DEPARTAMENTO DE AGRONOMÍA

Programa de Doctorado:

Ingeniería Agraria, Alimentaria, Forestal y de Desarrollo Rural Sostenible

TESIS DOCTORAL

Almond response to irrigation:
Deficit irrigation and water production function

Respuesta de la producción al riego en almendro: riego deficitario y función de producción

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Córdoba, Marzo de 2018

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Memoria de Tesis Doctoral presentada por **MANUEL LÓPEZ LÓPEZ**, Ingeniero Agrónomo, para optar al grado de Doctor por la Universidad de Córdoba con la mención de Doctorado Internacional

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TÍTULO DE LA TESIS: RESPUESTA DE LA PRODUCCIÓN AL RIEGO EN ALMENDRO: RIEGO DEFICITARIO Y FUNCIÓN DE PRODUCCIÓN

DOCTORANDO/A: MANUEL LÓPEZ LÓPEZ

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 de la Universidad de Córdoba, adscrito al Instituto de Agricultura Sostenible del CSIC, y director de la tesis titulada "**RESPUESTA DE LA PRODUCCIÓN AL RIEGO EN ALMENDRO: RIEGO DEFICITARIO Y FUNCIÓN DE PRODUCCIÓN**", y el Dr. **Francisco Orgaz Rosúa**, Investigador Científico del Departamento de Agronomía del Instituto de Agricultura Sostenible del CSIC y codirector de dicha tesis, realizada por **Manuel López López,**

INFORMAN QUE:

El trabajo del doctorando se ha centrado en obtener la información básica necesaria para optimizar el manejo del agua de riego del almendro, cultivo de importancia creciente en la agricultura española de regadío. Además de su relevancia científica, los resultados derivados de la tesis permiten programar los riegos de cualquier tipo de plantación para distintas disponibilidades de agua, lo que resulta de enorme importancia práctica para los usuarios, reflejada en la firma de un convenio de colaboración entre ASOCIAFRUIT (asociación privada que representa a los productores y exportadores de frutas, hortalizas, flores y plantas de Andalucía y

Extremadura) y el Instituto de Agricultura Sostenible, para el cálculo de las necesidades de riego del almendro en el Valle del Guadalquivir.

En su etapa predoctoral, M. López ha demostrado una extraordinaria capacidad para abordar el trabajo de investigación en equipo y para resolver cualquier tipo de problema relacionado con el mismo de forma independiente.
Consideramos, por tanto, que la tesis constituye una aportación original y muy útil en su campo y demuestra la capacidad del doctorando para desarrollar una carrera de investigación de forma autónoma.

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

López-López M, Espadafor M, Testi L, Lorite IJ, Orgaz F, Fereres E (2018a) Water use of irrigated almond trees when subjected to water deficits. *Agricultutal Water Management* 195:84-93

López-López M, Espadafor M, Testi L, Lorite IJ, Orgaz F, Fereres E (2018b) Yield response of almond trees to transpiration deficits. *Irrigation Science*:1-10

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Aportaciones a congresos internacionales

Espadafor M, González-Dugo V, Orgaz F, Testi L, **López-López M**, Fereres E (2015) Transpiration and wáter relations of almond tres (cv Guara) under moderate wáter déficits. VIII International Symposium on Irrigation of Horticultural Crops (ISHS). Lérida, España

López-López M, Espadafor M, Lorite IJ, Orgaz F, Testi L, Fereres E (2015) Measurement of Almond Evapotranspiration by Lysimetry in a Semiarid Environment. VIII International Symposium on Irrigation of Horticultural Crops (ISHS). Lérida, España

González-Dugo, Espadafor M, **López-López M**, Lorite IJ, Testi L, Fereres E (2015) use of crop wáter stress index for monitoring wáter status in young almond orchards. VIII International Symposium on Irrigation of Horticultural Crops (ISHS). Lérida, España

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Firma del director y del codirector

Fdo.: Elías Fereres Castiel   Fdo.: Francisco Orgaz Rosúa

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Aer	Aerodynamic term of the Penman-FAO ET_O equation
C_p	Specific heat of air at constant pressure
E_S	Evaporation from soil
E_{SO}	E_S from the portion of soil not wetted by the emitters
E_{SOi}	E_S from the portion of soil not wetted by the emitters at stage I, limited by available energy
E_{SOii}	E_S from the portion of soil not wetted by the emitters at stage II, dependent on soil properties
E_{SOiii}	Residual E_S from the portion of soil not wetted by the emitters at stage III, when the soil surface is completely dry
E_{SW}	E_S from the portion of soil wetted by the emitters
ET	Potential crop evapotranspiration
ET_a	Actual crop evapotranspiration
ET_O	Reference evapotranspiration
ET_{WB}	Crop evapotranspiration calculated by water balance
fIR	Fraction of photosynthetically active radiation intercepted by the canopy
f_w	Fraction of soil wetted by the emitters
G_0	Species/cultivar dependent parameter for leaf insertion angle
gc	Canopy conductance
IR	Irrigation applied
K_C	Crop coefficient
K_{cb}	Crop basal coefficient
K_e	Evaporation coefficient
Kr	reduction coefficient
k_{sw}	Microadvective coefficient
K_T	Transpiration coefficient
P	Precipitation
P_{eff}	Effective precipitation
Rad	Radiative term of the Penman-FAO ET_O equation
t	Time since the end of the stage I of evaporation from soil
T	Tree transpiration
T_{LYS}	Tree transpiration measured by lysimetry
T_{SF}	Tree transpiration estimated by sap-flow
u	wind speed
U	Amount of E_S required for a soil to enter the falling rate stage (II)

V_0	Volume of one tree
Vu	Volume of canopy per unit of area
WP	Water productivity (general concept)
WP_{ET}	Water productivity (ET as denominator)
WP_T	Transpiration efficiency
Y_{DW}	Kernel yield (dry weight)
α	Coefficient for the calculation of E_S at the falling rate stage (II)
γ	Psycrometric constant
λ	Specific heat of vaporisation
ρ	Density of air
τ	Vertical transmissivity
Ψ	Stem water potential

List of abbreviations

AW	Applied water
CAG	Calibrated Average Gradient
CG	Ground cover
CHP	Compensated Heat Pulse
DI	Deficit irrigation
DP	Deep percolation
FI	Full irrigation/fully irrigated
IWMP	Irrigation water marginal productivity
PA	Plant area
PAD	Plant area density
PD	Plantation density
RDI	Regulated deficit irrigation
RO	Runoff
SDI	Sustained deficit irrigation
SWC	Soil water content
SWD	Soil water depletion
Volc	Canopy volume
VPD	Vapor pressure deficit

Summary

Introduction

Almond is becoming a very extended tree crop in Spain, due to good prices in the last years and likewise good market perspectives. A fast intensification process is taking place; new plantations (of which the acreage has doubled from 2014 to 2016) have nothing to do with the traditionally marginal rainfed crop producing around 150 kg/ha. Instead, taking after the Californian scheme, some of them are sited in deep and fertile soils, receive much less pruning and more inputs for nutrition and crop protection, and are usually irrigated. However, water availability is lower here in Spain than in California or Australia, where irrigation allocation for almond is about 12,000 $m^3 \cdot ha^{-1}$. On the other hand, rainfall is somewhat higher in Spain. In addition, breeding programs have led to self-fertile and hard-shelled cultivars in Spain whereas self-incompatible and soft-shelled ones, such as Nonpareil, are more common in California. All these differences have generated a need for information about irrigation requirements of intensive almond orchards in our conditions.

Research content

In the present thesis, first, maximum crop transpiration (T) was measured by both a large weighing lysimeter and calibrated sap-flow probes, concluding that mid-stage transpiration coefficient (K_T) of a fully mature almond orchard (covering 85% of soil) should be around 1.04, but could be affected by high fruit loads. Measuring transpiration instead of evapotranspiration (ET) made our findings more easily transferable throughout different conditions, despite different irrigation management alternatives (for instance, one or two drip lines, or microsprinklers; the three of them presenting different soil wetting patterns). Then, we conducted water balance (WB) measurements on both fully and deficit irrigated (DI) almond four-trees-subplots, to get a relation between irrigation (IR) regimes and actual water use (ET_a). Evaporation from soil (E_S) was modelled and detracted from evapotranspiration to calculate

transpiration values. This method was compared to direct transpiration estimates from sap-flow.

Conclusions

Almonds were found able to consume up to 200 mm from the soil reservoir and to extract water from deeper than 2 meters. Finally, kernel yield and its components (fruit load and kernel unit weight) were related to all three, irrigation, evapotranspiration, and transpiration, thus establishing the water production functions for almond. Irrigation water marginal productivity (IWMP) ranged from 0.33 $kg \cdot m^{-3}$ in the most severe DI treatment to 0.11 $kg \cdot m^{-3}$ in the full irrigated treatment.

Resumen

Introducción

El almendro se está convirtiendo en un cultivo leñoso muy extendido en España, debido a los buenos precios en los últimos años y a las buenas perspectivas de mercado. Está teniendo lugar un rápido proceso de intensificación: las nuevas plantaciones (cuya superficie se duplicó entre 2014 y 2016) no tienen nada que ver con el cultivo tradicional, marginal, en secano y con rendimientos de unos 150 kg/ha. En cambio, siguiendo el esquema de California, estas nuevas plantaciones intensivas reciben mucha menos poda y más insumos tanto fertilizantes como fitosanitarios, están generalmente en riego y la mayoría se encuentran en suelos profundos y fértiles. Sin embargo, la disponibilidad de agua de riego es más baja aquí en España que en California o Australia, donde la dotación de riego para el almendro es de aproximadamente 12.000 $m^3 \cdot ha^{-1}$. Por otro lado, las precipitaciones son más altas en España. Además, los programas de mejora genética han llevado en España a variedades autocompatibles y autofértiles, y de cáscara dura, mientras que en California se han preferido los cultivares auto-incompatibles y de cáscara blanda como Nonpareil. Estas diferencias han generado una necesidad de información sobre las necesidades de riego de las plantaciones intensivas de almendro en nuestras condiciones.

Contenido de la investigación

En primer lugar, la transpiración máxima del cultivo se midió con un lisímetro de pesada y con sondas de flujo de savia calibradas. Se concluyó que el coeficiente de transpiración máximo de una plantación de almendros en plena producción (con un porcentaje de cobertura de suelo del 85%) debería rondar 1,04, pero podría verse afectado por niveles altos de carga. Medir la transpiración en lugar de la evapotranspiración hace que nuestros hallazgos puedan ser más fácilmente transferibles a diferentes condiciones, a pesar de las diferentes alternativas de manejo del riego (por ejemplo, una o dos líneas de goteo o microaspersores, cada uno con un

distinto patrón de mojado del suelo). Posteriormente, se hicieron medidas de balance de agua en 16 subparcelas de 4 árboles, donde se aplicaron un tratamiento de riego para satisfacer el total de las necesidades hídricas y tres tratamientos de riego deficitario, a fin de establecer una relación entre los regímenes de riego y el uso consuntivo de agua. La evaporación del suelo se modeló y se restó de la evapotranspiración para obtener la transpiración de los árboles. Esta metodología se contrastó con medidas directas de transpiración con sensores de flujo de savia.

Conclusiones

Se comprobó que los almendros pueden consumir hasta 200 mm del depósito del suelo y extraer agua a más de 2 metros de profundidad. Finalmente, se hallaron relaciones entre el rendimiento y sus componentes (carga de fruta y peso unitario del grano) y riego, evapotranspiración y transpiración, respectivamente, estableciendo así la función de producción de agua del almendro. La productividad marginal del agua de riego fue de 0.33 $kg \cdot m^{-3}$ en el tratamiento de riego deficitario más estresado a 0.11 $kg \cdot m^{-3}$ en el tratamiento control.

CHAPTER 1:

GENERAL INTRODUCTION

Chapter 1. General Introduction

1.1. Almond

Almond has traditionally been a very popular tree crop in Spain, where it is the third most important perennial crop after olive and vine. In fact, Spain is the country with the highest almond acreage (754,043 in 2017, according to MAPAMA). The crop is mainly in the South and East regions: 12.8% Aragón, 6.1% Cataluña, 18.9% Castilla La Mancha, 13.8% Comunidad Valenciana, 15.9% Región de Murcia, 26.2% Andalucía. Spain is also the first world almond importer (82,871 tons in 2015, that is 11% of total), second exporter (57,118 tons in 2015, again 11% of total) and the first consumer, together with Tunisia (1.40 and 1.37 kg per person and year, respectively, in 2015).

However, Spain accounted for just 4% of world almond production in 2016/2017, thus being the third producer after California (80%) and Australia (7%), according to Almond Board of California (2017). Spanish almond has normally been a typical low input marginal crop, rainfed and occupying poor shallow soils at locations of arid climate; 93,406 of the 754,043 were considered as “abandoned” by the MAPAMA survey on crop surfaces (ESYRCE) in 2017. Average kernel yield is about 150 kg/ha. On the contrary, it is treated as an intensive high-input tree crop in California and Australia, where almond receives approximately 12,000 m^3/ha and average kernel yield is around 2,250 kg/ha (Almond board of California, Almond Almanac 2017).

In the current conditions of increasing world demand (USDA 2017), prices tended to grow in the last decade (Fig. 1.1), which has promoted intensification of Spanish almond.

Recent plantations take after the Californian model: new varieties, irrigation, lower tree spacing, and minimal pruning. They now try to be set on deep fertile soils and at locations of milder climates. Fig. 1.2 displays almond acreage in Spain from 2005 to 2017, in which the steep increase of both irrigated surface and new and young (still non-bearing) plantations since 2012 (data from MAPAMA) can be observed. Irrigated surface was 12.6% of total in 2017, while it was just 4.7% in 2005. Yet, average kernel yield in Spanish irrigated almond orchards is around 1,600 kg/ha.

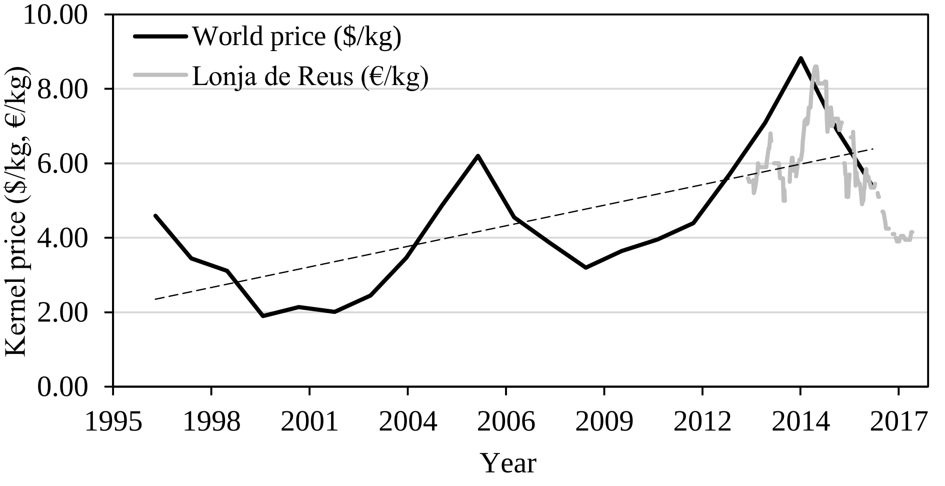

Figure 1.1. Evolution of almond world price to the farmer ($/kg) since December 1996 (**Source**: Almond Board of California); and Spanish price according to Lonja de Reus (€/kg), since July 2013 (Source: Lonja de Reus, http://proalmendra.com/hoja-de-precios/).

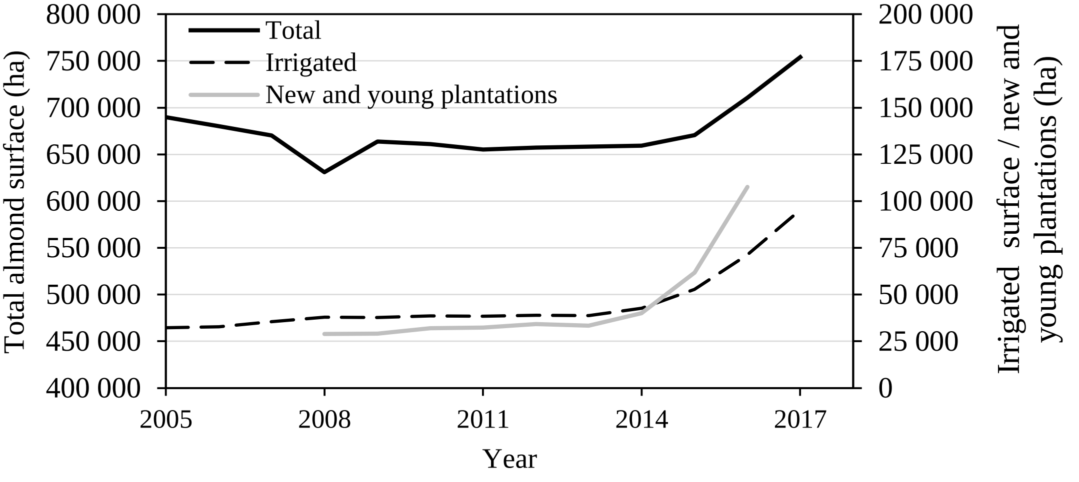

Figure 1.2. Evolution of total surface (primary axis) and irrigated and newly planted and young almond surface (secondary axis) in Spain since 2005. **Source:** ESYRCE, MAPAMA

There are some differences between California and Spain regarding almond irrigation. Firstly, water availability for almond in Spain is significantly lower than in California and Australia. On the other hand, some Spanish regions, such as Guadalquivir Valley in Andalusia, may compensate with higher seasonal precipitation and more retentive soils. Finally, soft-shell varieties are used in California, whereas breeding programs have kept hard-shelled varieties in Spain, in agreement with the developed industry. These differences have generated a gap of information about irrigation management of almond in Spain. What are the water requirements of a fully-mature high productive almond orchard? What may be the effects of supplying irrigation below crop water requirements?

1.2. Irrigation requirements

Water requirements of crops are determined by both atmospheric evaporative demand and crop features. The former depends on the main climatic variables, namely solar radiation, temperature and vapour content of the air, and wind speed. These variables are usually summed up by the combination Penman-Monteith equation (Monteith 1965; Allen et al. 1998), which is used to calculate reference evapotranspiration (ET_O). This is the water consumed by a hypothetic grass prairie under given weather conditions, and is used as the base to calculate water use of other crops (crop evapotranspiration, ET). Crop features, such as its species and developmental stage, are included in a so called crop coefficient (K_C). Therefore, ET can be calculated as:

$$ET = K_C \cdot ET_O \quad \text{Eq. 1.1}$$

ET_O, as well as the other climatic variables, are openly available thanks to weather stations. Crop coefficients have normally been calculated by water balance, that is, by measuring soil water content and depletion while the crop is not subjected to water limitations, neither pests or diseases. Lysimeters are the most precise technique for measuring ET, since all the in and out flows can be accurately monitored, and thus weight measurement remains the only source of error.

Doorenbos and Pruitt (1977) compiled K_C values in the Monograph 24 of FAO Irrigation and Drainage, which were afterwards revised in Monograph 56 of FAO

Irrigation and Drainage (Allen et al. 1998). The latter extends the K_C approach by proposing a dual crop coefficient which separates ET into crop transpiration (T) and evaporation from the soil (E_S). Nonetheless, crop intensification since then has led to new and usually higher K_C. Accurate measurements of K_C are required in order to design precise and sustainable irrigation systems and schedules. In the case of trees, this entails some difficulties in comparison to herbaceous crops, mainly derived from the facts that trees need several years to reach maturity and that, even at that point, cover of the soil by the canopies is incomplete. Hence, the values of K_C obtained previously for tree crops were influenced by specific orchard conditions (species and variety, tree spacing, age, pruning system, row orientation, soil management…), thus leading to a range of values corresponding to these specific conditions. Finally, Steduto et al. (2012) recommended to consider in-season rain and allowable soil water depletion (SWP) as components of ET in order to calculate site-specific irrigation requirements, since any amount of water beyond ET is not consumed by the crop. The E_S component might vary according to irrigation management, mainly, frequency and wetting pattern. On the contrary, the transpiration coefficient (K_T=T/ET_O) depends only on the crop.

To come back to almond, K_C of an adult orchard has increased from initial 0.8-0.95 to 1.0 (Allen and Pereira 2009), 1.12 (Stevens et al. 2012), 1.15 (Sanden et al. 2012). Therefore, Espadafor et al. (2015) used a large weighing lysimeter to measure transpiration of a young almond orchard in Southern Spain and found a constant relationship of 1.2 between K_T and fraction of intercepted radiation (fIR) during summer (mid-stage). On average, the mid-stage value of K_T proposed for a target adult orchard intercepting 85% of radiation would be of 1.02. In this regard, the current work extends the one of Espadafor et al. (2015) from young to mature almond trees.

1.3. Water scarcity and water productivity

Irrigation plays an utmost role in world food production. According to Fereres and Connor (2004), irrigated agriculture occupies about 17% of the food-producing land area on a global scale, while it produces more than 40% of total food. About 70% of fresh water is used by agriculture. Growing population, together with the development of other sectors which compete for this finite resource, entail the need of an increasingly efficient use of water by agriculture (Seckler et al. 1999), that is to "produce more with less"(Howell 2001). Jury and Vaux (2005) identified scarcity as the single biggest water problem worldwide.

In addition, frequency and duration of droughts has been predicted to grow in regions of Mediterranean climate (Stocker et al. 2013). Especially in Andalusia, Espadafor et al. (2011) confirmed a trend to higher temperature and lower relative humidity after the analysis of climatic data since 1960. Future water availability and supply is not sure in these regions, so trying to maximize water productivity (WP) may be more interesting than aiming for maximum yields at a regional scale. On the other hand, farmers may be unconcerned of WP issue, unless it reports any profit. Hence, there should be a tradeoff between yield and WP when water is scarce (Fereres et al. 2014).

Generally, WP depends on genotype, environment and management (Fereres et al. 2014). More thoroughly, Wallace and Batchelor (1997) signalled four interrelated categories to improve WP: agronomic (for example, capturing more precipitation, reducing evaporation from soil by mulching or moving the cropping season to periods of lower ET_O), engineering (designing more efficient irrigation systems, improving distribution uniformity…), management (better scheduling, deficit irrigation), and institutional (e.g., water pricing and legal incentives). In summary, we should either increase yield or reduce water use, which could be achieved by a) reducing runoff, deep percolation, evaporation losses; b) increasing the amount of biomass assimilated per unit of water transpired at leaf level; or c) breeding for higher harvest index.

However, there is some controversy regarding the concept of water productivity in irrigated agriculture, sometimes taken as a synonym of water use efficiency. Besides, numerator can be either biomass or usable yield and sometimes applied water has been used as denominator instead of water consumption (Perry et al. 2009). Besides, the term can be used at several scales, from leaf to field, as described by Sinclair et al. (1984).

Moreover, Howell (2001) highlighted the convenience of setting the rainfed crop as a reference when assessing the added value of irrigation in water use efficiency. Nonetheless, it is not easy to find good rainfed references to compare with neither yield or water use of irrigated fields, since other crop managements practices may differ.

