is a remarkable finding suggesting that ensuring some irrigation supply in years of severe water restrictions might be more beneficial for farmers than increasing their average water allocation. Such a strategy would avoid the dramatic effects that a drastic seasonal irrigation cut-off has on the productivity and survival of almond orchards.

This study also highlights the importance of developing proactive strategies to prevent irreversible and lasting damage affecting the long-term sustainability of almond plantations. The large capital investments being made face the risk of large losses due to tree death under severe irrigation restrictions. In the future, further studies should be conducted to investigate and document the minimal amount of irrigation required, and the optimal timing of application, to prevent irreversible damage for various cultivars and rootstocks, and different growing environments.

Acknowledgements

This research was partially funded by the Spanish Ministry of Science, Innovation and Universities (MICINN), project AGL2015-66141-R, co-financed by the European Union FEDER Funds, project INNOVA-Clima (PR.AVA.AVA2019.051) funded by the European Regional Development Fund (FEDER) and project PCI2019-103621 by the MICINN. D.M. is a holder of a pre-doctoral fellowship funded by MICINN. ÁL-B was supported by a postdoctoral fellowship of the 'Juan de la Cierva-Formación' program (FJCI-2015-24109, Spanish Ministry of Economy and Competitiveness). We acknowledge the support of K. Gutierrez, R. Luque, M. Orgaz, I. Calatrava, R. del Río and C. Martínez in the fieldwork.

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CHAPTER 4

General Conclusions

Chapter 4: General conclusions

The present work has produced a six-year almond production function. These productions functions have demonstrated some results previously obtained by this research group (López-López et al. 2018 a,b, c,) such as the ET_C requirements of a mature and intensive almond orchard in Southern Spain can exceed 1200 mm and the significance of soil water extractions to the water balance and its capacity to partially buffer the differences imposed by the use of regulated and sustained DI strategies. Moreover, this thesis highlights the importance of considering ET_C instead of IR as the driving variable in conditions of high water-holding soil capacity and/or considerable in-season precipitation

The six-year ET_C production function obtained resulted in a curvilinear function that covers a wide range of ET_C, from fully irrigated trees with ET_C >1300 mm down to the most water stressed trees with ET_C <600 mm. A mature almond orchard in our conditions can reach average productions over 2700 kg ha^{-1} when irrigation fully meets ET_C requirements, with averaged irrigation over 800 mm under the experimental growing conditions. The water production function also resulted in a curvilinear function showing an IWMP with a constant negative slope varying from 0.35 to 0.05 kg m^{-3} within the extremes of ETc covered in the experiment.

One of the most remarkable findings of this study is the lack of significant differences in the water production functions between the two experimental triennia of the experiment (i.e. 2014-2017 versus 2017-2019), which suggests the non-existence of exhaustion or adaptation phenomena or the compensation between them. Likewise, the absence of significant changes in the yield–ET_C relationships between triennia evidences the sustainability of deficit irrigation strategies in almond trees for at least six years.

A second outstanding finding of the present thesis is related to the physiological and yield responses to a single-season water deprivation analyzed in Chapter 3. Specifically, our study illustrates the vulnerability of well-irrigated almond plantations to severe water stress despite the drought-resistant reputation of this species. In our experiments, total irrigation cut off during one season resulted in the mortality of 92% of mature (cv. Guara) trees that had been previously cultivated under ample irrigation supply. The reasons for tree death appeared to be complex and attributable to several factors although the rate of development of water stress during the season might be critical for the survival of trees, as the lack of the necessary time may prevent trees to acclimate to the severe water stress conditions.

In-season yield reductions were in proportion to the severity of water deficits and exclusively attributed to reductions in kernel weight. Remarkably, even the RF trees that died in our study produced a rather high amount of nuts in the year of the irrigation cut off, highlighting the importance of encompassing various seasons to capture the long-term responses. Despite irrigation was re-established in the following years, the impacts of severe water stress on yield were extended beyond the season where the irrigation deprivation was applied and could be principally attributed to the decline in fruit load. The intensity and durability of these effects were directly related to the severity of water stress, being identified the occurrence of persistently low Ψ values (below -3.5 MPa) as a likely threshold for long-lasting negative effects on yield, apparently associated with massive spur mortality.