In the current work, we considered WP as the unit of harvestable crop produced (dry kernel yield, Y_{DW}) per unit of ET, WP_{ET} (kg·m^{-3}). When calculated on a T (regarded as the *beneficially consumed*) instead of an ET basis, we used the term transpiration efficiency (WP_T, kg·m^{-3}). The added value of irrigation was approached as irrigation water marginal productivity, IWMP (also kg·m^{-3}). This concept represents the infinitesimal increments or reductions in yield caused by infinitesimal increments or reductions in irrigation, respectively. IWMP was calculated as the derivative of the irrigation water production function. In our case, all these terms were considered at a field or orchard scale.

1.4. Deficit irrigation

In those regions where the water available for irrigation is that left after by other sectors of higher priority, farmers can either irrigate a smaller land area or distribute the available location over the whole area, yet not fulfilling crop water requirements (Fereres and Soriano 2007). Deficit irrigation (DI) can be defined as the deliberate application of water below ET (English 1990). In conditions of water scarcity, DI has been identified above in the text as a possible management strategy to increase water productivity (Wallace and Batchelor 1997).

It is difficult to reduce applied water (AW, that is irrigation plus in season rain) without affecting crop production, since water is transpired through the same stomata as carbon dioxide enters the leaf for its assimilation (Tanner and Sinclair 1983; Monteith 1990; Steduto et al. 2007), unless soil water reservoir is able to account for the difference between AW and ET. Nonetheless, this relation between water application and biomass or yield production, which is usually lineal for herbaceous crops (Hanks 1983), can behave differently in tree crops and vines depending on the moment of the stress (Fereres et al. 2012). Therefore, DI strategies in tree crops aims at reducing water application at stress-tolerant stages, which is known as regulated deficit irrigation (RDI). Conversely, a sustained deficit irrigation (SDI) strategy consists on distributing the stress equally throughout the season.

In the case of almond, Goldhamer and Viveros (2000) concluded this crop was relatively tolerant to stress during kernel filling, while water stress occurring at post-harvest was proved to jeopardize the fruit load in the forthcoming season. This is an interesting point, since kernel-filling occurs usually in July, which is the month of highest atmospheric demand in our conditions, when transpiration efficiency is the lowest. Later, other studies have dealt with the physiologic and agronomic responses of almond to various DI regimes and strategies in Spanish conditions (Esparza et al. 2001; Romero et al. 2004; Girona et al. 2005; Romero and Botía 2006; Egea et al. 2010; Egea et al. 2013; Espadafor et al. 2017). However, only the last one measured transpiration, whereas the results of the other studies were expressed in terms of irrigation or AW. Since the same irrigation regimes can lead to diverse water stress conditions depending on the depth of the root zone, winter effective precipitation and soil water holding capacity and ET_O, accurate monitoring of plant-based water stress indicators (such as stem water potential or canopy temperature) are necessary to compare DI studies conducted in different conditions (Fereres et al. 2012). In this regard, the aim of this thesis was to report responses and relationships of almond trees to water stress on an actual evapotranspiration (ET_a) and a T basis, in order to ease transferability to different conditions.

1.5. Water production function

Crop yield response to consumptive use of water is termed as water production function. Those functions can be used to quantify the effect of not reaching maximum ET. Most of water production functions for most field crops were defined in the Monograph 33 of FAO Irrigation and Drainage (Doorenbos and Kassam 1979).

However, building production functions for trees entail some difficulties when compared to herbaceous crops, since much more time is needed and variability among orchards is higher, so water production functions for tree crops and vines were dealt later in Monograph 66 of FAO Irrigation and Drainage, which also updates information of the former (Steduto et al. 2012). Figure 1.3, taken from this Monograph, presents the general pattern of response of tree crop relative yield to relative ET, as percentages of maximum yield and maximum ET, respectively (Fereres et al. 2012). However, there was missing information about almond ET, and a real production function could not be drawn at that moment.

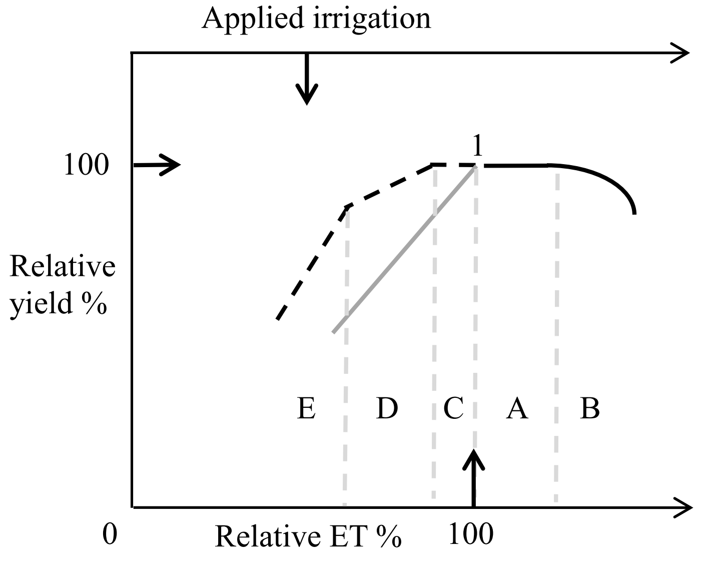

Figure 1.3. Generalized relationships between yield, ET and applied irrigation water in fruit trees. The dotted line represents the expected response of fruit and nut trees while the solid grey line indicates the typical response of an annual field crop for comparative purposes. Different letters represent response regions: A) Maximum yield, deep percolation losses increase after Point 1; B) Excessive water reduces yield; C) Yield is maintained despite deficit irrigation, D) Some yield loss occurs due to DI; and E) Severe water stress may cause commercial losses. **Source**: FAO 66 (Fereres et al. 2012).

Goldhamer and Fereres (2017) presented a yield response to AW in conditions of very low annual rainfall, so ET_a of each irrigation treatment could be assumed to be similar to AW (which ranged from 1,000 to 1,350 mm). Water deficit was applied at kernel-filling, and significantly affected kernel weight, but fruit load among treatments remained unaffected. This function explored the A-D response regions explained in Figure 1.3, but Spanish almond growers may deal with lower allocations (region E).

Water production functions are not only interesting for agronomists and farmers, but also for economists in order to optimize the use of water and maximize revenues (Vaux Jr and Pruitt 1983). In the current conditions described previously for almond in Spain, almond water production function at lower AW levels than that of Goldhamer and Fereres (2017) can be a useful tool for farmers to make decisions relating water distribution between crops, as well as for Water Authorities to assign appropriate irrigation allocations to this crop so that to make almond a profitable sector.

1.6. Objectives and outline of the thesis

The general objective of this thesis is to contribute to fill part of the knowledge gaps regarding water management for the new Spanish almond orchard typologies. Accordingly, the specific objectives set were:

a) To measure transpiration of a fully irrigated almond tree by lysimetry, and relate it to the atmospheric demand, taking into account possible sources of variability
b) To measure the consumptive use of water of deficit irrigated trees by water balance and to compare this methodology with direct measurements of transpiration with CHP-CAG sap-flow.
c) To establish a functional relationship between the previously calculated transpiration and yield and its components and assess water productivity

Each of these objectives is addressed in one of the following chapters, which have the structure of peer-reviewed publications. Therefore, Chapter 2 presents tree transpiration measurements calculated by weight loss of a large weighing lysimeter. CHP-CAG sap-flow probes were calibrated with lysimeter data to get continuous values of transpiration and its relation to ET_O. The sources of in-season and inter-season variability of this transpiration coefficient are analysed for the sake of transferability of the results.

In Chapter 3, actual evapotranspiration and transpiration of control and three deficit irrigated treatments are estimated by water balance down to 2.10 m deep. Water balance outputs are compared to direct measurements of transpiration by sap-flow. ET_a values are compared to the sum of irrigation and in-season rainfall, to highlight the important role of soil reservoir contribution in the complete water balance.

Then, Chapter 4 reports the effects of reduced water use on almond yield and its components, fruit load and unit kernel weight. Chapters 3 and 4 are modified versions of the published articles in order to standardise nomenclature, abbreviations, and figure format, and to avoid unnecessary repetitions.

Finally, Chapter 5 sums up the general conclusions taken after the elaboration of the current work.

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CHAPTER 2:

Water Requirements of Mature Almond Trees in Response to Atmospheric Demand

This Chapter is under review in Irrigation Science

Chapter 2: Water Requirements of Mature Almond Trees in Response to Atmospheric Demand

Summary

Accurate methods to determine irrigation requirements are necessary for the efficient use of water in agriculture. We conducted measurements of transpiration (T) of one almond tree placed in a large weighing lysimeter and instrumented with sap-flow probes for three-seasons (2014-2016; sixth to ninth year of the tree). Transpiration was related to reference evapotranspiration (ET_O) to obtain the coefficient of transpiration (K_T=T/ET_O). Average mid-season K_T was 0.55, 0.68 and 0.91 in 2014 2015, and 2016, respectively, and maximum ground cover (GC) was 55%, 59% and 55% for the same years. These K_T values were confirmed by the independent estimations of K_T obtained in small plots using the water balance. There were significant fluctuations in daily K_T during mid-season, which were related to environmental factors. Furthermore, the exceptionally high K_T in 2016 was apparently related to the very high crop load of that year (75% more than the other two normal years). Hourly canopy conductance values were obtained from lysimeter records to confirm the high transpiration rates prior to harvest during 2016. From the K_T values measured here, we propose that the mid-season K_T of fully-mature almond orchards, with a GC of 85%, should be around 1.04 in normal years.

2.1. Introduction

On a global scale, a more sustainable use of the resource water by the agricultural sector is demanded. Therefore, precise knowledge of crop water requirements is necessary (Lenton 2014). Water use or crop evapotranspiration (ET) of a healthy, well-watered crop is usually calculated as $ET = K_C \cdot ET_O$ (Doorenbos and Pruitt 1977) or $ET = (K_{cb} + K_e) \cdot ET_O$ (Allen et al. 1998), where ET_O is the reference evapotranspiration (dependent on climatic data), and K_C is the crop coefficient, which can be divided in K_{cb} (basal crop coefficient) and K_e (evaporation coefficient). ET represents the sum of crop transpiration (T) and evaporation from the soil (E_S). However, calculating ET of a tree crop with this methodology faces the issue of the coefficients being specific for the orchard conditions in which they were obtained (plantation age, training system and row orientation, soil management, irrigation method, etc..), which makes it difficult to recommend a single set of standard crop coefficients, as all those variables generate uncertainty in the determination of the actual consumptive use of an orchard (Fereres et al. 2012).

Weighing lysimeters are the most accurate tool to measure ET (Wright 1991), but again tree crops present the issue of requiring large and costly structures, and several years before trees reach maturity, in comparison with annual crops (Ayars et al. 2003). Besides, there is still the need of making this measurement transferable to other conditions. Given the variations in ET introduced by variations in E_S due to rainfall and irrigation method, it would be desirable to separate tree transpiration from evaporation from soil (Perry et al. 2009; Fereres et al. 2012), for which either the development of models or the direct measurement of T with sap-flow methodologies can be valid options (Swanson 1994; Orgaz et al. 2007; Villalobos et al. 2013).

There is evidence in the literature that light interception by tree canopies may be used to adjust standard K_C values of tree crops to specific conditions (Johnson et al. 2000; Johnson et al. 2001). Radiation interception was found to be the main factor influencing the relationship between ET and ET_O in peaches (Ayars et al. 2003), grapevine (Williams et al. 2003; Williams and Ayars 2005), apple (Green et al. 2003b; Auzmendi et al. 2011), citrus (Consoli et al. 2006) and almonds (Espadafor et al. 2015). However, other studies with trees in lysimeters have reported variations in this relationship (Girona et al. 2011; Marsal et al. 2014).

This work extends that of Espadafor et al. (2015) for young almond trees to mature ones. Espadafor et al. (2015) found a constant relationship of 1.2 between the transpiration coefficient (K_T=T/ET_O) and fraction of intercepted radiation (fIR) during summer (mid-stage). On average, the mid-stage value of K_T proposed for an adult orchard intercepting 85% of radiation was of 1.02. Other reports proposed mid-stage values of Kc (including E_S) of 1.0 (Allen and Pereira 2009), 1.12 (Stevens et al. 2012), 1.15 (Sanden et al. 2012) for mature almond trees. Goldhamer and Fereres (2017) determined a peak irrigation coefficient of 1.17 for a mature orchard with more than 60% ground cover (GC) irrigated with microsprinklers. All of these values are higher than the mid-stage K_C of 0.8-0.95 proposed earlier by Doorenbos and Pruitt (1977). This is probably due to the intensification that almond production has undergone since that time (higher tree densities and minimal pruning; Goldhamer and Fereres, 2017).

In the analysis herein, the K_T has been related to GC%, which may have some disadvantages in relation to intercepted radiation, but which is a measurement more accessible to growers. Three years of lysimeter data with mature trees are used to investigate the variability in tree transpiration in response to environmental factors and the role of stomata as a driver of tree T (Villalobos et al. 2000). Specifically, the objectives of this work are:

a) To measure the T of mature almond trees by both lysimetry and calibrated sap-flow techniques in order to establish a relation between almond T and the reference evapotranspiration (i.e., the transpiration coefficient, K_T), and

b) To examine the degree of variation in the relation between almond T and ET_O in response to environmental factors and to explore other sources of variation in such relationship.

2.2. Materials and methods

2.2.1. Experimental site

The experimental site consisted of a 5.5-ha almond orchard (cv. Guara grafted on GF-677 rootstock) planted in 2009 in a 6 × 7 m grid. The field belongs to the Research Centre of IFAPA-Alameda del Obispo, in Cordoba, Spain (37,8°N, 4,8°W). Pruning for scaffold formation was done during the first two years and only again in January 2016 to allow for machinery transit.

The soil of the field presents a sandy-loam texture in the first 1.5 m depth, and lighter texture in the deeper layers. It is of alluvial origin, more than 2.0 m deep. The typical field-capacity and wilting point limits of this soil are 0.23 and 0.08 cm3/cm3, respectively. Soil was kept free of weeds by both mower passes and herbicide applications, and pests and diseases were controlled following a treatment calendar, which was adjustable according to each season conditions. Trees were drip-irrigated to satisfy their full water requirements according to (Fereres et al. 2012) during the first year of study (2014) and according to Espadafor et al. (2015) in the following two years (2015 and 2016). Mineral fertilizers were applied according to the recommendations of the University of California (http://apps.cdfa.ca.gov/frep/docs/Almonds.html) and Muncharaz (2004).

Weather data of reference evapotranspiration (ET_O) and precipitation (P) were gathered from an automated weather station at 300 m from the orchard. Cordoba climate is typical Mediterranean, with hot summers and mild winters; average annual rainfall is around 600 mm, concentrated in autumn and winter.

In the centre of the 5.5 ha orchard there is a large weighing lysimeter with one representative almond tree, as described below. The tree in the lysimeter was equipped with two sap-flow probes.

2.2.2. Determination of tree transpiration

- Lysimeter

The stainless steel container of the lysimeter is 3x3x2.10 m deep. Real-time weight can be observed in a display, and 5-minute averages are recorded by a datalogger (Model CR1000, Campbell Scientific Inc., Logan, UT, USA). This lysimeter was described in detail by Lorite et al. (2012). Data were downloaded weekly. The lysimeter tree was daily irrigated by 24 2-l/h self-compensating emitters, so that the whole 9 m^2 of lysimeter area was wetted. Regarding other agricultural practices, the lysimeter tree received the same management as the rest of the field. Tree canopy height and size was representative of the trees in the orchard throughout the three years of the study.

To determine daily values of transpiration only (T_{LYS}), the surface of the lysimeter was covered with an impermeable black plastic layer, which was in turn covered with a 5-10 cm layer of straw (not to modify the albedo). In this way, evaporation from the soil was prevented. The surface of the lysimeter was covered at intervals of 3-5 days every two weeks.

- Sap-flow

The lysimeter tree was equipped with two sap-flow probes to get continuous daily readings of transpiration. The Compensation Heat Pulse (CHP) method was used in combination with the Calibrated Average Gradient (CAG) technique (Testi and Villalobos 2009) for the hours of the day when the sap flow is lower than 12 $cm \cdot h^{-1}$, which could reduce the accuracy of CHP.

The probes employed were designed and manufactured at the IAS-CSIC in Cordoba and were described in detail by Testi and Villalobos (2009). Briefly, they consist of a stainless steel heater plus two temperature sensors located, respectively, 10 mm above and 5 mm below the heater, and protected as well by stainless steel. Each sensor has four thermocouple junctions: at 5, 15, 25 and 35 mm from the cambium. A multiplexer (AM16/32, Campbell Scientific Inc., Logan, UT, USA) controlled by a datalogger (CR10X or CR1000, Campbell Scientific Inc., Logan, UT, USA) initiates a measurement cycle at intervals of 15 minutes. Along this cycle, Temperature difference (DT) is measured at 1-s intervals for 10 seconds, a 2-s heat beat (0.12 W/mm) is released, and DT is measured again at 1-s intervals for 3 minutes. DT readings, measured with less than 0.01 K error, were collected in the datalogger. The heat-pulse velocities had then to be checked for wounding effects (Green et al. 2003a). The time that sensors need to equilibrate is then used to calculate heat pulse velocities. These are first converted to sap velocity ($m \cdot h^{-1}$) and into sap-flow ($l \cdot h^{-1}$) by integrating both along the trunk radius and then around the azimuth angle (Green et al. 2003a). Sap-flow values were hourly averaged and then added up to get daily values. Sap flow going up the trunk was considered equal to the water transpired by the tree.

Sap-flow transpiration (T_{SF}) was calibrated with transpiration data from the lysimeter. One calibration coefficient (CC) per probe was obtained for every day when the lysimeter was covered as $CC=T_{SF}/T_{LYS}$. These values were used to establish the time trend of calibration coefficients and then applied to sap-flow readings to get actual daily transpiration values throughout the season.

Uncalibrated 30-min values of T_{SF} were used to calculate the portion of total daily transpiration occurring after midday as another source of information about the behaviour of stomata.

- Water balance

Transpiration outputs of the four fully irrigated subplots of the water-balance experiment described by López-López et al. (2018a) in the same field were taken to compare to the values obtained from the lysimeter tree. Briefly, soil water content (SWC) down to 2.10 m deep was measured every month with a neutron probe. In the period between SWC measurements, applied irrigation (IR) was metered, and precipitation (P) data were collected from the weather station nearby. Because of the field soil characteristics, no runoff (RO) happened, and deep percolation (DP) could be neglected based on the soil water content of the subsoil. Evapotranspiration (ET) was calculated from the following equation:

$$ET = IR + P - \Delta SWC - \cancel{RO} - \cancel{DP} \qquad \text{Eq 2.1}$$

Afterwards, evaporation from the soil (E_S) was modelled according to Bonachela et al. (2001), and subtracted from ET to get T values, as described in López-López et al. (2018b).

2.2.3. Relationship between transpiration and reference evapotranspiration

Both daily T_{LYS} and calibrated T_{SF} values, as well as T data from the four subplots of the water balance experiment, were related to ET_O values to assess the transpiration coefficient (K_T) seasonal evolution.

Based on the results of Espadafor et al. (2015) who showed significant scatter of K_T around an average value, relative values of K_T from T_{SF} were plotted against wind velocity (u, m/s) to see to what extent this variable accounts for K_T variability during July and August (when it is considered to remain constant). We used the relative instead of the absolute K_T values to remove the effect of the seasonal evolution of K_T. Therefore, relative values of K_T were calculated by dividing each daily value by its five-day moving average.

2.2.4. Tree growth and yield

Tree growth of the lysimeter tree was characterised by measuring ground cover percentage (GC%) every season. A single measurement was taken in 2014, and 4 measurements, separated about 2 months, were taken in 2015 and 2016, respectively. Two orthogonal diameters of the vertical projection of the canopy were measured with the help of a measuring tape, and GC% was calculated as the area of a circle of average diameter divided by tree spacing.

The time course of K_T was related to an interpolated GC% continuous function to find a ratio which may be transferable to different conditions of tree size, as in Espadafor et al. (2015).

Kernel yield (on a dry weight basis) and yield components of the lysimeter tree were measured as well. Therefore, the tree was hand harvested and the fruits weighed. Then, a sample of about 2 kg was taken, weighed in the field and then counted. The fruit load was estimated by dividing the field weight by the field unit weight (i.e., weight of the sample divided by the number of almonds within). Afterwards, a subsample of 100 almonds was oven-dried at 70ºC till constant weight and dry unit weight (g/kernel) was obtained. Kernel yield was calculated as number of almonds times unit weight.

2.2.5. Determination of canopy conductance

Using 30-min average T_{LYS} data (l/h), we determined canopy conductance (gc, $m \cdot s^{-1}$) by using the imposed evaporation equation (Tan et al. 1978; McNaughton and Jarvis 1983):

$$\lambda \cdot T =\cdot (\rho \cdot C_p \cdot VPD \cdot g_C)/\gamma \qquad \text{Eq. 2.2}$$

In our case,

$$g_C = T_{LYS} \cdot \lambda \cdot \gamma/(\rho \cdot C_p \cdot VPD \cdot 3600) \qquad \text{Eq. 2.3}$$

where λ is the specific heat of vaporisation (MJ·kg^{-1}), γ is the psycrometric constant (kPa·K^{-1}), ρ is the density of air (kg·m^{-3}), ·C_p is the specific heat of air at constant pressure (kJ·kg^{-1}), and·VPD is the vapour pressure deficit (kPa). The equations for these parameters may be found in Villalobos and Fereres (2017). Kurtosis and asymmetry analyses were conducted on the 2015 and 2016 gc curves in order to detect variations in the shape of the gc daily curves.

2.3. Results and Discussion

2.3.1. Weather

Seasonal ET_O averaged 1,278 mm for the three years (with a coefficient of variation of 1.7%) and showed the typical pattern along the cropping seasons: variable during spring and autumn, depending on clouds and rainfall, and fairly constant during summer with values higher than 7 mm·day^{-1}. Precipitation varied notably among years, in season values being 425 mm, 263 mm and 515 mm in 2014, 2015 and 2016, respectively. Spring was dryer in 2014 and 2015 than in 2016, and autumn was dryer in 2015 than in the other two seasons. Almost no rain occurred in summer, which is common of the Mediterranean climate of Cordoba (Fig. 2.1).

2.3.2. Transpiration coefficient (K_T) and its relation to tree size

K_T increased fast from budburst, in early March, as leaves sprout and expand, until completion of canopy development in early May. Afterwards, a *plateau* is maintained at a maximum value of K_T until the start of canopy senescence. Fig. 2.2 displays daily K_T values obtained from three sources: weight loss of the lysimeter, calibrated sap-flow probes, and calculated T from the water-balance experiment. It can be observed that the fast-growing stage went from March to early May in 2014 and 2015, while it was extended until early June in 2016. In addition, the steady-state stage lasted less in this last season. Sap-flow K_T values during this stage increased every season, thus averaging 0.55, 0.68 and 0.91 in 2014, 2015 and 2016 (from 1st June to 31st August), respectively. GC% of the lysimeter tree grew from 36.3% in spring to 55% in autumn

2014, 44.7% to 59% in 2015, and from 48.2% to 55% in 2016 (Fig. 2.3), a similar peak GC value as the other two years even though 2016 presented higher K_T values (Fig. 2.2). Thus, when maximum K_T was related to GC% (Fig. 2.4), 2016 also presented a remarkably higher average value than the two previous seasons, whereas 2014 and 2015 had similar values (1.74 in 2016 against 1.18 in 2014 and 1.28 in 2015, from 1st June to 31st August).