In addition, the differences in yield responses between the production function obtained in the chapter 2 and the results of the chapter 3 highlight the importance of the temporal distribution of water stress, showing large reductions in water productivity caused by the concentration of water stress in specific years. This remarkable finding suggest that ensuring some irrigation supply in years of severe water restrictions might be more beneficial for farmers than increasing their average water allocation. Such a strategy would avoid the dramatic effects that a drastic seasonal irrigation cut-off has on the productivity and survival of almond orchards. This study (chapter 3) also highlights the importance of developing proactive strategies to prevent irreversible and lasting damage affecting the long-term sustainability of almond plantations. The large capital investments being made face the risk of large losses due to tree death under severe irrigation restrictions.

Finally, we would like to highlight some issues that might deserve more research in the future such as the possible existence of cultivar differences in the response to severe water stress and the needed of further studies to investigate and document the minimal amount of irrigation required, and the optimal timing of application, to prevent irreversible damage for various cultivars and rootstocks, and different growing environments.

APPENDICES

Appendix 1: Supplementary Material to Chapter 2

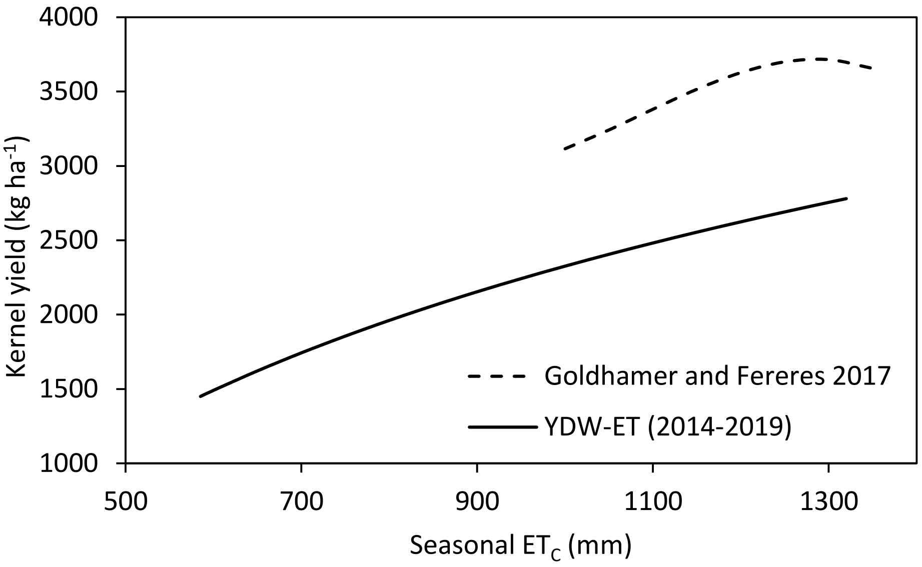


Figure S1. Six-year production function (Y_{DW}-ET_C) and production function of Goldhamer and Fereres (2017) for California corrected from kernel yield at 5% water content to dry weight, IR was assumed to be similar to ET_C in Goldhamer and Fereres (2017) given the conditions of very low Peff and very low soil water-retention capacity.

Appendix 2: Supplementary Material to Chapter 3

Appendix 2

Canopy time course 2017

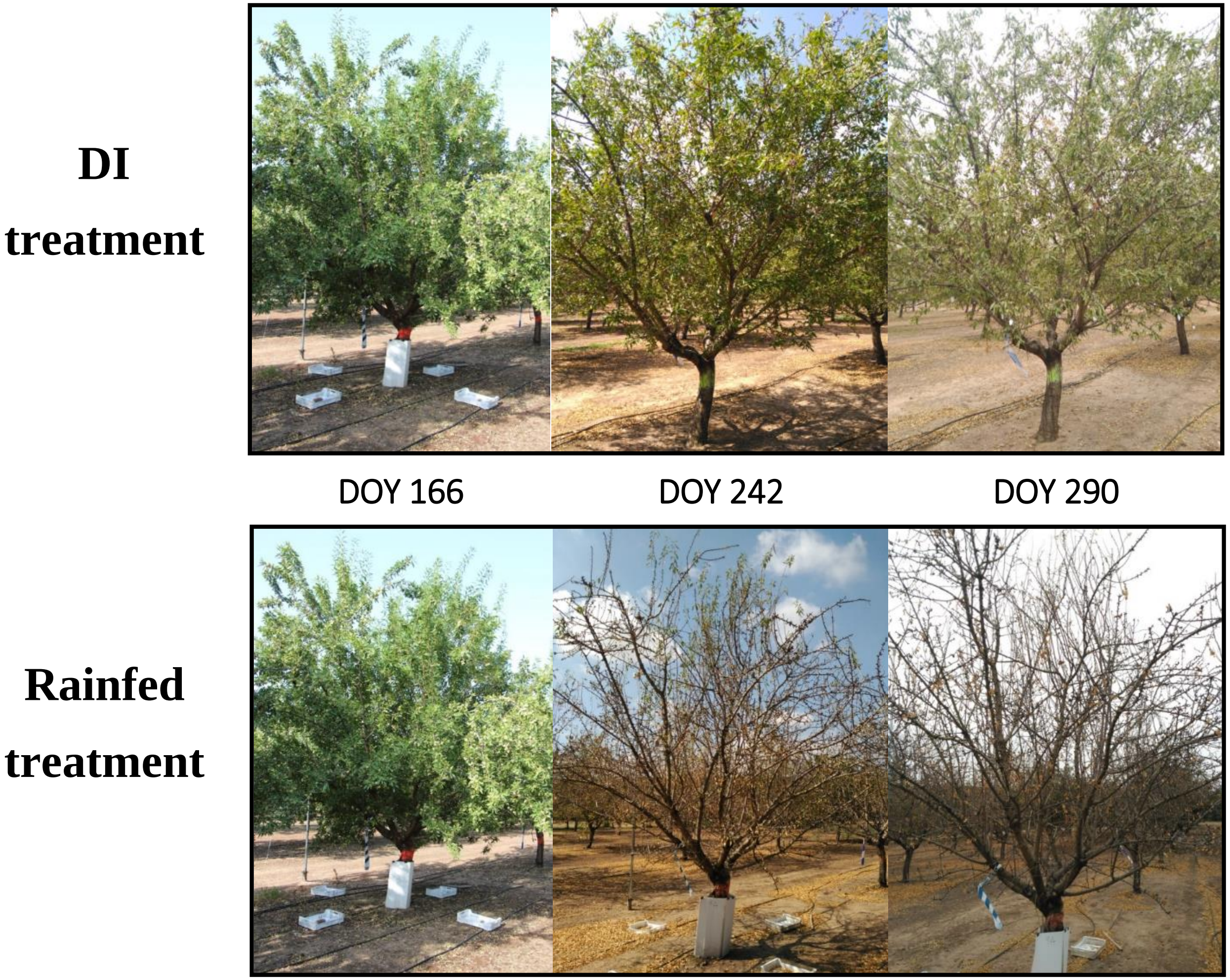
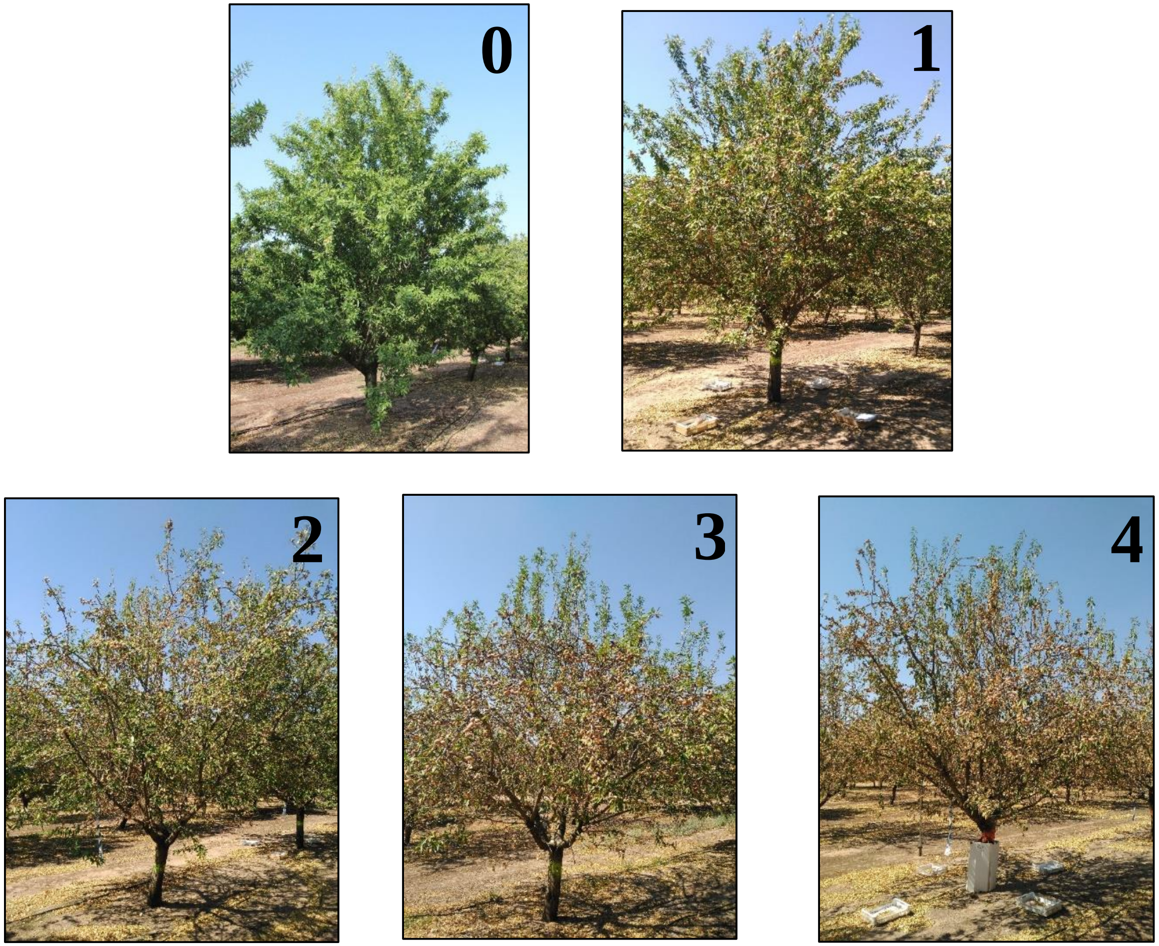