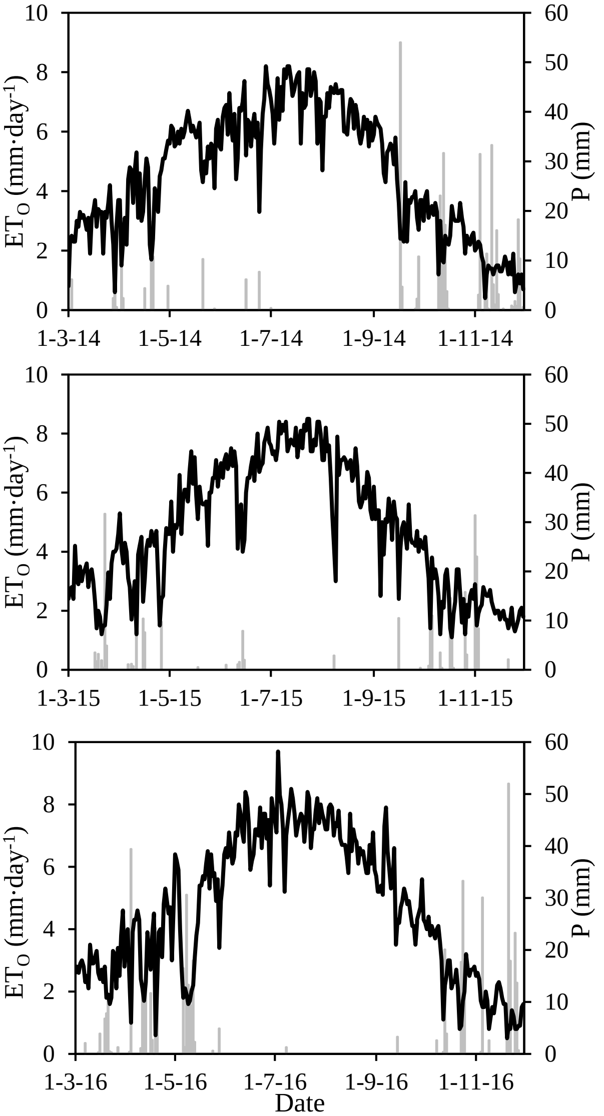

Figure 2.1. Daily values of reference evapotranspiration (ETo, black line) and precipitation (P, grey bars), both in mm, of the three seasons, 2014-2016.

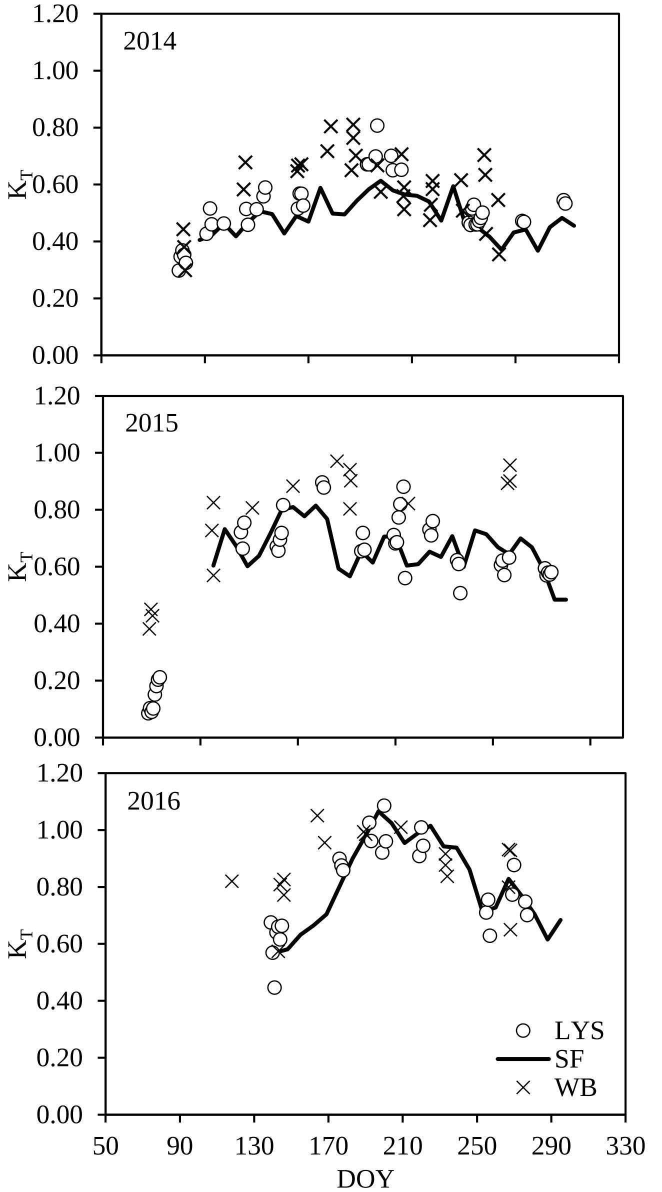

Figure 2.2. Daily K_T values obtained with the lysimeter (LYS, open circles) and weekly trend of the calibrated CHP-CAG sap-flow (SF; black line), for the three seasons under study. Crosses represent K_T values of well-irrigated four-tree-subplots calculated by water balance (WB).

Based on these values, for an hypothetical orchard covering 85% of the soil surface, this would mean a mid-season K_T value between 1.00 and 1.08 (if we consider 2014 and 2015 as normal years), which is in line with the other published values cited above (Allen and Pereira 2009; Sanden et al. 2012; Stevens et al. 2012; Espadafor et al. 2015; Goldhamer and Fereres 2017). However, the K_T value that may be calculated from the 2016 data, that is 1.74x0.85=1.48 seems much higher than those reported for almond. Nevertheless, the average 2016 K_T calculated independently with the water balance also gave the highest values of the three years. Values of mid-stage K_T were 0.64, 0.88 and 0.95 for GC% of 55.8%, 75.0% and 66.3% in 2014, 2015 and 2016, respectively, which resulted in average K_T/GC% ratios of 1.15, 1.17 and 1.44 in 2014, 2015 and 2016, respectively. K_T/GC% values measured in 2014 and 2015, both of the lysimeter and the water balance sub-plots are in agreement with the already mentioned K_T/fIR equal to 1.2, if we consider an almost unitary relationship between fIR and GC%, confirming the results in young almond trees of (Espadafor et al. 2015). The higher values found here for almond in 2016 were similar to those found in peach, i.e. K_C/fIR 1.67 with 60% of intercepted radiation at midday (Ayars et al. 2003); and to the maximum values around 1.6 reported by Marsal et al. (2014) for peach, apple and pear before harvest.

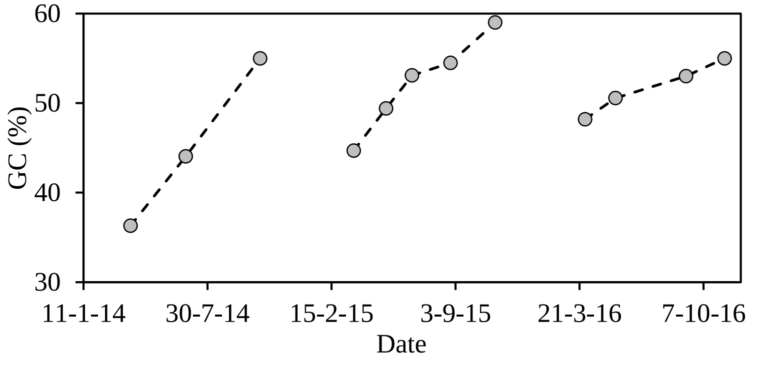

Figure 2.3. Time course of Ground Cover (GC, %) of the lysimeter-tree along the study.

In fact, intercepted radiation is a more appropriate variable than GC%, to relate K_T to tree characteristics since the former includes leaf area density, canopy architecture, tree height and row orientation. Unfortunately, we could not apply the methodology used by Espadafor et al. (2015), which consisted in estimating leaf area density from the analysis of photographs of the tree shade projected on a white screen, to our much larger trees, since neighboring trees made it impossible to get away from the lysimeter tree to take the pictures. On the other hand, if almond growers have to use a methodology to calculate water requirements of their own orchards, from the practical viewpoint GC% is a much easier measurement than intercepted radiation. Therefore, we propose that further research should be conducted on the relation between these two variables in the most common cultivars.

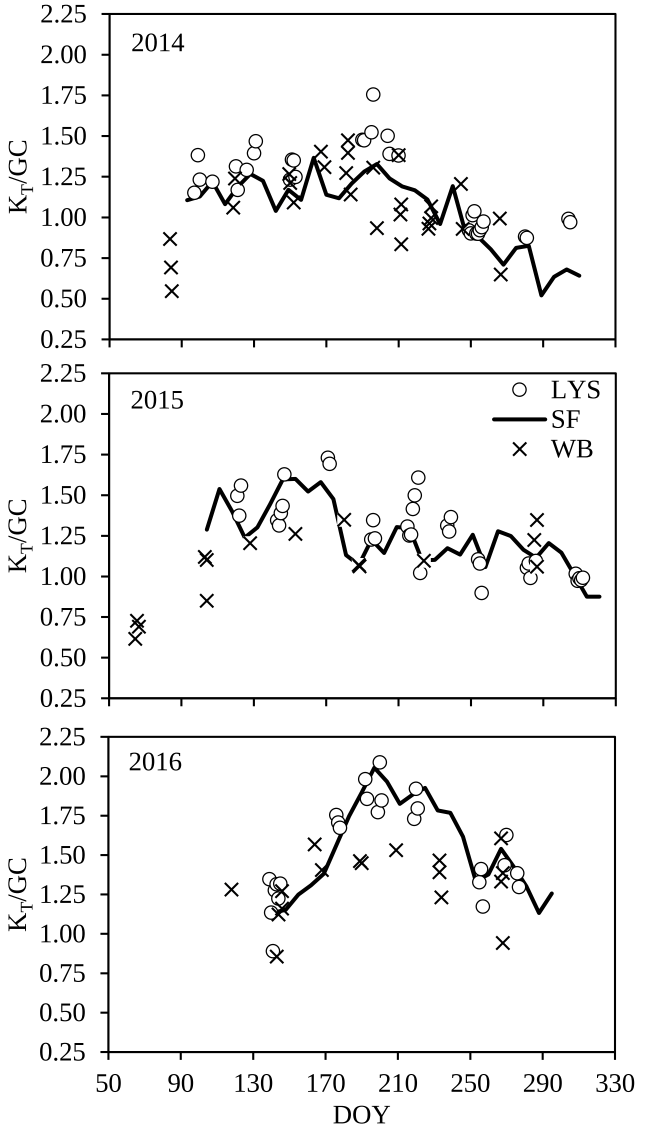

Figure 2.4. Daily K_T values obtained with the lysimeter (LYS, open circles) and weekly trend of the calibrated CHP-CAG sap-flow (SF; black line) related to CG%, for the three seasons under study. Crosses represent K_T values of well-irrigated four-tree-subplots calculated by water balance (WB) divided by their own GC%.

2.3.3. Sources of K_T variability

On a daily scale, K_T of the lysimeter tree showed significant scattering around an average value at the *plateau* stage. Relative values of K_T during July and August (calculated as daily value divided by its five-day moving average) were related to windspeed (u) and the results are shown in Fig. 2.5. The power regression fitted to the experimental data revealed that variation in u accounts for 42% of the daily variability of K_T during summer. It can be seen that relative K_T decreased with increasing u values. The decline in K_T in response to increased u may be related to the different responses of orchard T and ET_O to windspeed, in agreement with the conclusions of Espadafor et al. (2015). Note that the established methods of the FAO manuals 24 and 56 for Kc adjustment as a function of wind speed (Doorenbos and Pruitt 1977; Allen et al. 1998), recommend increasing the Kc values as u increases. We believe that this discrepancy needs to be investigated further due to its implications in the transferability of K_C and K_T values to different climatic conditions.

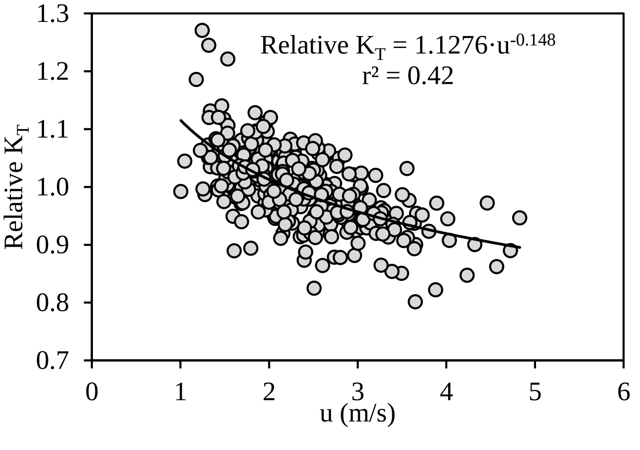

Figure 2.5. Relative K_T (calculated as everyday K_T divided by its five-days moving average) versus daytime wind speed (u, $m \cdot s^{-1}$).

On a seasonal scale, the drop in K_T after harvest (without changes in the canopy), reported by Girona et al. (2011) and Marsal et al. (2014), was also observed in our 2014 and 2016 data, but was not so evident in 2015 (Fig. 2.3). This drop was not observed by Espadafor et al. (2015) in the same almond tree when it was younger. It is possible that the younger tree of Espadafor et al. (2015) could resume vegetative growth immediately after harvest, thus increasing intercepted radiation and the K_T. No renewed growth after harvest was observed in our trees in 2016. By contrast, post-harvest vegetative growth was more evident in 2015, when GC% increased from 54.5% in late August to 59% in early November. This may explain why K_T did not fall after harvest in 2015.

Regarding variability among seasons, higher K_T in 2015 than in 2014 could be explained by additional tree growth, since the ratio K_T/GC is similar. However, 2016 presented a higher value unrelated to an increase in canopy size, and thus to intercepted radiation. Kernel yields of the lysimeter tree were 6.4 kg, 7.3 kg and 12.0 kg in 2014, 2015 and 2016, respectively. Fruit load was 4,265 fruits in 2014, 6,685 in 2015 and 8,838 in 2016. This made us hypothesize that an uncommonly high fruit load in 2016 could have been responsible for the higher transpiration per unit of GC%.

Fig. 2.6 presents some representative gc curves (obtained from lysimeter T data) comparing sunny days in 2014, 2015 and 2016 at the kernel filling stage and at post-harvest. The days selected had similar ET_O values. It can be seen that gc had a much higher value during kernel filling in 2016 than in 2014 and 2015 (approximately 0.0004 vs. 0.00025 $m \cdot s^{-1}$, respectively). Besides, this high value was maintained over midday, while the 2014 and 2015 curves are positively skewed, showing a decline in gc as the day advanced (Fig. 2.6). By contrast, the gc curves of the three seasons looked very similar at post-harvest. It appears that when the fruit load was very high, as in 2016, tree gc was also high throughout most of the day while under normal fruit load conditions, there was a midday decline in gc induced by partial stomatal closure. According to the skew and kurtosis ANOVA conducted on the 2015 and 2016 gc curves calculated from the lysimeter T data (Table 2.1), the different fruit load significantly affected the shape of the curves during the kernel filling stage. The more negative skew point to higher gc values maintained during the afternoon, and positive kurtosis (leptokurtic distribution) indicates the curve has a higher peak than the normal distribution. No significant differences were observed at post-harvest. In line with this analysis, Fig. 2.7 shows that a significantly higher fraction of daily sap-flow transpiration occurred after midday in 2016 than in 2015 during kernel filling stage (61.9% against 57.4%, $p=0.00001$), thus confirming the differences in gc curves of Fig. 2.6 obtained from lysimeter data.

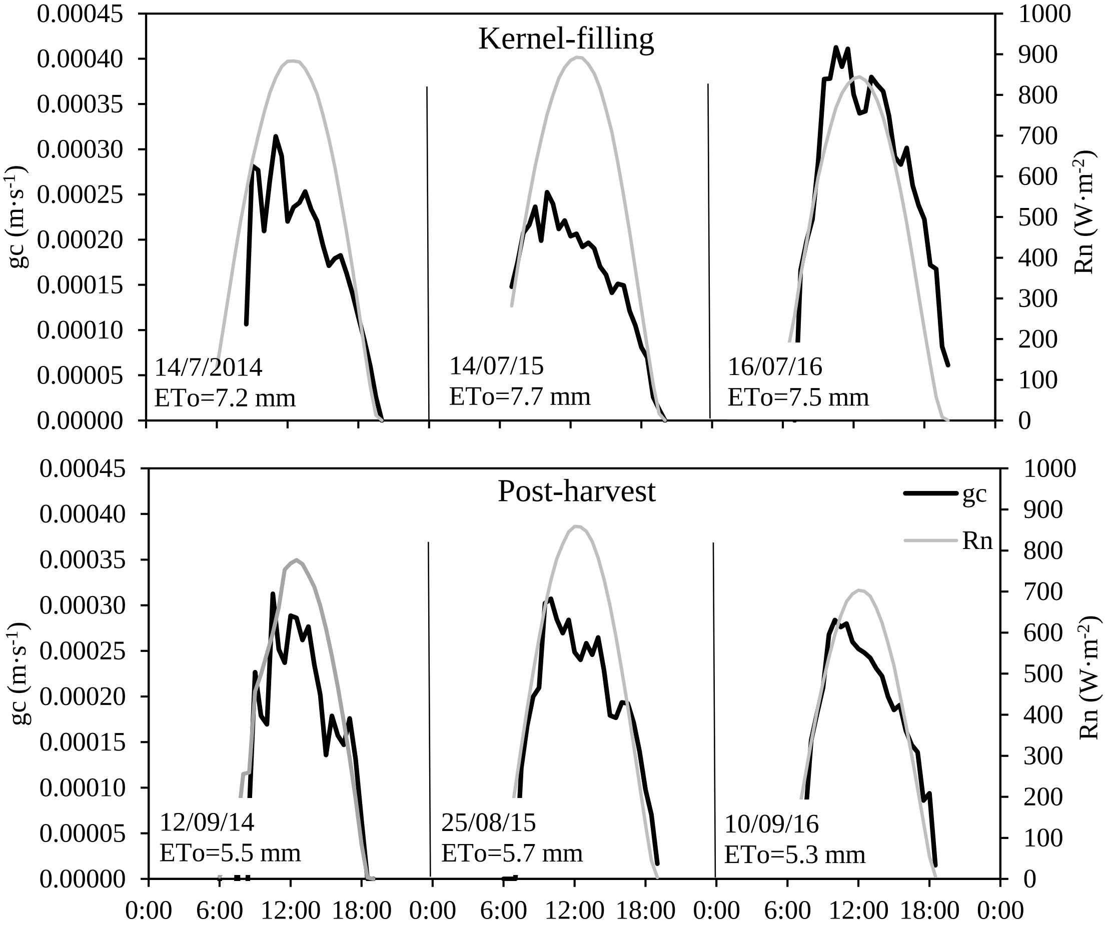

Figure 2.6. Examples of representative daily curves of gc ($m \cdot s^{-1}$) at one clear-sky day during kernel filling and one at post-harvest in two years with normal yields (2014 and 2015) and a year with exceptionally high yield (2016). The corresponding net radiation curves ($W \cdot m^{-2}$) are also shown, and ET_O values of the days selected are also indicated in mm.

Table 2.1 Skew and kurtosis ANOVA of the gc curves calculated from the hourly values of T_{LYS} in days when the lysimeter was covered during the kernel filling stage (11 values in 2015 and 12 values in 2016) and at post-harvest (3 values in 2015 and 7 in 2016).

Stage	Year	Skew	Kurtosis
Kernell-filling	2015	-0.6145	-0.3516
	2016	-1.1356	1.1256
	P-Value	*0.0468*	*0.0206*
Post-harvest	2015	-0.8582	0.3177
	2016	-0.8936	0.1994
	P-Value	*0.9294*	*0.9174*

As proposed for various tree species by Villalobos et al. (2013), it would be possible to model gc which appear to be closely related to T in almond trees. On the one hand, both Nortes et al. (2009) and Saa and Brown (2014) found reduced photosynthetic assimilation by leaves of fruit bearing spurs in comparison to non-bearing ones apparently due to competition for nitrogen, but found no differences in leaf conductance. On the other hand, there are some studies about the positive feedback effect of high crop loads on leaf photosynthesis and conductance in other *Prunus* species: plum (Gucci et al. 1991), cherry (Layne and Flore 1995), peach (Mimoun et al. 1996) and nectarine (Di Vaio et al. 2001), and in other fruit trees such as apple (Palmer et al. 1997) and olive (Martín-Vertedor et al. 2011a; Naor et al. 2013). Still, upscaling from leaf to canopy level is difficult (Testi et al. 2006). At canopy level, Martín-Vertedor et al. (2011b) and Bustan et al. (2016) found higher T rates in fruit bearing olives than in non-bearing or defruited olive trees, and Wünsche et al. (2000) reported that apple trees with very high fruit loads transpired significantly more than trees with medium, low or no fruit load presented different responses of T to fruit load in apple, after completion of leaf development. Two weeks before harvest, apple T was adjusted gradually according to fruit load.

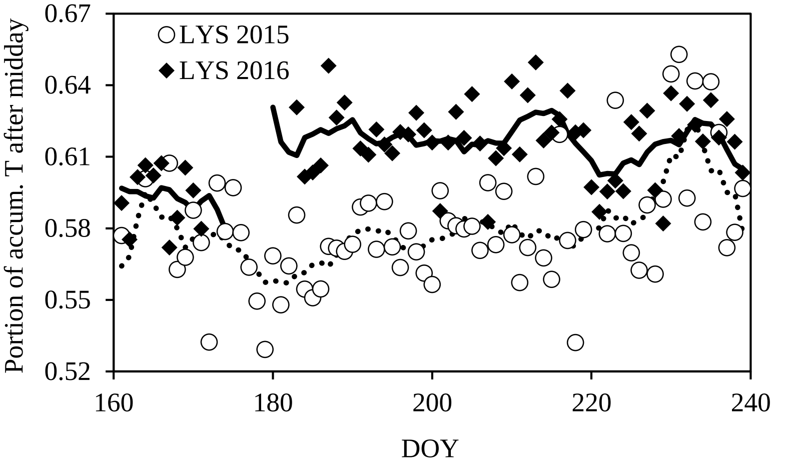

Figure 2.7. Daily relation between accumulated transpiration (T_{SF}) during the afternoon (after 12:00 GMT) and total daily T_{SF} in 2015 (normal fruit load) and 2016 (exceptionally high fruit load) during kernel filling stage. Arrows indicate harvest dates, which were on DOY 217 2015 (discontinue arrow) and 220 2016 (black arrow), respectively.

Besides, the seasonal time course of K_T along 2016 appeared retarded in relation to the two previous seasons (K_T is increasing until the end of June). Berman and DeJong (2003) commented that fruit bearing peach trees had lower leaf biomass accumulation than defruited ones at stage I of fruit growth. If almond tree behaved similarly, this could be a possible explanation for the different shape of the K_T evolution curve in 2016: full canopy cover and therefore maximum K_T might have been delayed by a retarded growth and development of leaves due to the very high fruit load. In the case of apple tree, Wünsche et al. (2000) measured a reduction in mature leaf size and in canopy light interception with increasing fruit load.

2.4. Conclusions

K_T value for mature almond trees covering 85% of the soil was around 1.04, although it seemed that exceptionally high sink source could make it increase by affecting the stomata behavior. Lysimeter weight loss and CHP-CAG sap-flow of the lysimeter tree agreed with the outputs of the water balance of small plots.

The ratio K_T/GC% was affected by daily K_T scattering, as well as by in-season and inter-season variations, the latter apparently related to crop load, as shown by differences in the daily patterns of canopy conductance between a year with very high crop load and the two other years with normal crop load. Further research is needed on the relationship between GC and fIR of the most popular varieties with the aim of giving practical recommendations to the farmers.

Wind speed was found to account for 42% of the scattering behavior of K_T. High wind speed days led to relatively lower K_T than that in days of lower wind speed, and this has implications for making crop coefficient adjustments in tree crops to variable wind conditions.

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CHAPTER 3:

Water Use of Irrigated Almond Trees when Subjected to Water Deficits

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Summary

Recently planted intensive almond plantations may have access to limited water supply due to water scarcity thus, information on almond water use under limited irrigation is needed. Here, the soil water balance was used to assess the consumptive use (ET) of full irrigated, moderately stressed and severely stressed almond trees over a three-year study, as well as the relation between applied water (AW) and ET. Sap flow measurements in eight experimental trees were used to obtain independent transpiration (T) measurements. Evaporation from soil (E_S) was modelled to estimate tree T from the water balance. Relative consumptive use in the deficit irrigation (DI) treatments largely exceeded the relative applied water, highlighting the need to measure ET in stressed treatments for hydrologic purposes. The moderately stressed treatments (irrigated at 65.5% of full irrigation) consumed 79.0% of maximum evapotranspiration (ET of 897 mm), while the severely stressed treatment consumed 63.6% of ET (ET of 722 mm) when applied water was only 39.6% of control. On average, almond ET approached 1,200 mm, Seasonal evolution of the transpiration coefficient yielded maximum peak values ranging from 0.99 to 1.08, and minimum peak values of 0.33 attained with a severe deficit irrigation strategy. Transpiration measured by Compensated Heat Pulse-Calibrated Average Gradient sap-flow (x), was compared to water balance T estimates (y), and yielded a very good relation over the three years of study ($y=0.90x+4.23$, $r^2=0.81$). The sap flow measurements proved to be useful to overcome the limitations of the soil water balance technique, revealing that almond trees were able to extract water from below the monitored depths and suggesting that deep percolation events must have occurred in spring and autumn.

3.1. Introduction

Almond is one of the major tree crops in Spain in terms of cultivated area, 619,915 ha according to ESYRCE 2016 (MAPAMA, 2016). Although it has been grown traditionally in marginal lands under rainfed conditions, recently, irrigation has been introduced with concomitant changes for intensification of production. However, due to chronic water scarcity, Spanish Water Basin Authorities of most areas are unable to allocate irrigation water for almond production to meet its potential requirements. Thus, deficit irrigation (DI) strategies for almonds must be applied in order to reduce water consumption with a minimum impact on crop productivity (Fereres and Soriano 2007). In order to design successful DI strategies and to assess consumptive use at the hydrologic basin scale, both the maximum crop evapotranspiration (ET) and the actual evapotranspiration (ET_a) under different conditions of climate, soil, water availability and plantation typology must be known.

Potential crop evapotranspiration (ET) can be measured by mass transfer or energy balance methods, and can also be estimated using models such as the Penman-Monteith equation (Allen et al. 1998). In the case of well-watered almond trees, there have been recent studies measuring ET with eddy covariance (Stevens et al. 2012) or with a large weighing lysimeter (Espadafor et al. 2015).

There are many more difficulties in determining ET_a of tree crops under field conditions. One option is to use the water balance approach to compute ET_a when ET is limited by water deficits. In the case of almond trees, Girona et al. (2005), Egea et al. (2010) and Egea et al. (2013) have dealt with the responses to variable irrigation, but the ET_a of stressed treatments was not measured nor calculated, as all the results were expressed in terms of applied water (AW, that is irrigation, IR, plus effective precipitation, P_{eff}). The extrapolation of these responses beyond the soil and climatic conditions where they were obtained is questionable. Recently, Spinelli et al. (2016) measured ET_a of deficit-irrigated almond trees with eddy covariance, but surprisingly, they found that ET_a was the same as the ET of well-watered trees.

The goodness of a soil water balance depends on the accurate estimation of soil water depletion (SWD) by the root system. For this purpose,, volumetric soil water content measured with the neutron probe method is considered to be advantageous over the use of other instrumentation such as tensiometers, FDR or TDR (Evett and Steiner 1995). However, in all cases, the spatial variability of soil water properties (Nielsen et al. 1973) makes it necessary to seek a compromise between accuracy and practicality regarding the number of measuring points. In a drip-irrigated tree crop, the variability coming from unevenly wetted soil surface is another issue, requiring additional spatial variations in soil moisture observations. Andreu et al. (1997) described the soil moisture variability and dynamics around a single irrigated almond tree. They showed that, regardless of the depths of measurement, there is often significant uncertainty in the magnitude of the deep percolation component (DP). Nevertheless, there are a number of studies that have used the water balance approach in irrigated tree crops (Fereres et al. (1982) and Franco et al. (2000) in young almond trees; Garnier et al. (1986), Girona et al. (2002) and (Ayars et al. 2003) in peach; Klaij and Vachaud (1992) and (Kang et al. 2003) in pear; de Azevedo et al. (2003) and da Silva et al. (2009) in mango and Iniesta et al. (2008) in pistachio). Besides, the soil water balance approach has been incorporated into most crop simulation models for an array of conditions (Belmans et al. 1983; Brisson et al. 1992; Eitzinger et al. 2003; Choudhury et al. 2013; Campos et al. 2016; Phogat et al. 2017).

For determining ET from the soil water balance, one needs to quantify the water fluxes entering (namely, precipitation, P, and irrigation, IR) and leaving (runoff, RO, and deep percolation, DP) the soil profile under study during a period spanning two soil water content (SWC) measurements. Once all the fluxes are measured or estimated, ET can be determined from the balance of inputs minus outputs. Additionally, if evaporation from soil (E_S) can be measured or estimated (Ritchie 1972; Bonachela et al. 1999; Bonachela et al. 2001), transpiration (T) can also be known.

Sap-flow probes allow the direct estimation of tree transpiration by integrating sap flow velocity deduced from measurements of heat diffusion. Within the available sap-flow measuring methods, the Compensated Heat Pulse (CHP) has been proposed by Fernández et al. (2001) as a tool for irrigation scheduling. This technique is able to detect water stress as measured by the fall in tree transpiration relative to ET_O or when a reference T value is obtained (Fernández et al. 2001; Tognetti et al. 2004; Tognetti et al. 2005). However, the azimuthal variations in sap velocity within a probed tree trunk makes calibration of sap-flow sensors highly recommended (Nortes et al. 2008; López-Bernal et al. 2010; López-Bernal et al. 2015).

There are only a few reports that combine the water balance technique with sap-flow measurements for calculating ET, such as in pines in USA (Oren et al. 1998), pear trees (Kang et al. 2002) and apple trees in north China (Gong et al. 2007).

In the context of almond production intensification under limited water supply, the objectives of this research were a) to determine the ET_a of almond trees undergoing different deficit irrigation regimes, b) to relate the ET_a to the level of AW, in order to assess the relevance of soil water extraction under deficit irrigation; and c) to compare the soil water balance method for estimating T against sap-flow measurements of T in almond trees.

3.2. Materials and methods

3.2.1. Experimental site and field management

The three-year experiment was conducted between 2014 and 2016 in a 5.5-ha almond (cv. *Guara*) orchard planted in 2009. Trees were grafted on G-677 rootstock and planted in a 6 x 7 m grid. The field is located at the Research Centre of IFAPA-Alameda del Obispo, in Cordoba, Spain (37,8ºN, 4,8ºW). Trees were pruned the two first years for scaffold formation and only again in January 2016 to ease machinery traffic. There is an automated weather station about 300 m apart from the orchard, from which climate data were collected along the study. In the centre of the orchard there is one large weighing lysimeter with one almond tree (Lorite et al. 2012), which is representative of the rest of the orchard.

Cordoba climate is typical Mediterranean: hot and dry summers and mild winters; annual rainfall averages around 600 mm. The experimental soil, of alluvial origin, is deep, of sandy loam texture in the first 150 cm depth, and lighter texture in the deeper layers. The typical upper (field capacity) and lower (wilting point) limits of soil water storage are 0.23 and 0.08 cm^3/cm^3, respectively.

The experimental trees were irrigated to satisfy their full water requirements since planting until the onset of the differential irrigation treatments in 2013. The control treatment and the rest of the trees outside the experimental area were fully irrigated. Trees were daily irrigated with 12 pressure-compensating drippers (4 l/h, with 1 m distance between drippers) per tree, using two drip laterals, each about 80-100 cm away from the tree rows. In 2014, there was one water meter per treatment. In 2015, individual water meters (WS15170 DN-15-3/4, Abering, Madrid, Spain) were installed in every experimental plot. Water meter readings were collected every two weeks in the new meters, while the old ones were used for daily irrigation monitoring and management.

Soil was kept free of weeds by both mower passes and herbicide applications, and pests and diseases were controlled following a treatment calendar, which was adjustable according to each season conditions. Mineral fertilization was calculated according to University of California recommendations (http://apps.cdfa.ca.gov/frep/docs/Almonds.html), and its application followed the recommendations by (Muncharaz 2004).

3.2.2. Experimental design

Irrigation treatments started in spring 2013, by applying different limited irrigation levels, with full irrigation supply as the control. To induce a moderate stress level, both sustained deficit irrigation and regulated deficit irrigation strategies were tested, while severe water stress was induced by a more limited RDI regime. Thus, irrigation treatments were thus planned as follows (Table 3.1):

-Fully irrigated control (FI).

These trees received the water requirements (ET) calculated as in (Fereres et al. 2012). From 2015 on, the relation between ground cover (GC) and a transpiration coefficient ($K_{T,}$=T/ET_O) proposed by Espadafor et al. (2015), that is K_T/ GC=1.2, was used with an added 15%, to account for the evaporation from emitters wet surfaces. The addition of 15% was calculated using Bonachela et al. (2001) model assuming tree intercepted radiation of 60% and a wetted area by emitters of 25%. By delaying the onset of irrigation, some SWC depletion by the trees was allowed early in the season to avoid deep percolation, which would be significant if applying water to the soil at field capacity after winter rains.

-Moderate sustained deficit irrigation (SDI_M)

This treatment received 75 % of FI (75% of ET) throughout the irrigation season.

-Moderate regulated deficit irrigation (RDI_M)

This treatment received the same amount as FI in spring and after harvest, but only 40% of FI during the kernel-filling stage (pre-harvest period). The aim was that the total seasonal amount would be the same as that of SDI_M.

-Severe regulated deficit irrigation (RDI_S)

In 2014, this treatment received the same as FI in spring and after harvest, and only 15% of FI during the kernel-filling stage. However, in the other two seasons the total irrigation amount was modified to apply 60 % of FI during spring and in post-harvest, and 20% of FI during kernel filling.

Each experimental plot consisted of 16 (4x4) trees of which the central four were considered as experimental trees while the remaining 12 served as border. Treatments were repeated four times in a randomized complete block design. In addition, a single plot of 20 trees in the same 5.5 ha orchard was left rainfed to observe the response to extreme stress.

Table 3.1. Irrigation treatments: scheduling and deficit distribution per periods (spring, stress-period and post-harvest) for the four treatments.

	FI (100%ET)	P_{eff}	Irrigation Treatment			
			FI	SDI_M	RDI_M	RDI_S**
Spring	ET_1	P_{eff1}	ET_1- P_{eff1}	75%Irrig/n*- P_{eff1}	100%ET_1- P_{eff1}	60%ET_1- P_{eff1}
Stress-period	ET_2	P_{eff2}	ET_2- P_{eff2}	75%Irrig/n- P_{eff2}	40%ET_2- P_{eff2}	20%ET_2- P_{eff2}
Post-harvest	ET_3	P_{eff3}	ET_3- P_{eff3}	75%Irrig/n- P_{eff3}	100%ET_3- P_{eff3}	60%ET_3- P_{eff3}
Seasonal	$ET=\sum ET_{1-3}$		Irrig	<75%Irrig	<75% Irrig	<35% Irrig

*For SDI_M, total FI irrigation was divided equally by months along the irrigation season (n)
**The description of RDI_S treatment corresponds to 2015 and 2016

3.2.3. Canopy architecture and radiation interception

Three to four measurements of canopy diameters and tree height were taken during each season with the help of a measuring tape and a marked pole. Ground cover percentage (GC%) was calculated as the area of a circle of average tree diameter divided by the tree spacing. Canopy volume (Vol_C) was approached as an ellipsoid. Vertical transmissivity was measured close to canopy architecture measurement dates with a Plant Canopy Analyzer (LAI-2000, LI-COR Biosciences, Linconln, Nebraska, USA) in the trees bearing sap-flow probes. One reference and up-to seven (depending on tree size) radiation measurements were taken every 50 cm in four orthogonal transects. Afterwards, reference values were interpolated in time and transmissivity was calculated as the measured below canopy radiation divided by its reference value. Only the first ring (vertical) of the Plant Canopy Analyzer was considered. According to Lang (1987), plant area for each transect (PA_t) can be calculated as:

$$PA_t = \sum_{i=1}^{n} PA_i = -\pi \cdot x^2/G_0 \cdot \sum_{i=1}^{n} (2i-1) \cdot ln\, \tau_i \qquad \text{Eq. 3.1}$$

where n is the number or measurement points, x is the distance between them (50 cm), G_0 is a cultivar-dependent parameter for leaf insertion angle and τ is transmissivity. The value of G_0 used was 0.492 according to Crespillo (2016). Each transect was assigned a 90º sector of the whole canopy. Plant area density (PAD) was finally calculated as PA/Vol_C, and assumed not to vary between trees within the irrigation treatment.

Intercepted radiation, fIR was calculated by adapting a simplified model developed for olive trees (Mariscal et al. 2000).

$$\text{fIR} = 1 - \exp(-k_r \cdot V_u) \qquad \text{Eq. 3.2}$$

$$k_r = 0.52 + 0.00079 \cdot PD - 0.76 \cdot \exp(-1.25 \cdot PAD) \qquad \text{Eq. 3.3}$$

$$V_u = V_0 \cdot PD/10000 \qquad \text{Eq. 3.4}$$

Where fIR is percentage of intercepted radiation, k_r is a reduction coefficient, V_u is volume of canopy per m^2 of surface (m^3/m^2), PD is plantation density (trees/hectare), PAD is plant area density (m^2/m^3) and V_0 is the volume of one tree (m^3).

3.2.4. Evapotranspiration assessment by water balance

- Change in soil water content (ΔSWC)

Soil water content in the first 210 cm of soil profile was measured with a neutron probe (Campbell Pacific Nuclear Scientific, Model 503). Monitoring started at budburst and ended in October prior to leaf fall, with an average interval between measurements of three to four weeks. The neutron probe was calibrated for the experimental soil by taking soil samples for volumetric moisture content (Θ, cm^3 of water/cm^3 of soil) at the time of access tube installation. Two separate calibration equations were used, one for the first 15 cm of soil and another for the rest of the profile down to the 2.10 m depth. Readings were taken at 30 cm intervals, but for the first two readings near the surface, which were taken between 0-15 cm and 15-30 cm depths.

The experimental plots of all treatments in Replicate 1 were equipped with eight neutron probe tubes installed in the area between the four central trees, while the plots of the other three replicates were equipped only with three neutron probe access tubes.

SWC was calculated as a weighted average according to the area represented by each tube. The three tubes were installed, one near the irrigation lateral, one almost in the middle of the lane and a third one in-between, as shown by the black open circles of Fig. 3.1. We compared the soil water measurements averaged over the eight tubes in Rep. 1 against those determined with the three tubes in the other three replicates, as shown in the Results Section. The rainfed plot was monitored with nine access tubes.

Seasonal change in SWC was calculated by addition of the SWC changes between measurement dates.

- Effective precipitation (P_{eff})

Due to the relatively high soil infiltration rate and the flat field, 100% of the rainfall over 0.2 mm was considered as effective precipitation (Villalobos and Fereres 2017).

- Evaporation from soil (E_S)

Daily E_S was calculated following Bonachela et al. (2001), which divides orchard evaporation into two terms; one from emitters wetted surface and another from the rest of the soil surface. The percentage of emitter wetted soil surface ranged from 5% in the RDI_S during the severe deficit period to 25%,35%, 40% in the FI in 2014, 2015 and 2016 respectively. The Microadvective coefficient *ksw*= 1.0 was taken throughout spring and after harvest against 1.2 during summer (Bonachela et al. 2001). In the RDI_S treatment, fallen leaves created a mulch above the surface wetted by the emitters, so a 50% reduction coefficient was used (Allen et al. 1998). Ritchie's model (1972) was used to calculate evaporation from the rest of the soil, which required intercepted radiation values (see Chapter 4).

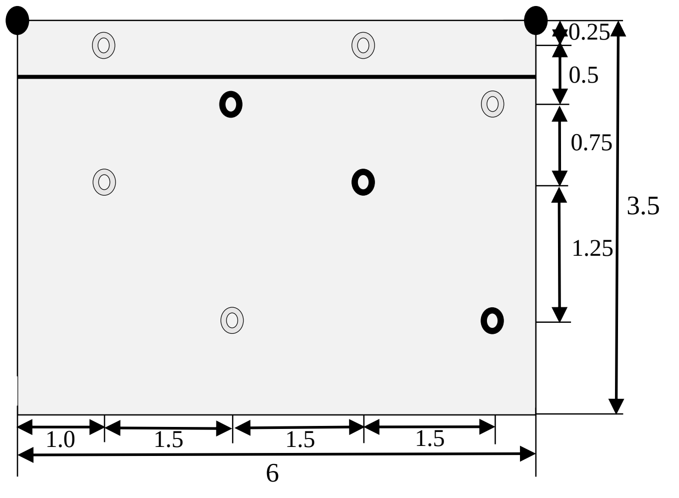

Figure 3.1. Eight neutron probe access tube locations in the space between two experimental trees (full circles in the upper corners) in Block 1 plots. The three black rings indicate the locations of the three access tubes installed in in the rest of blocks. Black line represents the drip lateral with emitters a meter apart. Distances are in meters

- Evapotranspiration (ET_{WB}) and Transpiration (T_{WB})

ET_{WB} was calculated from water balance between SWC readings. T_{WB} came from subtracting E_S from ET_{WB}. Seasonal ET and T resulted from adding partial calculations. The DP component could not be measured or estimated by water balance, so it was not considered in our calculations.

$$ET_{WB} = Peff + Ir - \Delta SWC - DP \qquad \text{(Eq. 5)}$$

$$T_{WB} = ET_{WB} - E_S \qquad \text{(Eq. 6)}$$

Calculated T_{WB} for all the treatments in Replicate 1 was compared to the one measured with sap-flow, both seasonally and between SWC measurements.

3.2.5. Transpiration measurements with CHP sap-flow (T_{SF})

Two sap-flow probes were installed in a single tree per treatment in replicate 1 plus a second tree in RDI_S, as well as in two rainfed trees and in the lysimeter tree. The method used was the Compensation Heat Pulse (CHP) plus the Calibrated Average Gradient

(CAG) for the hours of the day when the sap flow is very low (Testi and Villalobos 2009).

The probes, designed and produced at the IAS-CSIC laboratory in Cordoba, Spain, are made of a 4.8 W 2 mm diameter stainless steel needle which emits heat pulses and two temperature sensors (protected by stainless steel). The upper temperature probe was 10 mm above the heater, while the lower was 5mm below the latter. Each temperature probe has four thermocouple junctions along it, so heat pulse velocities can be known at different depths. Temperature difference (DT) between thermocouple junctions at the same depth was measured with less than 0.01 K error. Every 8 probes were connected to a multiplexer (AM16/32, Campbell Scientific Inc., Logan, UT, USA) controlled by a datalogger (CR10X or CR1000, Campbell Scientific Inc., Logan, UT, USA). At given intervals, the multiplexer triggers a measurement cycle along which DT is measured at 1-s intervals for 10 seconds, a 2-s heat beat (0.12 W/mm) is released, and DT is measured again at 1-s intervals for 3 minutes. DT readings are collected in the datalogger. The heat-pulse velocities had then to be checked for wounding effects (Green et al. 2003).

Sap-flow measurements were calibrated with transpiration data from the lysimeter, by covering the surface of the lysimeter with black plastic (a thin layer of straw was placed over the plastic not to change the albedo) thus avoiding soil evaporation in several 3-10 days' periods along the year. The rest of probes were calibrated, assuming a constant relation between their T and their GC at the start of the season, before any stress had taken place. The seasonal evolution of the calibration coefficient for every probe was assumed to follow the same pattern as the lysimeter probes.

Sap-flow measured transpiration of only one out of four trees which were taken into account in the water balance of each experimental plot. To compare the two methods, we needed to estimate from the water balance the transpiration (T_{WB}) of the probed tree. For that purpose, we used a weighing factor that corrected for the specific canopy volume (Vol_C) of the probed tree.

3.3. Results

3.3.1. Canopy volume and radiation interception

Fig. 3.2 shows the time course of canopy volume (Vol_C) and percentage of intercepted radiation (fIR) in the different treatments along the study. ANOVA and subsequent LSD test conducted for the indicated dates showed that FI trees were always significantly larger and intercepted more radiation than severely stressed ones, although 2016 winter pruning evened tree sizes somewhat. Regarding moderately stressed treatments, both SDI_M and RDI_M were smaller than FI at budburst, but did not differ significantly from FI trees later on in the seasons of 2015 and 2016. Average FI Vol_C achieved at the end of 2016 was 85.7 m^3, whereas RDI_S averaged 60.0 m^3. fIR exceeded 60% of incoming radiation in FI, RDI_M and SDI_M from 2015 onward. On the contrary, in the most stressed treatment, fIR remained below 60% in 2015 and under 55% in 2016, respectively.

3.3.2. Soil water dynamics

Fig. 3.3 presents the comparison between the 3-tubes weighed average SWC and the 8-tubes average SWC, taken at the same time, in the four treatment plots of Replicate 1. The excellent correlation obtained ($y=0.949 \cdot x$, $r^2=0.97$) indicates that SWC could be measured practically with three as well as with eight tubes. Therefore, SWC in replicates 2-4 could be well measured with just three tubes. Even though, the regression equation of Fig. 3.3 was reversely applied to the replicates 2-4 SWC measurements to correct the 3-tubes SWC data.

Fig. 3.4 presents the time course of SWC for the three seasons. Soil under FI trees had significantly higher soil moisture than in the other treatments at the end of 2014 and 2016, while no differences among treatments were found at the end of 2015 due to rainfall. In October 2016, a LSD test could also segregate RDI_M from RDI_S, and placed SDI_M in an intermediate group. Regarding the Rainfed plot, it can be observed that trees depleted the first 2.10 m of soil by early July 2014.