Figure S2. Pictures of the canopy time course for DI and RF treatment along the season. Date is shown in day of the year (DOY)

Appendix 2

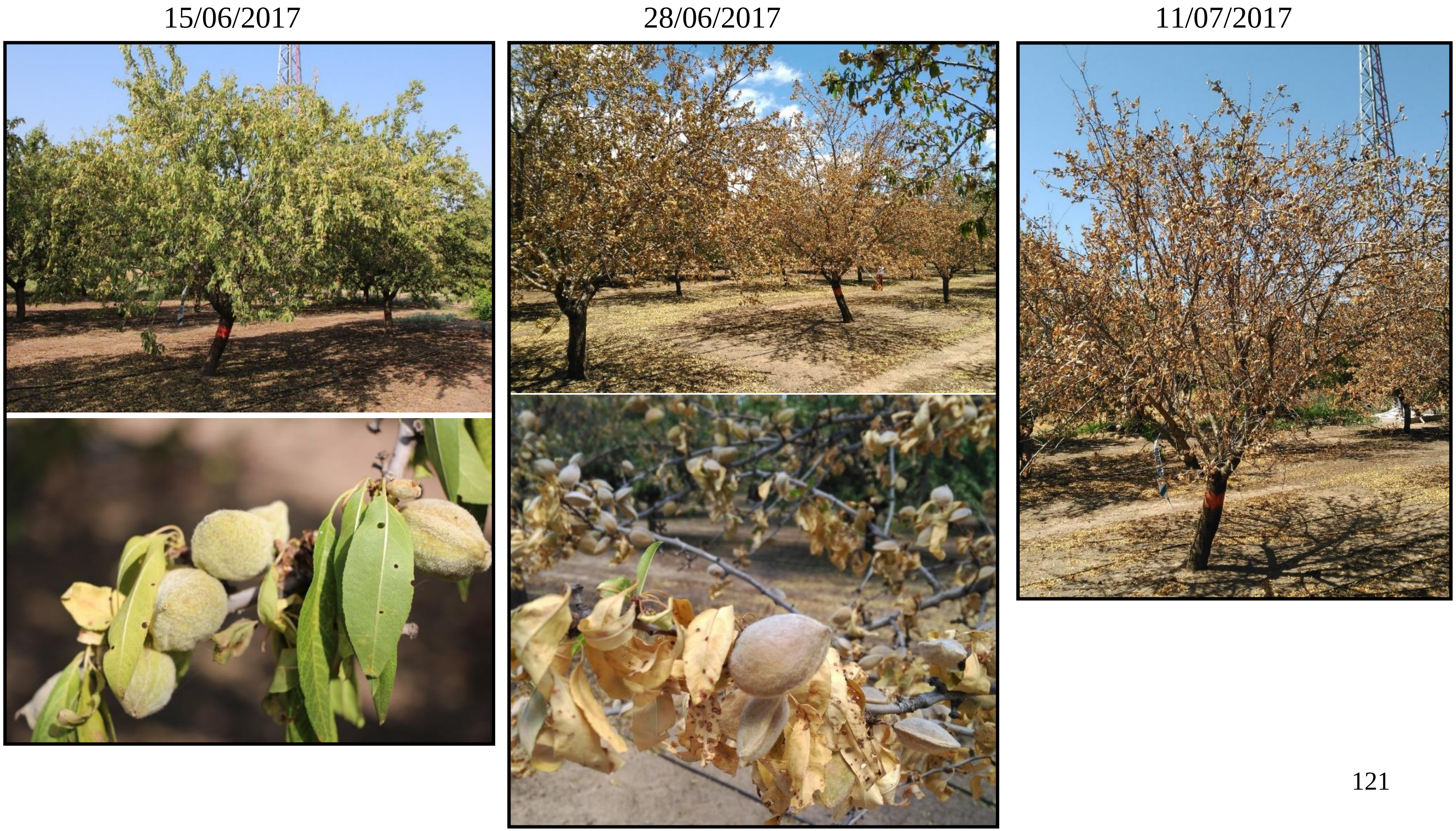


Defoliation Index (0 <20%; 1 =21-40%; 2 =41-60%; 3 =61-80%; 4 ≥80%)

Figure S3. Example images for each of the five categories of the defoliation index used to evaluate defoliation (0 <20%; 1 =21-40%; 2 =41-60%; 3 =61-80%; 4 ≥80%)

Appendix 2

Detail images of the rapid water stress development in Rainfed treatment trees



15/06/2017

28/06/2017

11/07/2017

Figure S4. Detail images of trees under rainfed treatment showing symptoms of a rapid and severe water stress.

Appendix 2