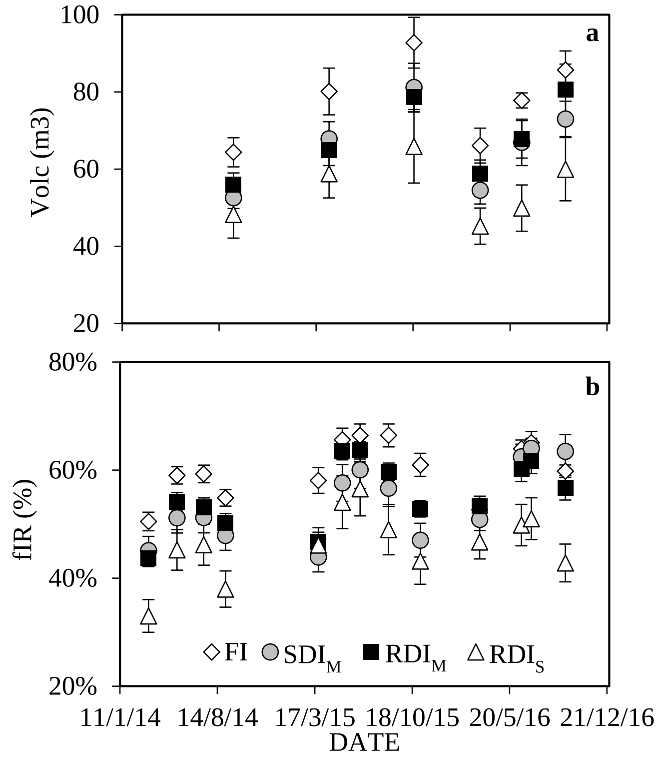

Figure 3.2. a) Canopy volume (Vol_C, m^3) trends along the three-year study; and, **b)** Time course of the percentage of intercepted radiation (fIR, %). Points are average of four replicates. Vertical bars are standard error of the means.

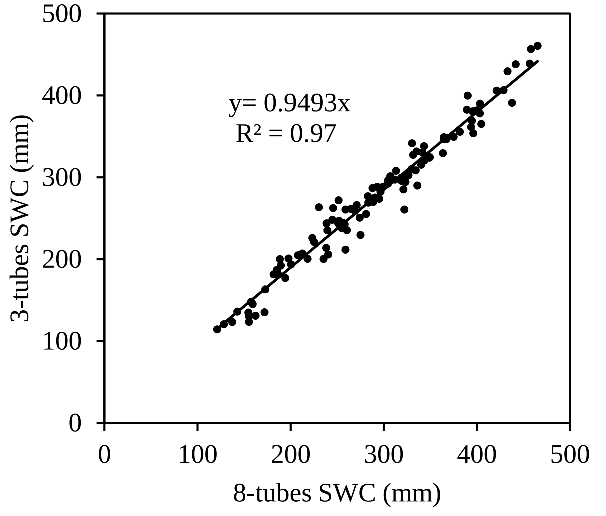

Figure 3.3. Best-fit linear regression of total Soil Water Content (SWC, mm) measured with 8 neutron probes access tubes against 3 tubes in Replicate 1 for years 2014-2016. Points are individual SWC measurements of all treatments.

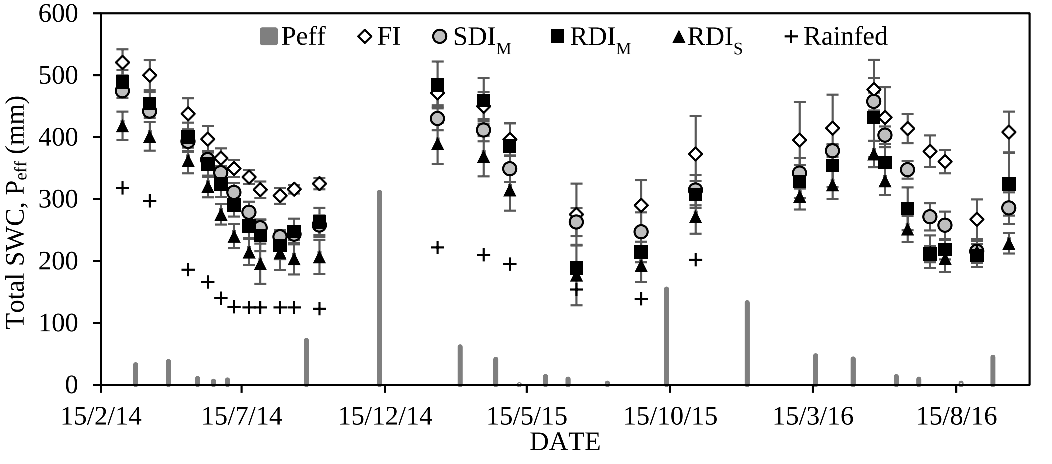

Figure 3.4. Total soil water content (SWC, mm) evolution along the three years of study. Points are averages of the four blocks, but for the Rainfed treatment, which had no replicates. Vertical bars are standard error of the means. Grey bars show effective precipitation accumulated over the interval between two consecutive SWC measurements

Fig. 3.5 depicts representative examples of volumetric soil moisture (Θ, cm^3 water/cm^3 soil) along 2016 at different depths in FI and RDI_S to illustrate the differences in soil water patterns. Data from two tubes per treatment are shown, one inside the drip-wetted area and the other in the middle of the lane. From the soil water content measurements, we presume that deep percolation may have occurred from 4th March to early August under the emitters in the FI treatment (Fig. 3.5a). Water extraction can also be seen at upper layers in FI, and soil water outside the influence of the dripper was consumed by the time of harvest (Fig. 3.5b). In the case of RDI_S, those treatments had depleted the monitored SWC inside and outside the influence of the emitters (Figs. 3.5c and 3.5d) and transpired just what was applied as irrigation.

Fig. 3.6 displays the time course of the average Θ for the four treatments. Summing up, FI profile remained wetter than the rest throughout the season; SDI_M depleted more soil water than RDI_M by the end of the season. Winter rains recharged the soil below 150 cm in RDI_S and spring rainfall was consumed completely by the end of the irrigation season in early autumn. A rainy spring in 2016 (see Table 3.2) filled all the treatments' profile from budburst to the start of RDI treatments.

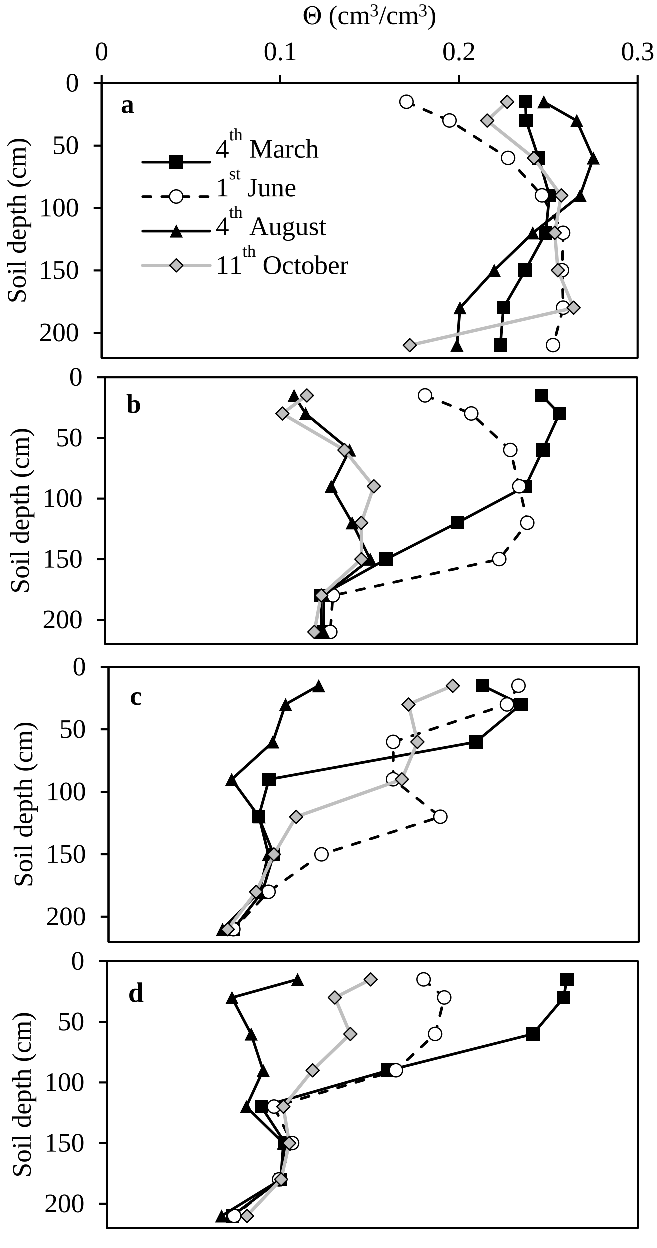

Figure 3.5. Examples of volumetric soil moisture (Θ, cm^3/cm^3) seasonal evolution with depth (cm) along 2016 season in one neutron probe access tube nearby a dripper (**a** and **c**) and other in the middle of the lane (**b** and **d)**, for both FI and RDI_S treatments.

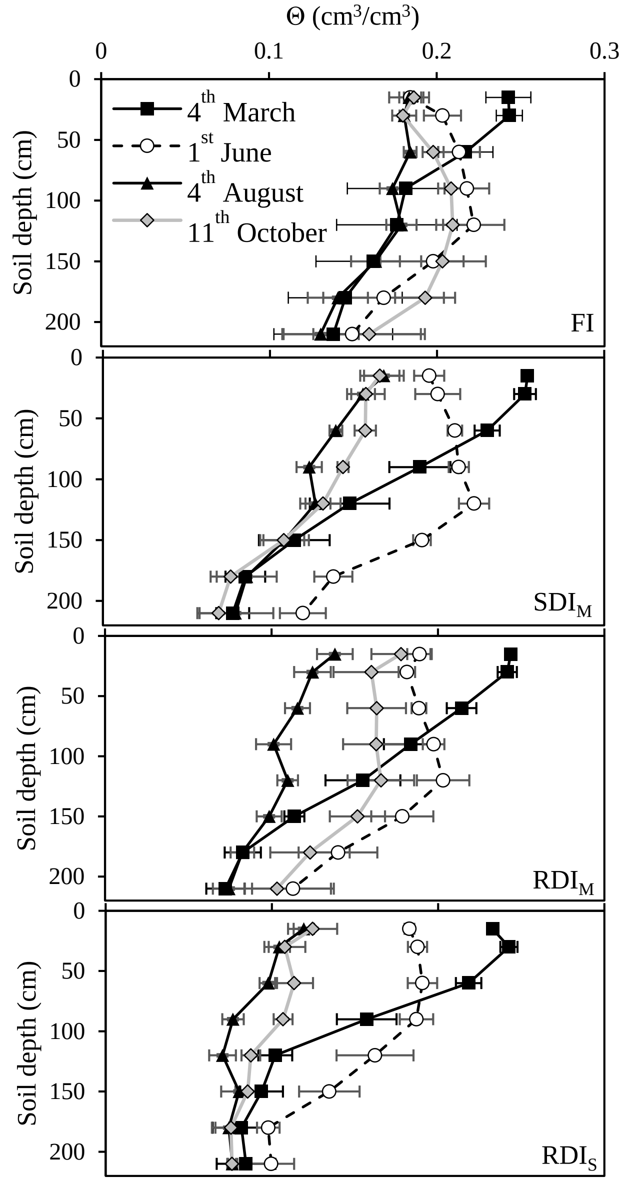

Figure 3.6. Volumetric soil moisture (Θ, cm^3/cm^3) at different soil depths (cm) of the four treatments at four 2016 dates: budburst, start and end of Regulated Deficit Irrigation treatments and last soil moisture measurement. Horizontal bars show standard error of the means.

3.3.3. Crop evapotranspiration and transpiration coefficient

Table 3.2 displays ET_O, calculated ET for irrigation scheduling, P_{eff}, and actual irrigation and the actual ET calculated from the water balance for the four treatments. Average ET_O and P_{eff} throughout the study were 1,071 mm and 243 mm respectively. Average three years ET was 1,134 mm for FI, of which 800 mm were contributed as irrigation. Moderate DI strategies averaged seasonal ET_a of 897 mm (79.0% of FI) with 524 mm irrigation (65.5%). There were no significant differences in ET_a between SDI_M and RDI_M. Besides, RDI_S treatment reduced ET_a to 722 mm (63.6%) with 317 mm irrigation (39.6%).

For each season, data are presented as seasonal values and divided into three periods: spring, pre-harvest period (where the deficits are applied in RDI) and post-harvest.

Randomized Complete Block ANOVA conducted on calculated ET showed no significant differences amidst treatments from budburst to the start of pre-harvest period in the first two years. In pre-harvest, FI had the highest ET values; the two moderately stressed treatments presented significantly lower values than FI and higher than the severely stressed one. After harvest, LSD test segregated FI from all deficit treatments in 2014, whereas in 2015 RDI_S ET values were significantly lower than those of the other treatments. Finally, in 2016 means were separated in three groups: FI, both SDI_M and RDI_M, and RDI_S.

On a seasonal scale, FI consumed more water than the rest, and the moderately stressed treatments consumed more than the severely stressed one. No differences were found between SDI_M and RDI_M.

Table 3.2. Seasonal and per-periods (spring, pre-harvest and post-harvest period) reference evapotranspiration (ET_O), effective precipitation (P_{eff}), irrigation and evapotranspiration (ET_{WB}), all in mm. Different letters within the same time period indicate statistically significant differences (P<0.05) among treatments according to LSD test.

	ET_O	ET	P_{eff}	Treatments							
				FI		SDI_M		RDI_M		RDI_S	
				IR	ET_{WB}	IR	ET_{WB}	IR	ET_{WB}	IR	ET_{WB}
2014											
Spring (10 March-18 May)	274.8	160.3	73.3	94.3	250	96.1	251	97.2	259	112.5	241
Pre-harvest (19 May-3 Aug)	457.1	422.9	22.3	270.7	416a	177.9	340b	153.3	334b	52.6	234c
Post-harvest (4 Aug-5 Oct)	304.2	249.4	72.1	194.7	257a	112.2	180b	147.0	198b	117.2	178b
Seasonal	1036.1	832.6	167.7	559.7	923a	386.3	771b	393.1	779b	281.4	647c
2015											
9 Feb-27 April	192.9	119.6	103.3	5.5	184	1.7	186	7.3	202	3.9	182
28 April-13 Sept	810.0	726.5	29.1	715.6	851a	483.1	614b	451.9	629b	288.9	441c
14 Sept-8 Nov	127.6	116.8	152.4	99.7	160a	54.1	139a	76.3	136a	24.1	97b
Seasonal	1130.5	962.9	284.8	820.8	1195a	538.9	939b	532.0	972b	314.0	722c
2016											
Spring (1 March-30 May)	272.6	211.7	270.1	109.8	343a	90.0	313ab	98.3	323.6a	60.1	305ab
Pre-harvest (31 May-2 Aug)	424.9	457.0	1.3	487.6	561a	301.7	448b	234.2	389.7b	131.7	258c
Post-harvest (3 Aug-9 Oct)	348.5	378.9	5.9	421.9	380a	239.7	218b	334.0	233.8b	185.0	166c
Seasonal	1046.0	1047.6	277.3	1019.4	1284a	642.1	984b	651.2	932b	376.8	730c

Fig. 3.7 represents the calculated seasonal ET against AW (IR+P_{eff}) for the four treatments and the three study years. The 1:1 line represents a situation where all applied water is consumed by the crop ET and no SW depletion takes place. The vertical distance between the 1:1 line and the points above it represents the SWD. Points below the 1:1 line in Fig. 3.7 indicate that some deep percolation took place, as it must have happened in some FI replicates in 2016. From Fig. 3.7 it can be estimated that the maximum seasonal SWD was about 200 mm under the experimental conditions.

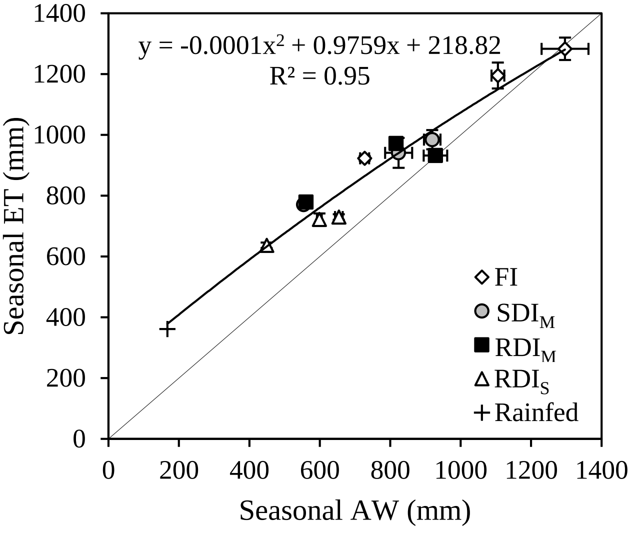

Figure 3.7. Seasonal ET calculated from water balance (ET_{WB}) against seasonal applied water (AW, irrigation plus effective precipitation), both in mm. Points are averages of the four replicates each of three years (3 points per treatment), but for the Rainfed trees, which had no replicates, and was just measured in 2014. Vertical and horizontal bars show standard error of the means.

The time course of the transpiration coefficient (K_T) calculated with water balance in the first and the last study years is shown in Fig. 3.8. Maximum K_T values for FI were 0.87 and 1.16 in 2014 and 2016, respectively. In the RDI$_S$ treatment, K_T dropped to minimum values of 0.14 and 0.33 in 2014 and 2016, respectively. Regarding the moderate deficit treatments, the K_T of RDI$_M$ was lower than in SDI$_M$ during summer, but recovered after harvest, and both treatments showed similar values at the end of the season, around 0.46 in 2014 and 0.59 in 2016.

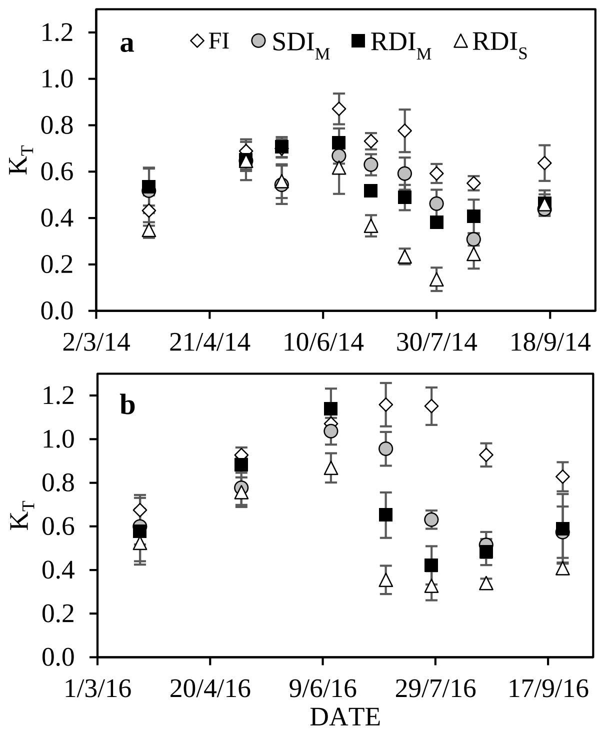

Figure 3.8. Seasonal evolution of the relation between transpiration and reference evapotranspiration (K_T=T/ET_O) for years 2014 (**a**) and 2016 (**b**). Points are averages of the 4 blocks over periods between two consecutive SWC measurement dates and vertical bars are standard error of the means

3.3.4. A comparison of water balance estimates of Ta against sap-flow Ta measurements

Fig. 3.9 presents the comparison between the two methods of determining Ta for every period between two SWC measurements. Generally, both methods agreed in the estimates of Ta for RDI_S, whereas there were some discrepancies in the other treatments. In 2014 (Fig. 3.9a), the sap-flow measurements of Ta were lower than those obtained with the WB method in the period when irrigation was resumed after harvest in both RDI_M and FI. During summer, T_{SF} was greater than T_{WB} in RDI_M. Whereas, in 2015 (Fig. 3.9b), the same happened in SDI_M. Again, FI showed T_{SF} lower than T_{WB} after harvest. In 2016 (Fig. 3.9c), some points over the 1:1 line can be seen in FI and RDI_M, obtained during spring and autumn, while before harvest, T_{SF} of RDI_M was greater than T_{WB}. Fig. 3.9d shows data of the four treatments and three years. Overall, the correlation was very good with a linear regression: y=0.90x+4.23 (r^2=0.81).

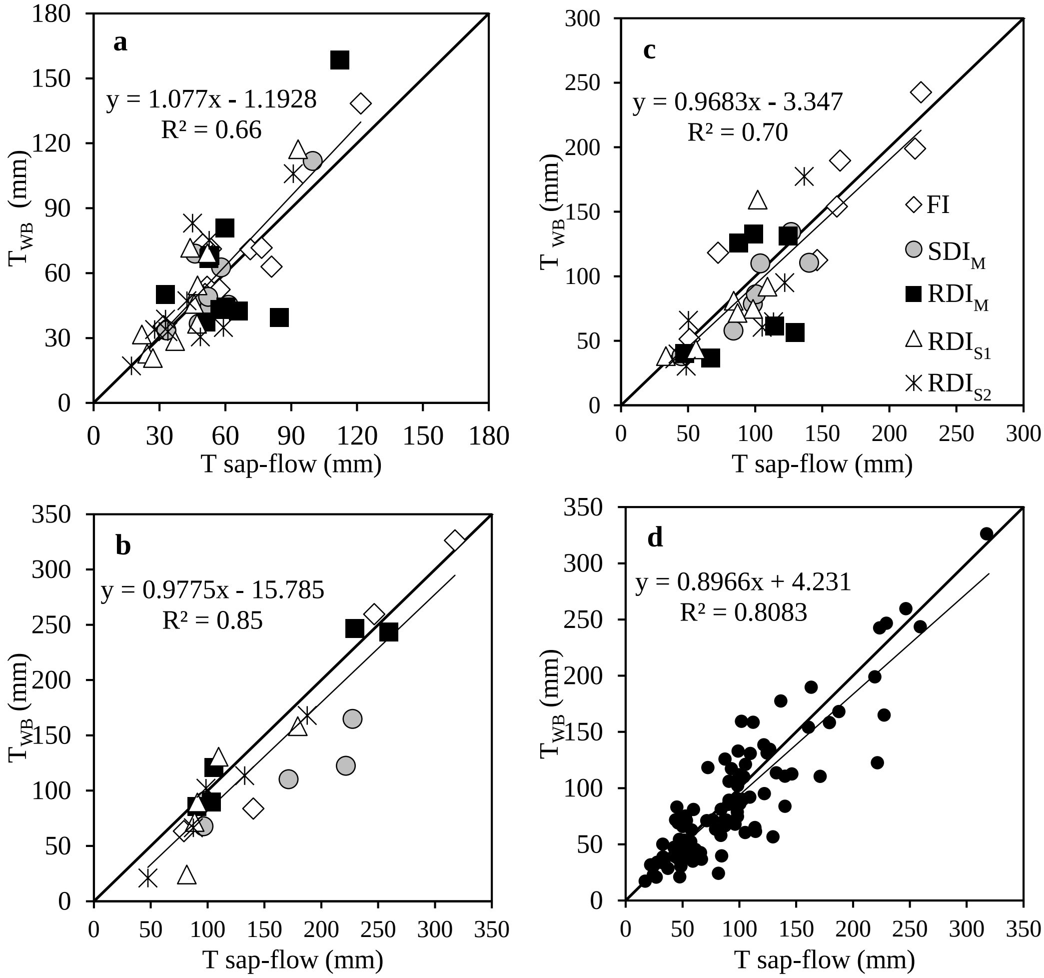

Figure 3.9. Transpiration calculated with water balance (T_{WB}) against transpiration measured with sap-flow (T_{SF}), both in mm. Each point corresponds to a period of time between two consecutive measurements of SWC with the neutron probe: **a)** 2014, **b)** 2015, **c)** 2016 and **d)** all five probed trees and three years are included.

3.4. Discussion

In our three-year study, a DI regime that applied 39.6% of FI irrigation (RDI_S) resulted in a much higher relative consumptive use, equivalent to 63.6% of ET (ET_a of 722 mm). Our results contrast with those of Spinelli et al. (2016), that measured ET_a of a deficit irrigated almond orchard with eddy covariance and found no decrease in comparison with the well irrigated treatment. Other DI works on almonds (Girona et al. 2005; 2010; Egea et al. 2013) reduced irrigation to 40% and 28% of their control treatments in their most severely stressed treatment. However, they did not take into account either precipitation or changes in SWC when establishing relations between irrigation regimes and crop response. If we consider the large climatic and soil variability throughout the almond growing areas, it would be difficult to extrapolate tree responses to irrigation amounts to conditions other than those where they were obtained. In Fig. 3.7, it can be seen that the intersection point between almond ET and AW was around 1200 mm, and maximum seasonal SWD, observed in the rainfed plot in 2014 as well as in deficit irrigated trees, was near 200 mm, which is 27.7% of the three-year average ET_a of RDI_S, in the experimental conditions. This is particularly important if mild stressed or over-irrigated treatments are chosen to analyse the effects of irrigation on crop response, since different irrigation regimes could result in the same ET_a. This is because the mild stressed tress would extract more water from the soil, while the over-irrigated treatments would have percolation losses below the root zone.

Along with canopy size and ET_{WB}, T and K_T increased from the first to the last study year too. On the one hand, FI K_T pattern reveals some sustained stress in 2014, possibly because of insufficient irrigation. On the other, the highest average K_T obtained (1.16) can be overestimated due to percolation, but experimental plots without percolation gave K_T values between 0.99 and 1.08 along the summer, leading to corresponding K_C values from 1.10 to 1.27 which is in accordance with recently published K_C values for almond (Stevens et al. 2012; Espadafor et al. 2015; García Tejero et al. 2015; Goldhamer and Fereres 2017). The RDI_S made K_T drop to 0.14 in 2014 and 0.33 in 2016 during the pre-harvest period. Stress was too severe in 2014, and this treatment was increased in the deficit period from. 280 mm up to 370 mm to avoid too severe stress. When comparing SDI_M with RDI_M, both reduced transpiration along summer, but K_T of SDI_M remained higher until full irrigation was resumed in RDI_M after harvest. Thus, SDI_M got minimum values of 0.31 and 0.48 by early August, 2014 and 2016, respectively, while RDI_M reached minimum values of 0.38 and 0.42 by late July 2014 and mid July 2016, respectively. Nonetheless, there were no differences in ET_{WB}:

smaller drip-wetted surface in RDI_M made E_S relatively lower during the months of highest ET_O. Both treatments had recovered transpiration by mid-September.

In Table 3.2 and in Fig. 3.7 we can appreciate that ET of FI treatment increased noticeably from 2014 to 2015. There are a couple of possible explanations for this. Firstly, Vol_C and fIR increased from 2014 to 2015 (Fig. 3.2), so growth had not finished yet. Secondly, predicted ET for irrigation scheduling was lower than actual ET_{WB}, so the Kc used in 2014 may have been underestimated. As well, red leaf blotch was not under total control in 2014, and it reduced leaf area density and hence fIR. Trees were much healthier the following seasons. On the other hand, percolation events due to the rainy spring together with the need to irrigate for fertilizing rose 2016 ET values of FI. Therefore, the shape of the regression line in Fig. 3.7 should be blunter at the upper extreme. We can observe that the 2016 rainy spring after a dry winter brought points corresponding to the rest of the treatments under the regression line as well: there was not so much SWC available at the beginning of this season (Fig. 3.4), and subsequent rainfall was already computed as AW instead of SWD.

If we think of carryover effects of DI on SWC, the most severe treatment kept similar values of total SWC throughout the three years (Fig. 3.4). However, no recharge of the deepest layers was observed after winter and spring rains (Fig 3.5c and 3.5d) as in moderately stressed treatments and FI (Fig. 3.6, Fig. 3.5a and 3.5b), which may entail a change in the relation between AW and ET on a longer term by reducing SW reservoir, or after particularly dry winters.

Regarding water balance limitations, such as soil variability within an irrigated tree orchard, our SWC estimation with 3 neutron probe access tubes (one nearby the irrigation lateral, one almost in the middle of the lane and a third one in-between) resulted a good representative of the SWC (Fig. 3.3). However, the water balance method overestimated ET when DP is significant and underestimates it when SWD occurs outside the monitored soil volume, in this case below the 2.1 m depth. We delayed irrigation until late spring to prevent applying water to the soil at field capacity after the winter rains, and thus have the trees consumed part of the SW reservoir. However, we cannot rule out the possibility that DP events may have occurred in the FI treatment which received the highest irrigation depths. This would make the, ET of the FI treatment overestimated. In the case of DI treatments, the dryness of the soil (consequently with very low hydraulic conductivity) should have prevented DP, leading to more precise estimates of almond ET_a values.

The use of the CHP-CAG sap-flow technique allowed to detect these events in one of the replicates. Thus, in 2014 (Fig. 3.9a), RDI_M must have extracted water below 2.10 m, since the sap-flow measurements led to Ta values greater than those of the WB method. On the contrary, there must have been some deep percolation in the period when irrigation was resumed after harvest in both RDI_M and FI. In 2015 (Fig. 3.9b), it is SDI_M which seemed to have extracted water beyond 2.10 m deep. Again, FI showed deep percolation after harvest that year. In 2016 (Fig. 3.9c), it seems that deep percolation occurred in spring and autumn in FI and RDI_M, while extraction below 2.10 m took place during the deficit period in the latter. This all seems consistent with the irrigation schedule and the treatments applied.

We found other three works in which water balance and sap-flow methodologies were combined (Oren et al. 1998; Kang et al. 2003; Gong et al. 2007), but not contrasted, because E_S was not estimated independently, as in our case. The comparison presented in this work is therefore the first that presents three years of data and different levels of water status and time periods (Fig. 3.9d), and demonstrates a robust correlation between the two methodologies. Nonetheless, there were also limitations in the sap-flow technique. One is the gum exudation in almond due to needle wounds that altered the calibration coefficient during the season, which was corrected just in the FI tree, when it was compared to the lysimeter tree. In the case of the DI treatments, a different calibration approach would be required for greater accuracy.

Finally, as in other studies where deficit irrigation was applied to almond trees, water shortage resulted in reduced canopy size (Hutmacher et al. 1994; Goldhamer and

Viveros 2000; Romero et al. 2004; Egea et al. 2010). Although this could have negative effects on production, Goldhamer et al. (2006) pointed it as a chance to increase yield via increased plantation density, while consuming less water. More years of study may be needed to assess the performance of DI throughout the functional duration of a commercial almond plantation.

3.5. Conclusions

Moderate deficit irrigation strategies averaged a seasonal ET_a of 897 mm (79.0% of FI) with 524 mm of irrigation (65.5% of FI). There were no significant differences in ET_a between Sustained Deficit Irrigation and Regulated Deficit Irrigation strategies. By contrast, a more severe Regulated Deficit Irrigation treatment reduced ET_a to 722 mm (63.6%) with 317 mm of irrigation (39.6%). As a consequence of the reduced water application, the SWC in the DI treatments was much less than in FI at the end of the season, with the risk of incomplete soil profile recharge, particularly in dry winters.

The intersection point between almond ET and Applied Water was somewhat lower than 1200 mm, and maximum seasonal SWD was near 200 mm in our soil and climate conditions. Furthermore, sap-flow measurements revealed that almond trees of some treatments extracted water from depths below the lowest measuring depth of 2.1 m. Therefore, depending on rainfall distribution and soil water holding capacity, both precipitation and SW extraction may play an important role in seasonal crop water consumption and should be considered when analysing the effects of watering regimes on other crop features such as vegetative growth and yield.

Both techniques CHP-CAG sap-flow and water balance presented limitations for the accurate estimation of ET_a and Ta. However, the combination of both methods reduced the uncertainty in the determination of orchard ET, caused either by an unknown deep percolation and/or by soil water depletion outside the monitored soil volume. Improvements in the calibration of the sap-flow technique should enhance the accuracy of the determination of Ta in almond trees under variable irrigation supply.

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CHAPTER 4:

Yield Response of Almond Trees to Transpiration Deficits

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Chapter 4: Yield Response of Almond Trees to Transpiration Deficits

Summary

Irrigation optimization under limited water supply requires knowledge of the relation between consumptive use and production. The recent expansion of almond production is highly dependent on irrigation which may be limited by water scarcity in the future. A three-year experiment was conducted in Cordoba, Spain, to determine the yield and water productivity (WP) responses of almond (cv. Guara) to irrigation deficits. Maximum yields of 2508.4 $kg \cdot ha^{-1}$ (3-year average) were obtained when the crop evapotranspiration (ET) was fully met. Three deficit irrigation treatments that supplied 66.9%, 69.7% and 43.2% of the full irrigation requirements, yielded 2147.5, 2038.2, and 1496.9 $kg \cdot ha^{-1}$, respectively. Assessment of the consumptive use (ET) and its components, E_S and T, yielded seasonal values of 1088, 887, 894 and 699 mm of ET, of which T represented 831, 640, 648 and 479 mm, for the four different treatments, respectively. The relations between yield and irrigation, ET, and T were used to determine whether the WP values were affected by water regimes. Although values varied from year to year, the WP_{ET} averaged 0.23 $kg \cdot m^{-3}$ for the three years and did not differ among treatments. The transpiration efficiency (WP_T) had a value of 0.32 $kg \cdot m^{-3}$ and was roughly the same for all treatments. Irrigation water marginal productivity (IWMP) was 0.11 $kg \cdot m^{-3}$ and 0.33 $kg \cdot m^{-3}$ for the irrigation amounts corresponding to the fully irrigated and the severely stressed treatment, respectively.

4.1. Introduction

Spain is the third almond producing country in the world, after Australia and USA (5%, 8% and 80% of total world production, respectively (Californian Almond Board, 2015). In terms of cultivated area, almond is the third tree crop in Spain (nearly 736,000 ha; MAGRAMA, 2016). Most of the area is devoted to traditional rainfed production but recently, newly planted almond orchards are undergoing a fast intensification process. Attractively high international prices are pushing farmers in Spain to shift from the extensive, low-input management in marginal soils (with yields of less than 200 $kg \cdot ha^{-1}$) to high-yielding plantations that receive high levels of irrigation and fertilization. However, there are water supply restrictions for new plantations in many areas, so deficit irrigation (DI; Fereres and Soriano, 2007) strategies are necessarily adopted.

When a crop is subjected to DI, it is necessary to know the possible long-term effects of water stress on crop growth and production. Almond growers need to understand the relation between water use and yield and its components, and thus income, to make appropriate management decisions (such as allocating limited water to various crops). Also, public institutions need this basic information in order to assign water allocation for the new intensive and more demanding plantations.

Plant water relations in almond have been thoroughly studied, and water stress is known to affect stomatal conductance and photosynthetic assimilation at leaf level (Castel and Fereres 1982; Romero et al. 2004b; Romero and Botía 2006; Nortes et al. 2009; García-Tejero et al. 2011), and provokes premature defoliation (Goldhamer and Viveros 2000; Klein et al. 2001; Romero et al. 2004a). The effects of water stress on growth and yield, and its components, of almonds of different ages and at different stages of the crop cycle (generated by a variety of DI strategies), have also been examined in several multi-year experiments. Summing up, water stress diminishes vegetative growth and hence canopy size and affects the accumulation of reserves. During kernel-filling stage, water stress can reduce nut weight, while when it occurs after harvest, it lessens the crop load of the next season (Hutmacher et al. 1994;

Goldhamer and Viveros 2000; Esparza et al. 2001; Girona et al. 2005; Egea et al. 2010; Egea et al. 2013; Mousavi et al. 2015).

It is known that DI can increase water use efficiency (WUE; Howell 2001; Fereres and Soriano 2007) . Some authors have reported values of water productivity (WP) around 0.17-0.22 $kg \cdot m^{-3}$ and 0.30-0.34 $kg \cdot m^{-3}$ for well-watered and water-stressed almonds, respectively (Hutmacher et al. 1994; Romero et al. 2004a; Goldhamer et al. 2006; Egea et al. 2013). Conversely, Egea et al. (2010) presented much higher values: 0.32 $kg \cdot m^{-3}$ for the fully irrigated treatment and 0.71 $kg \cdot m^{-3}$ for the stressed one. Phogat et al. (2013) calculated water productivity in terms of irrigation (IR), evapotranspiration (ET) and transpiration (T), showing that while IR-WP varied noticeably from fully irrigated trees to deficit irrigated ones, ET-WP and T-WP differed less regardless of the irrigation regime. This highlights the need to generalize WP assessments by measuring the amount of water that the crop actually consumes.

Goldhammer and Fereres (2017) recently published an applied-water production function for almonds in California, with data from a 5-year experiment. Their research was conducted in an environment of very low rainfall and in a soil with low water-retention capacity, thus one would expect very small differences between IR and ET under those conditions. However, this is not the case in many other areas, including the Mediterranean Basin, where intensive almond orchards are being planted. There are almond growing environments with substantial in-season rainfall as well as with soils of high water storage capacity. In those locations, soil water depletion can represent an important percentage of seasonal ET. Also, the minimum irrigation treatment applied by Goldhamer and Fereres (2017) was 1,000 mm, thus there is a need to investigate the response at lower irrigation levels, which would be required in conditions of lower water availability for irrigation. Finally, Goldhamer and Fereres (2017) worked on 'Nonpareil', a soft-shell almond cultivar, while hard-shell cultivars are more commonly grown in other areas of Europe. All of these differences justify the need to develop a consumptive-water production function which considers lower levels of applied water in the hard-shell cultivar ‘Guara’, which is commonly grown in Spain.

Therefore, the objectives of the present study were: a) to determine a functional relationship between yield and its components and the consumed water, and b) to analyse the effect of different water regimes on transpiration efficiency and on the marginal productivity of irrigation water in almond trees.

4.2. Materials and Methods

4.2.1. Experimental site

The experiment was carried out in a 5.5-ha almond orchard located at the Research Centre of IFAPA-Alameda del Obispo, in Cordoba, Spain (37.8ºN, 4.8ºW) from 2014 to 2016. The climate is typical Mediterranean, with hot and dry summers, mild winters and average annual rainfall of around 600 mm. The soil of the experimental field is of alluvial origin, and more than 200 cm deep. Soil texture is sandy loam in the first 150 cm depth and lighter in the deeper layers. The typical upper and lower limits of soil water storage are 0.23 and 0.08 cm^3/cm^3, respectively.

Almond trees (cv. *Guara*) were grafted on GF-677 rootstock and planted in 2009 in a 6 x 7 m grid (238 trees·ha^{-1}). Pruning was done during the two first years for scaffold formation and only again in January 2016 to ease machinery traffic. A treatment calendar was followed for the chemical control of pests and diseases. This calendar was adjusted according to each season conditions. Weeds were controlled by combining mowing and herbicide applications. Mineral fertilization was calculated according to University of California guidelines (http://apps.cdfa.ca.gov/frep/docs/Almonds.html), and its application followed the recommendations by Muncharaz (2003).

Two drip irrigation laterals were placed 80 away from tree rows in 2014-2015, and 100 cm in 2016, with a total of 12, 4 l/h-pressure-compensating emitters per tree. The control treatment and the non-experimental trees were irrigated to cover their full requirements, though allowing some soil water depletion in spring to avoid deep percolation. The rest of the experimental trees were fully irrigated until the start of differential irrigation treatments in 2013.

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

4.2.2. Experimental design

Four differential irrigation treatments (three DI levels and one control) started in 2013. Irrigation was scheduled on a biweekly basis to match the net water requirements (pre-estimated ET minus P_{eff}). All treatments had the same number of emitters and irrigated daily, differing in the duration of irrigation. Afterwards, actual ET was calculated by water balance. Irrigation amounts for the three years are presented in the third column of Table 4.1 in mm and in the sixth column as percentages of the control treatment.

-Control (FI)

These trees received the irrigation amount required to allow application of the full pre-estimated ET, which was calculated in 2014 as in Fereres et al. (2012). From 2015 on, we used the relation between transpiration coefficient (K_T=T/ET_O) and ground cover (GC), K_T/GC=1.2 (Espadafor et al. 2015), plus 15% more to account for the evaporation from the emitters' wet surfaces to estimate previous ET, in order to schedule irrigation. This 15% was calculated according to Bonachela et al. (2001) for 25% of wetted surface and 60% of intercepted radiation, which were the average values for the control treatment in 2014. In order to avoid deep percolation as much as possible, 75-125 mm of soil water content (SWC) depletion was allowed early in the season by postponing the start of irrigation, except in the last year when, despite the rainy spring, we still had to apply the fertilizers via irrigation, and SWC was not depleted.

-Moderate sustained DI (SDI_M)

SDI_M received 75 % of FI (75% of ET) steadily throughout the irrigation season.

-Moderate regulated DI (RDI_M)

RDI_M was irrigated as FI in spring and after harvest, but only 40% of FI was applied during the kernel-filling stage (pre-harvest period, usually occurring from mid-June to late-July in the area). The cumulative irrigation amount at the end of the season was targeted equal to that of SDI_M.

-Severe regulated DI (RDI_S)

RDI_S was given the same irrigation as FI in spring and after harvest, and only 15% of FI during the kernel-filling stage in 2014. However, trees underwent severe stress in 2014, and some of them dropped all their leaves. In 2015 and 2016 we reconsidered treatment RDI_S in order to avoid severe stress. We increased the total water allocation and redistributed the water deficit as follows: 60 % of FI was applied in spring and after harvest, and 20% of FI during kernel filling.

The experiment had a randomized complete block design with four replications, each experimental plot being composed of four central experimental trees plus their borders (4x4). Irrigation of the whole orchard was withdrawn the 10-15 days previous to harvest to minimize the risk of tree debarking by the mechanical shaker.

4.2.3. Evapotranspiration (ET) and transpiration (T)

ET was calculated using the soil water balance method. For the calculation of ET, we needed to measure or estimate the rest of fluxes involved in the soil water balance as follows:

-Irrigation (IR):

One water meter was installed per experimental plot, from which readings were taken every fortnight.

-Effective precipitation (P_{eff}):

Precipitation data from the first SWC measurement to the last one were collected from the automated weather station nearby. Since the soil has a high infiltration rate and null slope, runoff was assumed to be zero, and therefore P_{eff} was considered 100% of precipitation. The proportion of rain directly intercepted by the plant canopies was neglected in this work, basically because the rainy season coincides with winter, when almond trees have no leaves. Events smaller than 0.2 mm were not taken into account (Villalobos and Fereres 2017).

-Change in soil water content (ΔSWC)

A neutron probe (Campbell Pacific Nuclear Scientific, Model 503) was used to measure SWC down to 210 cm in different locations within the experimental plots. There were three tubes per replicate, one in the emitter wetted area, a second in the middle of the lane, and a third in an intermediate location. A sketch of the layout of access tubes can be found in (López-López et al. 2018). The neutron probe was calibrated for the experimental soil by taking soil samples for volumetric moisture content (Θ, cm^3 of water/cm^3 of soil) when the access tubes were installed. One calibration line was used for the first 15 cm of soil and another for the rest of the profile down to the 210 cm depth. The SWC of the 0-30 cm depth was characterized with two readings at 7.5 and 22.5 cm deep. Then, readings were taken at 30 cm intervals down to 210 cm.

SWC was measured at budburst, one week before and one after the differential treatments started, one week before and one after irrigation resuming, and one last time in early October. The deep percolation (DP) component was considered negligible based on the SWC readings of the deeper depths (López-López et al. 2018). The ET of every interval was computed as:

$$ET = IR + Peff - \Delta SWC - DP \qquad \text{Eq. 4.1}$$

-Evaporation from soil (E_S):

The calculation of daily E_S was performed by separating evaporation into two components; one from the surface wetted by the emitters (E_{SW}), and the other as the evaporation from the rest of the soil surface (E_{SO}) (Orgaz et al. 2006). The model developed by Bonachela et al. (2001) was used to calculate E_{SW} as follows:

$$E_{SW} = f_w \cdot K_{sw} \cdot (Rad \cdot (1 - fIR) + Aer) \quad \text{Eq. 4.2}$$

Where, f_w (0-1) is the fraction of soil wetted by the emitters. Rad and Aer are the radiative and the aerodynamic terms of the Penman-FAO ET_O equation, as described in Bonachela et al. (1999). K_{sw} is a microadvective coefficient that accounts for the enhancement of evaporation from the emitter wetted soil surface due to being surrounded by a drier area (adimensional). The relation between this coefficient and the microadvective conditions of the orchard was empirically determined by Bonachela et al. (2001), from *Ksw* =1.0 when advection is not present (that is when the soil apart from the emitters is not completely dry) to *Ksw* =1.6 for highly microadvective conditions (small surface wetted by emitters surrounded by a very dry soil, and a very high fraction of direct radiation reaching the soil). According to our conditions, we considered *Ksw* = 1.0 in spring and after harvest, and *Ksw* = 1.2 during summer. Finally, fIR is the fraction of intercepted radiation, which was reported for this experiment in (López-López et al. 2018). Thus, 1-fIR represents the fraction of radiation reaching the soil surface. fIR is determined by tree canopy size and GC% (Bonachela et al., 2001).

Measurements of f_w were taken every time irrigation scheduling was modified with the help of a measuring tape. Also, a 50% reduction was applied to the evaporation from emitter-wetted surface in RDI_S, to account for the mulch created by the fallen leaves due to severe water stress (Allen et al. 1998).

For the rest of the soil, Philip (1957) described the Es process in three stages. After a rainfall event, the soil is completely wet, and E_{SO} is limited by incoming radiation. E_{SO} during Stage I was calculated as described in Bonachela et al. (1999) (Eq. 4.3). Once accumulated E_{SO} reaches a certain value U (mm), E_{SO} enters a falling rate stage (Stage II), in which it is determined by soil hydraulic properties and time (t) since the end of Stage I. We used Ritchie's model (1972) to calculate E_{SO} at Stage II (Eq. 4.4). Finally, Philip described a third stage at which E_{SO} reached a steady state at a very low value.

$$E_{SOi} = (1 - f_w) \cdot (Rad \cdot (1 - fIR) + Aer) \quad \text{Eq. 4.3}$$

$$E_{SOii} = (1 - f_w) \cdot \alpha \cdot t^{0.5} \quad \text{Eq. 4.4}$$

The values of U and α for our soil are 8 mm and 4 mm·day$^{-0.5}$ (Bonachela et al. 1999), where t is the time (days) since the end of Stage I . According to Ritchie's expression, E_S from our soil reaches $E_{SOiii,}$ after one month following wetting. This value was kept until a new rainfall returned soil to Stage I. Unpublished data collected in our conditions suggest that the E value at Stage III (E_{SOiii}) is between 0.3 and 0.5 mm·day^{-1} (FJ Villalobos, personal communication), thus we assumed E_{SOiii} = 0.4 mm·day^{-1}. Note that whether we chose 0.3 or 0.5 mm·day^{-1} for Stage III (enduring about three months in our conditions), the seasonal E would differ by 18 mm, a small amount considering the value of ET. Isolated rains in the middle of summer were considered to evaporate directly, without resetting to stage I and without interrupting the value of t.

$$E_S = E_{SW} + E_{SO} \quad \text{Eq. 4.5}$$

-Tree Transpiration:

T was calculated as

$$T = ET - E_S \quad \text{Eq. 4.6}$$

Seasonal ET, E_S and T values were calculated by adding the partial values corresponding to the periods between two consecutive SWC measurements, from leafing out to leaf fall.

4.2.4. Plant water status

Tree water stress caused by the DI regimes was monitored by measuring midday stem water potential (Ψ, MPa) before and after the onset of DI treatments in early June and before and after resuming irrigation at post-harvest (in mid-August), respectively. Measurements were taken on two covered leaves per tree with a Scholander-type pressure chamber (Model 3005F01, Santa Barbara, CA, USA). Leaves were selected near the trunk or a scaffold-branch and were covered with aluminium foil for at least 30 minutes before measuring.

4.2.5. Yield and yield components

Harvest took place around the second week of August. All four experimental trees of every plot were manually harvested and mechanically de-hulled. Then, field fruit weight (FW, kg) was measured. A 1-2 kg sample was taken per tree (FW_{SAMPLE}). Almonds in the sample were counted (N_{SAMPLE}) so that to estimate fruit load as:

$$Fruit\ load\ (Nº/tree) = FW \cdot N_{SAMPLE}/FW_{SAMPLE} \qquad \text{Eq. 4.7}$$

Afterwards, a subsample of 100 almonds was oven-dried at 70ºC until constant weight and de-shelled. Kernels were weighed to calculate unit kernel weight (g/almond).

Finally, kernel yield, in terms of dry weight per hectare (Y_{DW}, $kg{\cdot}ha^{-1}$) was calculated as:

$$Y_{DW}\ (kg \cdot ha^{-1}) = Fruit\ load \cdot\ Unit\ weight(g) \cdot 238(trees/ha)\ /1000\ (g/kg) \qquad \text{Eq. 4.8}$$

Yield and yield components were averaged per treatment and subjected to Randomized Complete Block ANOVA and subsequent LSD test.

4.2.6. Water production functions

3-year-average Y_{DW} was related to the seasonal IR, ET, and T of each experimental plot. Best-fit regression analysis was conducted with the software Statistix 10.0.

4.2.7. Water productivity (WP_{ET}), Transpiration efficiency (WP_T) and Irrigation Water Marginal Productivity (IWMP)

WP_{ET} and WP_T ($kg \cdot m^{-3}$) were calculated as Y_{DW}/ET and Y_{DW}/T, respectively. ANOVA and subsequent LSD test were conducted on seasonal and three-year-average WP_{ET} and WP_T data. The IWMP is defined as the infinitesimal increments or reductions in yield caused by infinitesimal increments or reductions in irrigation, respectively. An IWMP ($kg \cdot m^{-3}$) function was obtained as the derivative of the Y_{DW}-IR expression fitted, as in Goldhamer and Fereres (2017).

4.3. Results

4.3.1. Evapotranspiration and transpiration

Calculated ET, E_S and T values are presented in Table 4.1. ET and T of FI increased every year, and were significantly higher than the values of the rest of treatments. There were no ET or T differences between SDI_M and RDI_M, which had average ET values of 887 and 894 mm (81.5% and 82.2% of FI), and T values of 640 and 648 mm (77.0% and 78.1% of FI), respectively. RDI_S had significant lower ET and T than the rest of treatments, with an average ET of 699 mm and average T of 479 mm (64.2 and 57.7% of FI, respectively). ET_O and P_{eff} from the automated weather station are summarized in Table 4.2, from the first to the last SWC measurement dates. Daily values of ET_O and P were presented in Fig. 2.1 (see Chapter 2).

The fraction of the total soil surface wetted by the emitters varied with the irrigation treatment. It went from 0.05 in RDI_S to 0.25, 0.30 and 0.4 in FI in 2014, 2015 and 2016 respectively. The calculation method is very sensitive to this variable. The time course of GC along the study can be seen in Fig. 4.1. Average E_S was 263 mm, 247 mm, 246 mm and 220 mm in FI, SDI_M, RDI_M and RDI_S, respectively. The depth of E_S from the emitter wetted area only for FI was 25 mm, 20 mm and 94 mm more than that of RDI_S in 2014, 2015 and 2016, respectively. In terms of E_S for the entire orchard floor, these differences were 15 mm, 20 mm and 88.5 mm. Fig. 4.2 depicts the average monthly distribution of the two E_S components in the four treatments.

Table 4.1. Seasonal irrigation (IR), crop evapotranspiration (ET), soil evaporation (E_S) and transpiration (T) of the four treatments over the three years of study (2014-2016) and their average. Values are expressed in mm and as % of every season control treatment (FI). Different letters in the same column indicate different homogenous groups according to LSD test after Randomized Complete Block ANOVA at $P<0.001$.

Year	Treat.	Absolute values (mm)				% of FI			
		IR	ET	Es	T	IR	ET	Es	T
2014	FI	559.7	923 a	236 a	687 a				
	SDI_M	386.3	771 b	230 b	541 b	69.0	83.5	97.4	78.8
	RDI_M	393.1	779 b	232 b	547 b	70.2	84.4	98.3	79.6
	RDI_S	281.4	648 c	216 c	432 c	50.3	70.2	91.5	62.9
2015	FI	820.5	1125 a	275 a	847 a				
	SDI_M	538.9	939 b	279 a	660 b	65.7	83.5	101.4	77.9
	RDI_M	530.6	975 b	272 a	699 b	64.7	86.7	98.9	82.6
	RDI_S	314.0	722 c	254 b	468 c	38.3	64.2	92.3	55.3
2016	FI	904.5	1220 a	278 a	961 a				
	SDI_M	642.1	984 b	231 b	754 b	71.0	80.7	83.1	78.4
	RDI_M	651.2	932 b	234 b	698 b	72.0	76.4	84.2	72.6
	RDI_S	376.8	730 c	189 c	541 c	41.7	59.8	68.0	56.2
Average	FI	754.2	1088 a	263 a	831 a				
	SDI_M	504.3	887 b	247 b	640 b	66.9	81.5	93.9	77.0
	RDI_M	525.5	894 b	246 b	648 b	69.7	82.2	93.9	78.1
	RDI_S	325.7	699 c	220 c	479 c	43.2	64.2	83.6	57.7

Table 4.2. Seasonal reference evapotranspiration (ET_O) and effective precipitation (P_{eff}), in mm, from 2014 to 2016 and their average.

Year	ET_O (mm)	P_{eff} (mm)
2014 (10 March-5 Oct)	1,036.1	167.7
2015 (9 Feb-8 Nov)	1,130.5	284.8
2016 (1 March-9Oct)	1,046.0	277.3
Average	1,070.9	243.3

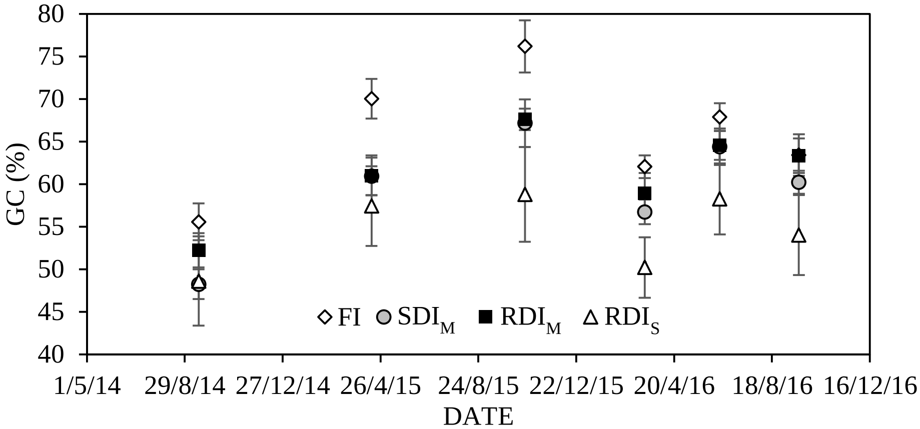

Figure 4.1. Time course of ground cover percentage (GC%) along the three years of study.

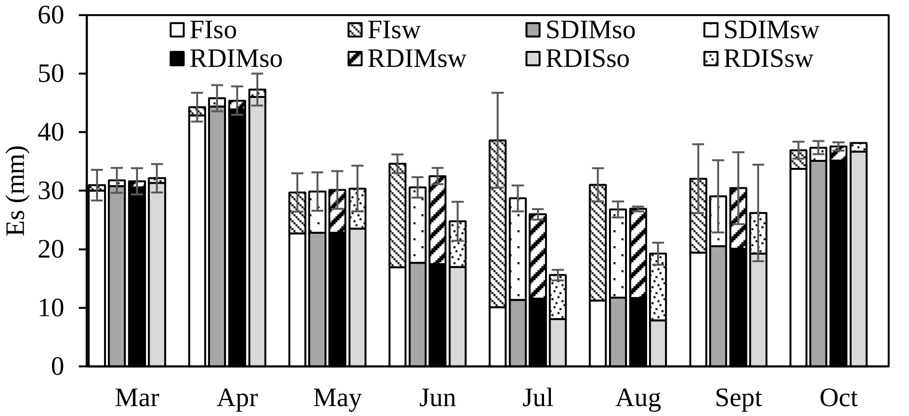

Figure 4.2. Average monthly total soil evaporation, Es (full height of the columns) separated into evaporation from the emitter-wetted zone, Esw (woven part of the column), and evaporation from the rest of the soil, Eso (full part of the columns) for the three seasons, 2014 to 2016, of the four treatments. Vertical bars correspond to standard error of total E_S among years.

4.3.2. Plant water status

The differential irrigation treatments resulted in different patterns of stem water potential (Ψ) along the season. FI stayed between -1.0 and -1.2 MPa. SDI_M and RDI_M had lower Ψ than FI in the mid-July measurement, -1.9 MPa and -2.1 MPa, respectively, and reached -1.6 and -2.0 MPa. After harvest, they both had -1.3 MPa, a similar value to that of FI. Regarding RDI_S, it already had lower Ψ than the other three in mid-June (-1.4 MPa), reaching a minimum of almost -3.0 MPa in mid-July. RDI_S stayed somewhat lower after irrigation resumption, around -1.7 MPa. Time course of stem Ψ in 2016, presented as an example year, can be seen in Fig. 4. 3.

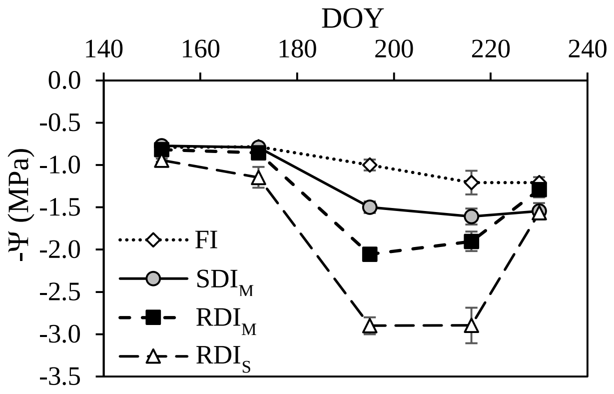

Figure 4.3. Time course of stem water potential (-Ψ, MPa) in 2016, taken as an example year. Each point is the average of four treatment replications, and vertical bars are standard error of the means. In each experimental plot, two leaves were measured in all four experimental trees, so each point is an average of 32 leaf measurements. The five presented dates correspond to one week before and one week after reducing irrigation to RDI treatments, mid-July, and one week before and after resuming full irrigation after harvest**.**

4.3.3. Yield and yield components

The highest yields were observed in 2014 (2678.2 kg·ha^{-1} in FI), while 2015 had the lowest yields (2093.1 kg·ha^{-1} in FI, see Table 4.3). During 2014 and 2016, the yield of SDI$_M$ and RDI$_M$ did not differ significantly from that of FI. However, in 2015, lower nut loads in SDI$_M$ and RDI$_M$ led to significantly lower yields than FI, but not significantly different from RDI$_S$. The more severely stressed treatment (RDI$_S$) had always lower yields than FI. The interplot coefficients of variation (COV) for yield varied between 0.1% and 23.6% (corresponding to FI in 2016 and RDI$_S$ in 2015, respectively), the average value for the three years and four treatments being 11.5%. The intraplot COV varied between 0.4% and 39.8% (values of RDI$_M$ and RDI$_S$ in 2014), with an overall average of 19.4%.

Regarding nut loads, FI and SDI$_M$ had similar values in 2014, RDI$_S$ had significantly lower fruit loads and RDI$_M$ had an intermediate value. In 2015, FI had higher nut load than the rest of treatments, with no differences between them. In 2016, there were no significant differences among treatments, although RDI$_S$ trees bore an average of about 1000 almonds less than FI (a difference of 12%, which was not statistically significant).

On average, FI had higher nut loads than RDI_S (7,830 vs 5,933), and SDI_M and RDI_M had intermediate values (6,823 and 6,490, respectively).

Unit kernel weight was significantly reduced by severe stress during kernel-filling stage all the three years (1.08 g vs 1.34 g, on average for RDI_S and FI, respectively), while moderate stress only affected it in 2016. On average, there were not significant differences in kernel weight among FI, SDI_M and RDI_M.

Table 4.3. Dry weight kernel yield (kg·ha^{-1}) and yield components (nut load and unit weight) over the three-years study (2014-2016) and their average. Different letters in the same column indicate different homogenous groups according to LSD test. ANOVA *P-values* are shown.

Yield and yield components	Treat.	Year 2014	2015	2016	Average 2014-2016
Kernel yield (kg·ha^{-1})	FI	2678.2 a	2093.1 a	2552.1 a	2508.4 a
	SDI_M	2573.6 a	1506.0 b	2380.2 a	2147.5 a
	RDI_M	2414.9 ab	1565.7 b	2236.0 a	2038.2 a
	RDI_S	1659.6 b	1248.5 b	1579.1 b	1496.9 b
	P-value	*0.0593*	*0.0499*	*0.0006*	*0.0197*
Fruit load (N°/tree)	FI	7109 a	8209 a	7804 a	7830 a
	SDI_M	6929 a	5826 b	7692 a	6823 ab
	RDI_M	6283 ab	5770 b	7959 a	6490 ab
	RDI_S	4971 b	5930 b	6870 a	5933 b
	P-value	*0.0641*	*0.0594*	*0.3576*	*0.1310*
Unit weight (g)	FI	1.55 a	1.09 ab	1.37 a	1.34 a
	SDI_M	1.56 a	1.10 a	1.30 a	1.31 a
	RDI_M	1.62 a	1.13 a	1.18 b	1.34 a
	RDI_S	1.38 b	0.88 b	0.98 c	1.08 b
	P-value	*0.0152*	*0.0226*	*0.0005*	*0.004*

4.3.4. Water production functions

Y_{DW}-IR was adjusted to a quadratic expression: $Y_{DW}=-0.0025 \cdot IR^2 + 4.87 \cdot IR + 243$ ($r^2=0.72$, *P=0.0001*). On the other hand, Y_{DW}-ET and Y_{DW}-T were best-fitted by logarithmic expressions: $Y_{DW}=2220.2 \cdot \ln(ET)-13000$ ($r^2=0.78$, *P=0.0001*) and

Y_{DW}=1801.3·ln(T)-9574 (r^2=0.79, $P=0.0001$), respectively. Average values for each experimental plot together with the fitted expressions are shown in Fig. 4.4.

4.3.5. Water productivity, Transpiration efficiency and Irrigation Water Marginal Productivity

WP_{ET} and WP_T averaged 0.23 kg·m^{-3} and 0.32 kg·m^{-3}, respectively, with noticeable variability among the three seasons. Our differential irrigation treatments did not affect significantly WP_{ET} and WP_T in any of the study years (Table 4.4).

The derivative of the quadratic curve fitted to Y_{DW}-IR is equivalent to the IWMP (kg·m^{-3}) = -0.00005·IR (m^3·ha^{-1}) +0.49. According to this expression, IWMP takes a value of 0.11 kg·m^{-3} for the average irrigation amount of FI, and values of 0.24, 0.23 and 0.33 kg·m^{-3} for SDI_M, RDI_M, and RDI_S, respectively. IWMP becomes zero when IR reaches a value of 10.000 m^3·ha^{-1}.

Table 4.4. Water productivity (WP_{ET}) and Transpiration efficiency (WP_T) in kg·m^{-3}. ANOVA *P-values* are shown.

	Treat.	**Year**			**Average**
		2014	**2015**	**2016**	**2014-2016**
WP_{ET} (kg·m^{-3})	FI	0.29	0.19	0.21	0.24
	SDI_M	0.33	0.16	0.24	0.25
	RDI_M	0.31	0.16	0.24	0.23
	RDI_S	0.26	0.17	0.22	0.22
	P-value	*0.3617*	*0.5983*	*0.4397*	*0.1270*
WP_T (kg·m^{-3})	FI	0.39	0.25	0.27	0.31
	SDI_M	0.47	0.23	0.32	0.35
	RDI_M	0.44	0.22	0.32	0.32
	RDI_S	0.39	0.27	0.29	0.32
	P-value	*0.4211*	*0.3603*	*0.4451*	*0.7070*

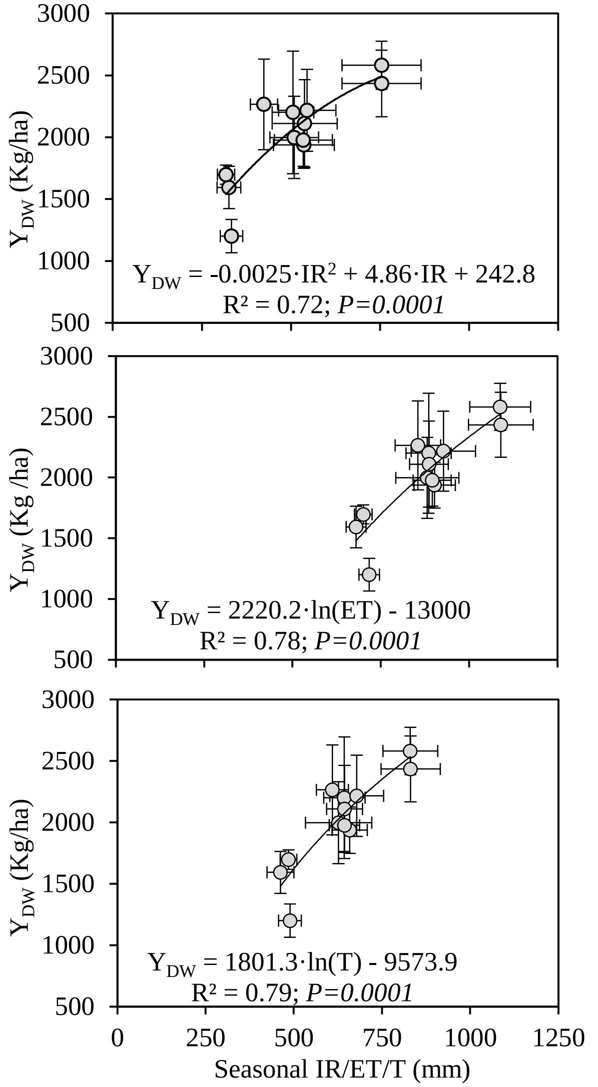

Figure 4.4. Average kernel yields expressed as dry weight (Y_{DW}, $kg \cdot ha^{-1}$) against seasonal irrigation (IR), crop evapotranspiration (ET) and transpiration (T). Points are three-year averages of individual replicates. The best-fit expressions obtained are presented under the corresponding lines. Error bars represent standard error of the means among different years.

4.4. Discussion

In this three-year-long study, we determined water production functions not only for IR but also in terms of ET and T.

The Y_{DW}-IR expression obtained gives Y_{DW}=243 kg·ha^{-1} at no irrigation. Regarding Y_{DW}-ET and Y_{DW}-T expressions, yield would be reduced to 0 when ET is lower than 349 mm or T is below 203 mm.

In Fig. 4.4, the x-axis distance between Y_{DW}-IR and Y_{DW}-ET curves indicates that the combined contribution of P_{eff} and ΔSWC was, on average, around 350 mm. This amount is 30% of the ET of FI and 50% of the ET of RDI_S. These numbers highlight the importance of considering ET instead of IR as the driving variable in conditions of soils with high water-holding capacity or significant in-season rainfall.

Moreover, the model developed by Bonachela et al. (1999; 2001) allowed us to calculate E_S and detract it from ET to obtain T values (see Table 4.1). In our study, the frequency of irrigation was maintained even though the IR declined in the deficit treatments. This makes the values of E_S relatively higher as ET declines due to lower T values. Under deficit irrigation, it would be desirable to decrease irrigation frequency leading to lower E rates from the emitter wetted areas, which represented, on average, 34.3% and 19.6% of total E_S in FI and RDI_S, respectively. Meanwhile, E_S accounted for 23.6% of ET in FI, on average, and around 30.0% in RDI_S. It seems that although FI had higher E_S from wetted areas due to higher IR, larger canopies compensated slightly by reducing E_S from the rest of the soil in spring and autumn. The difference in E_S between the two treatments, FI and RDI_S, was more pronounced in 2016, both in terms of E_S from the emitter wetted areas and for total E_S, because f_w of FI was also the greatest (0.4). Other studies which have estimated E_S are reported in Orgaz et al (2006) in olive trees and Iniesta et al (2008) in pistachios. In the first one, the Es of a drip-irrigated olive orchard with GC% of 65% and f_w=0.1 accounted for 21% of ET during the irrigation season. Iniesta et al (2008) reported Es between 35% and 41.3% of ET of full-irrigated and deficit-irrigated pistachios. These high values correspond to a f_w=1 due to the use of sprinklers.

Since E_S depends on irrigation system (sprinklers or drippers), irrigation frequency (daily or otherwise…) and soil infiltration rate (affecting the size of the emitter wetted areas), Y_{DW}-T relations would be more easily transferrable than Y_{DW}-ET relations to conditions other than those where they were obtained. Growers and public institutions should afterwards convert the proposed Y_{DW}-T relationship to a specific Y_{DW}-IR relation according to their own conditions of climate, soil and irrigation system. Nevertheless, more accurate methods for measuring the percentage of soil surface wetted by the emitters would be necessary in order to get better estimates of E_S, which has proven to be an important component of ET in this study. Our T calculations were compared with direct T estimates of sap-flow in (López-López et al. 2018), which made us feel confident about our E_S estimates.

Actually, the relationship between Y_{DW} and T varies according to each season particular conditions as well as depending on previous seasons' carry-over effects. Both in Table 4.3 and Fig. 4.4 (error bars) we can appreciate the great variability among years. In our orchard, 2013 had a very low harvest due to rainy weather during flowering, so vegetative growth was promoted, and lots of flower buds developed for 2014 season. On the other hand, in 2014 red leaf blotch could not be controlled properly and it caused reduced leaf area and consequently, transpiration. The combination of an exceptionally high number of fruiting positions determined during the previous season and an uncommonly lower T resulted in high WP_{ET} and WP_T values in 2014. By contrast, healthy trees transpired more in 2015 and 2016, and WP decreased. The year 2016 showed an intermediate behaviour in ET, T and thus WP_{ET} and WP_T.

Regarding yield and its components (Table 4.3), RDI_S had always a lower kernel yield than FI, while the response of SDI_M and RDI_M depended on the season. The yield found here for the well-irrigated treatment (2,508 kg·ha^{-1} on average) is higher than those reported in the rest of experiments conducted on hard-shell almond varieties (Romero et al. 2004a; Girona et al. 2005; García-Tejero et al. 2011; Egea et al. 2013; Mousavi et al. 2015), while it is still lower than those of soft-shell almonds (Goldhamer et al. 2006; Stevens et al. 2012; Phogat et al. 2013; Goldhamer and Fereres 2017; Naor et al. 2017). The explanation of the differences among yields of hard-shell varieties may be related to not meeting the full water requirements in some of the experiments, but there is insufficient information in most of the reports to make a detailed assessment of ET and IR. The yield difference between hard and soft-shell cultivars may be related to differences in fruit load. Some examples of fruit load values reported in soft-shelled varieties averaged 9, 400 (Goldhamer et al. 2006); 14,700 nuts/tree (Goldhamer and Fereres 2017) and 11,600 (Naor et al 2017), against 7,800 nuts/tree in FI here; 5,400 (Egea et al 2013) and around 6,000 (Girona et al 2005).

FI had also the highest fruit load, RDI_S the lowest one and SDI_M and RDI_M were similar and had intermediate values. However, reductions in yield were mainly due to smaller nuts, in line with Egea et al. (2010) and Goldhamer and Fereres (2017). Kernel unit weight was significantly affected by severe stress at the kernel-filling stage (RDI_S trees reached a SWP of almost -3.0 MPa before harvest) in the three study seasons: on average, 1.08 g/kernel in RDI_S against 1.34 g/kernel in FI. Similar results were reported by Hutmacher et al. (1994) and Mousavi et al. (2015). RDI_M had statistically significant smaller nuts than SDI_M in 2016. This was the only noticeable difference we found between applying a regulated or a sustained deficit irrigation strategy. Therefore, one should be careful when applying stress during the kernel-filling stage. Our SDI_M did not present a lower nut load as a result of water deficit after harvest as it would have been expected (Goldhamer and Viveros 2000; Goldhamer et al. 2006), but we believe stress was not sufficiently severe to provoke this effect (Fig. 4.3): the RDI treatment with post-harvest stress and the lowest irrigation amount reached predawn leaf water potential values of -3.0 MPa, and the most severe SDI treatment reached predawn leaf water potential of -1.6 MPa (Goldhamer et al. 2006). In fact, ET_O usually decreases in late-August, and storms become frequent in the location where our study was conducted.

Goldhamer and Fereres (2017) applied all their DI treatments biased towards the kernel-filling stage to avoid the known effects of post-harvest stress on kernel number (Goldhamer and Viveros 2000), and they found a tight relation between applied water and unit kernel weight, as Naor et al. (2017) confirmed recently.

The derivative of Y_{DW}-IR function, IWMP, has a constant negative slope. This indicates that a given reduction in irrigation amount causes a proportionally larger drop in yield as IR decreases from the amount required for maximum transpiration. A similar behaviour was found in olive trees (Moriana et al. 2003). One can look at this from two points of view: on the one hand, starting from a fully irrigated orchard, DI could be applied to reduce irrigation amount without large impacts on yield. On the other hand, starting from a rainfed crop, small increases in water application will cause proportionally larger increases in yield. By contrast, the WP_T of a given year was largely unaffected by the irrigation regime, supporting the conservative behaviour observed in the relation between T and crop productivity (Steduto et al. 2007). Nevertheless, WP_T values were found to differ from year to year which must be related to variations in climatic conditions among seasons (occurring at flowering and pollination) determining different levels of fruit load, as well as to the physiological responses of the different treatments in reaction to stress (Table 4.4).

Finally, given that a commercial plantation has a life cycle of 20 years or more, the conclusions of this three-year study must be supported by longer-term observations that will document the carry-over effects of persistent water stress, where both acclimation and the depletion of carbohydrate reserves would play a role in determining the response of almond orchards to deficit irrigation throughout the life of the orchard.

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CHAPTER 5:

General Conclusions

Chapter 5: General Conclusions

Mature, well-watered almond trees consume more water than what was determined several decades ago. Mid-stage K_T of a target mature well-watered almond orchard near full radiation interception was found to be 1.04, and this would lead to a Kc of 1.10-1.20, depending on the method of irrigation. For the Guadalquivir Valley of Southern Spain, this would be equivalent to irrigation requirements between 7,500 and 8,000 $m^3 \cdot ha^{-1}$. The ratio K_T/GC% was not constant during mid-season and exhibited significant scatter from day to day. The K_T oscillations were related to windspeed: the higher the windspeed, the lower the K_T. Furthermore, the mid-season K_T/GC% ratio of the lysimeter tree varied among seasons, being higher in a year of very high fruit load (12 kg/tree in 2016) than in the two other experimental years (6.4 in 2014 and 7.3 kg/tree in 2015). To refine the estimates of almond water use, further research is needed on the relationship between GC and intercepted radiation of the most common cultivars.

Under moderate deficit irrigation, an average reduction of 32% of seasonal irrigation amount caused an 18% reduction in ET_a, with no significant differences between SDI and RDI strategies. By contrast, a more severe RDI regime applying 57% less irrigation water reduced ET_a by 36%. Thus, irrigation reductions were compensated in good measure by soil water depletion (SWD) and by in-season precipitation. Seasonal SWD measured down to 2.1 m deep reached a maximum of about 200 mm, and calibrated sap-flow observations revealed that there was some additional water extraction beyond that depth. Hence, in the semi-arid climate of Andalusia, both SWD and P played a very important role in the overall water balance and should be considered when analysing the impact of irrigation regimes on the physiological and agronomical responses of almond to irrigation. The relative importance of SWD and P varied with the years, depending on the rainfall amount and on the degree of profile recharge during winter. Furthermore, as a consequence of the cumulative effects of the reduced water application in the DI treatments, the soil profile became increasingly dry as the study progressed, if seasonal rainfall was insufficient to recharge it fully.

Regarding the effects of DI on yield, FI averaged 2,500 $kg \cdot ha^{-1}$, moderate DI treatments (both SDI and RDI) averaged 2,100 $kg \cdot ha^{-1}$, and a more severe RDI averaged 1,500 $kg \cdot ha^{-1}$, with the irrigation and ET deficits described above. The production function obtained relating yield to water is therefore not lineal, but becomes curvilinear at some point before reaching maximum yield. Consequently, irrigation water marginal productivity has a constant negative slope, which indicates that a given reduction in irrigation amount causes a proportionally larger drop in yield as IR decreases from the amount required for maximum transpiration. IWMP had values of 0.11 $kg \cdot m^{-3}$ and 0.33 $kg \cdot m^{-3}$ at the irrigation rates of 7,540 $m^3 \cdot ha^{-1}$ and 3,250 $m^3 \cdot ha^{-1}$, respectively. By contrast, the transpiration efficiency of a given year was largely unaffected by the irrigation regime. We did not find differences between regulated and sustained DI with equal seasonal irrigation amounts, since in both treatments, severe stress immediately after harvest was avoided. Nonetheless, severe stress at pre-harvest significantly affected both fruit load (5,933 vs 7,830 in RDI_S and FI, respectively) and kernel weight (1.08 against 1.34 g in RDI_S and FI, respectively). The reduction in fruit load could be attributed in some part to the smaller size of the trees of the severe RDI regime after three years of DI (average canopy volume of 85.7 m^3 in FI and 60 m^3 in RDI_S).

Appendix 1: Published Works Directly Related to the Thesis

Find attached the two published scientific contributions directly derived from this Doctoral Thesis, corresponding to Chapters 3 and 4:

López-López M, Espadafor M, Testi L, Lorite IJ, Orgaz F, Fereres E (2018a) Water use of irrigated almond trees when subjected to water deficits. *Agricultutal Water Management* 195:84-93

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Research Paper

Water use of irrigated almond trees when subjected to water deficits

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ABSTRACT

Recently planted intensive almond plantations may have access to limited water supply due to water scarcity thus, information on almond water use under limited irrigation is needed. Here, the soil water balance was used to assess the consumptive use (ET) of full irrigated, moderately stressed and severely stressed almond trees over a three-year study, as well as the relation between applied water and ET. Sap flow measurements in eight experimental trees were used to obtain independent transpiration (T) measurements. Evaporation from soil (E_S) was modelled to estimate tree T from the water balance. Relative consumptive use in the deficit irrigation (DI) treatments largely exceeded the relative applied water, highlighting the need to measure ET in stressed treatments for hydrologic purposes. The moderately stressed treatments (irrigated at 65.5% of full irrigation) consumed 79.0% of maximum evapotranspiration (ET of 897 mm), while the severely stressed treatment consumed 63.6% of ETc (ET of 722 mm) when applied water was only 39.6% of control. On average, almond ETc approached 1200 mm, Seasonal evolution of the transpiration coefficient yielded maximum peak values ranging from 0.99 to 1.08, and minimum peak values of 0.33 attained with a severe deficit irrigation strategy. Transpiration measured by Compensated Heat Pulse-Calibrated Average Gradient sap-flow (x), was compared to water balance T estimates (y), and yielded a very good relation over the three years of study ($y = 0.90x + 4.23$, $r^2 = 0.81$). The sap flow measurements proved to be useful to overcome the limitations of the soil water balance technique, revealing that almond trees were able to extract water from below the monitored depths and suggesting that deep percolation event must have occurred in spring and autumn.

1. Introduction

Almond is one of the major tree crops in Spain in terms of cultivated area, 619,915 ha according to ESYRCE 2016 (MAPAMA, 2016). Although it has been grown traditionally in marginal lands under rainfed conditions, recently, irrigation has been introduced with concomitant changes for intensification of production. However, due to chronic water scarcity, Spanish Water Basin Authorities of most areas are unable to allocate irrigation water for almond production to meet its potential requirements. Thus, deficit irrigation (DI) strategies for almonds must be applied in order to reduce water consumption with a minimum impact on crop productivity (Fereres and Soriano, 2007). In order to design successful DI strategies and to assess consumptive use at the hydrologic basin scale, both the maximum crop evapotranspiration (ET_C) and the actual evapotranspiration (ETa) under different conditions of climate, soil, water availability and plantation typology must be known.

Potential crop evapotranspiration (ETc) can be measured by mass transfer or energy balance methods, and can also be estimated using models such as the Penman-Monteith equation (Allen et al., 1998). In the case of well-watered almond trees, there have been recent studies measuring ETc with eddy covariance (Stevens et al., 2012) or with a large weighing lysimeter (Espadafor et al., 2015).

There are many more difficulties in determining ETa of tree crops under field conditions. One option is to use the water balance approach to compute ETa when ET is limited by water deficits. In the case of almond trees, Girona et al. (2005), Egea et al. (2010) and Egea et al. (2013) have dealt with the responses to variable irrigation, but the ETa of stressed treatments was not measured nor calculated, as all the results were expressed in terms of applied water (AW, that

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is irrigation, Ir, plus effective precipitation, Peff). The extrapolation of these responses beyond the soil and climatic conditions where they were obtained is questionable. Recently, Spinelli et al. (2016) measured ETa of deficit-irrigated almond trees with eddy covariance, but surprisingly, they found that ETa was the same as the ETc of well-watered trees.

The goodness of a soil water balance depends on the accurate estimation of soil water depletion (SWD) by the root system. For this purpose, volumetric soil water content measured with the neutron probe method is considered to be advantageous over the use of other instrumentation such as tensiometers, FDR or TDR (Evett and Steiner, 1995). However, in all cases, the spatial variability of soil water properties (Nielsen et al., 1973) makes it necessary to seek a compromise between accuracy and practicality regarding the number of measuring points. In a drip-irrigated tree crop, the variability coming from unevenly wetted soil surface is another issue, requiring additional spatial variations in soil moisture observations. Andreu et al. (1997) described the soil moisture variability and dynamics around a single irrigated almond tree. They showed that, regardless of the depths of measurement, there is often significant uncertainty in the magnitude of the deep percolation component (DP). Nevertheless, there are a number of studies that have used the water balance approach in irrigated tree crops (Fereres et al. (1982) and Franco et al. (2000) in young almond trees; Garnier et al. (1986), Girona et al. (2002) and (Ayars et al., 2003) in peach; Klaij and Vachaud (1992) and (Kang et al., 2003) in pear; de Azevedo et al. (2003) and da Silva et al. (2009) in mango and Iniesta et al. (2008) in pistachio). Besides, the soil water balance approach has been incorporated into most crop simulation models for an array of conditions (Belmans et al., 1983; Brisson et al., 1992; Campos et al., 2016; Choudhury et al., 2013; Eitzinger et al., 2003; Phogat et al., 2017).

For determining ET from the soil water balance, one needs to quantify the water fluxes entering (namely, precipitation, P, and irrigation, Ir) and leaving (runoff, RO, and deep percolation, DP) the soil profile under study during a period spanning two soil water content (SWC) measurements. Once all the fluxes are measured or estimated, ET can be determined from the balance of inputs minus outputs. Additionally, if evaporation from soil (E_S) can be measured or estimated (Bonachela et al., 1999, 2001; Ritchie, 1972), transpiration (T) can also be known.

Sap-flow probes allow the direct estimation of tree transpiration by integrating sap flow velocity deduced from measurements of heat diffusion. Within the available sap-flow measuring methods, the Compensated Heat Pulse (CHP) has been proposed by Fernández et al. (2001) as a tool for irrigation scheduling. This technique is able to detect water stress as measured by the fall in tree transpiration relative to ETo or when a reference T value is obtained (Fernández et al., 2001; Tognetti et al., 2004, 2005). However, the azimuthal variations in sap velocity within a probed tree trunk makes calibration of sap-flow sensors highly recommended (López-Bernal et al., 2010; López-Bernal et al., 2015; Nortes et al., 2008).

There are only a few reports that combine the water balance technique with sap-flow measurements for calculating ET, such as in pines in USA (Oren et al., 1998), pear trees (Kang et al., 2002) and apple trees in north China (Gong et al., 2007).

In the context of almond production intensification under limited water supply, the objectives of this research were a) to determine the ETa of almond trees undergoing different deficit irrigation regimes, b) to relate the ETa to the level of AW, in order to assess the relevance of soil water extraction under deficit irrigation; and c) to compare the soil water balance method for estimating T against sap-flow measurements of T in almond trees.

2. Materials and methods

2.1. Experimental site and field management

The three-year experiment was conducted between 2014 and 2016 in a 5.5-ha almond (cv. *Guara*) orchard planted in 2009. Trees were grafted on G-677 rootstock and planted in a 6 × 7 m grid. The field is located at the Research Centre of IFAPA-Alameda del Obispo, in Cordoba, Spain (37,8°N, 4,8°W). Trees were pruned the two first years for scaffold formation and only again in January 2016 to ease machinery traffic. There is an automated weather station about 300 m apart from the orchard, from which climate data were collected along the study. In the centre of the orchard there is one large weighing lysimeter with one almond tree (Lorite et al., 2012), which is representative of the rest of the orchard.

Cordoba climate is typical Mediterranean: hot and dry summers and mild winters; annual rainfall averages around 600 mm. The experimental soil, of alluvial origin, is deep, of sandy loam texture in the first 150 cm depth, and lighter texture in the deeper layers. The typical upper (field capacity) and lower (wilting point) limits of soil water storage are 0.23 and 0.08 cm^3/cm^3, respectively.

The experimental trees were irrigated to satisfy their full water requirements since planting until the onset of the differential irrigation treatments in 2013. The control treatment and the rest of the trees outside the experimental area were fully irrigated. Trees were daily irrigated with 12 pressure-compensating drippers (4 l/h, with 1 m distance between drippers) per tree, using two drip laterals, each about 80–100 cm away from the tree rows. In 2014, there was one water meter per treatment. In 2015, individual water meters (WS15170 DN-15-3/4, Abering, Madrid, Spain) were installed in every experimental plot. Water meter readings were collected every two weeks in the new meters, while the old ones were used for daily irrigation monitoring and management.

Soil was kept free of weeds by both mower passes and herbicide applications, and pests and diseases were controlled following a treatment calendar, which was adjustable according to each season conditions. Mineral fertilization was calculated according to University of California recommendations (http://apps.cdfa.ca.gov/frep/docs/Almonds.html), and its application followed the recommendations by Muncharaz (2003).

2.2. Experimental design

Irrigation treatments started in spring 2013, by applying different limited irrigation levels, with full irrigation supply as the control. To induce a moderate stress level, both sustained deficit irrigation and regulated deficit irrigation strategies were tested, while severe water stress was induced by a more limited RDI regime. Thus, irrigation treatments were thus planned as follows (Table 1):

2.2.1. Fully irrigated control (FI)

These trees received the water requirements (ETc) calculated as in (Fereres et al., 2012). From 2015 on, the relation between ground cover (GC) and a transpiration coefficient (K_T = T/ETo) proposed by Espadafor et al. (2015), that is K_T/GC = 1.2, was used with an added 15%, to account for the evaporation from emitters wet surfaces. The addition of 15% was calculated using Bonachela et al. (2001) model assuming tree intercepted radiation of 60% and a wetted area by emitters of 25%. By delaying the onset of irrigation, some SWC depletion by the trees was allowed early in the season to avoid deep percolation, which would be significant if applying water to the soil at field capacity after winter rains.

Table 1
Irrigation treatments: scheduling and deficit distribution per periods (spring, stress-period and post-harvest) for the four treatments: FI = Full Irrigation, SDI_M = Moderate Sustained Deficit Irrigation, RDI_M = Moderate Regulated Deficit Irrigation and RDI_S = Severe Regulated Deficit Irrigation.

	FI (100%ETc)	Peff	Irrigation Treatment			
			FI	SDI_M	RDI_M	RDI_S [b]
Spring	ETc_1	$Peff_1$	ETc_1 - $Peff_1$	75%Irrig/n[a] - $Peff_1$	100%ETc_1 - $Peff_1$	60%ETc_1 - $Peff_1$
Stress-period	ETc_2	$Peff_2$	ETc_2 - $Peff_2$	75%Irrig/n- $Peff_2$	40%ETc_2 - $Peff_2$	20%ETc_2 - $Peff_2$
Post-harvest	ETc_3	$Peff_3$	ETc_3 - $Peff_3$	75%Irrig/n- $Peff_3$	100%ETc_3 - $Peff_3$	60%ETc_3 - $Peff_3$
Seasonal	$ETc = \sum ETc_{1-3}$		Irrig	<75%Irrig	<75% Irrig	<35% Irrig

[a] For SDI_M, total FI irrigation was divided equally by months along the irrigation season (n).
[b] The description of RDI_S treatment corresponds to 2015 and 2016.

2.2.2. Moderate sustained deficit irrigation (SDI_M)

This treatment received 75% of FI (75% of ETc) throughout the irrigation season.

2.2.3. Moderate regulated deficit irrigation (RDI_M)

This treatment received the same amount as FI in spring and after harvest, but only 40% of FI during the kernel-filling stage (pre-harvest period). The aim was that the total seasonal amount would be the same as that of SDI_M.

2.2.4. Severe regulated deficit irrigation (RDI_S)

In 2014, this treatment received the same as FI in spring and after harvest, and only 15% of FI during the kernel-filling stage. However, in the other two seasons the total irrigation amount was modified to apply 60% of FI during spring and in post-harvest, and 20% of FI during kernel filling.

Each experimental plot consisted of 16 (4 × 4) trees of which the central four were considered as experimental trees while the remaining 12 served as border. Treatments were repeated four times in a randomized complete block design. In addition, a single plot of 20 trees in the same 5.5 ha orchard was left rainfed to observe the response to extreme stress.

2.3. Canopy architecture and radiation interception

Three to four measurements of canopy diameters and tree height were taken during each season with the help of a measuring tape and a marked pole. Ground cover percentage (GC%) was calculated as the area of a circle of average tree diameter divided by the tree spacing. Canopy volume (Volc) was approached as an ellipsoid. Vertical transmissivity was measured close to canopy architecture measurement dates with a Plant Canopy Analyzer (LAI-2000, LI-COR Biosciences, Linconln, Nebraska, USA) in the trees bearing sap-flow probes. One reference and up-to seven (depending on tree size) radiation measurements were taken every 50 cm in four orthogonal transects. Afterwards, reference values were interpolated in time and transmissivity was calculated as the measured below canopy radiation divided by its reference value. Only the first ring (vertical) of the Plant Canopy Analyzer was considered. According to Lang (1987), plant area for each transect (PA_t) can be calculated as:

$$PA_t = \sum_{i=1}^{n} PA_i = -\pi \cdot x^2 / G_0 \cdot \sum_{i=1}^{n} (2i - 1) \cdot \ln \tau_i \quad (1)$$

where n is the number or measurement points, x is the distance between them (50 cm), G_0 is a cultivar-dependent parameter for leaf insertion angle and τ is transmissivity. The value of G_0 used was 0.492 according to Crespillo (2016). Each transect was assigned a 90° sector of the whole canopy. Plant area density (PAD) was finally calculated as PA/Volc, and assumed not to vary between trees within the irrigation treatment.

Intercepted radiation, Q_e was calculated by adapting a simplified model developed for olive trees (Mariscal et al., 2000).

$$Q_e = 1 - \exp(-k_r \cdot V_u) \quad (2)$$

$$k_r = 0.52 + 0.00079 \cdot PD - 0.76 \cdot \exp(-1.25 \cdot PAD) \quad (3)$$

$$V_u = V_0 \cdot PD / 10000 \quad (4)$$

Where Qe is percentage of intercepted radiation, k_r is a reduction coefficient, V_u is volume of canopy per m^2 of surface (m^3/m^2), PD is plantation density (trees/hectare), PAD is plant area density (m^2/m^3) and V_0 is the volume of one tree (m^3).

2.4. Evapotranspiration assessment by water balance

2.4.1. Change in soil water content (ΔSWC)

Soil water content in the first 210 cm of soil profile was measured with a neutron probe (Campbell Pacific Nuclear Scientific, Model 503). Monitoring started at budburst and ended in October prior to leaf fall, with an average interval between measurements of three to four weeks. The neutron probe was calibrated for the experimental soil by taking soil samples for volumetric moisture content (Θ, cm^3 of water/cm^3 of soil) at the time of access tube installation. Two separate calibration equations were used, one for the first 15 cm of soil and another for the rest of the profile down to the 2.10 m depth. Readings were taken at 30 cm intervals, but for the first two readings near the surface, which were taken between 0 and 15 cm and 15–30 cm depths.

The experimental plots of all treatments in Replicate 1 were equipped with eight neutron probe tubes installed in the area between the four central trees, while the plots of the other three replicates were equipped only with three neutron probe access tubes. SWC was calculated as a weighted average according to the area represented by each tube. The three tubes were installed, one near the irrigation lateral, one almost in the middle of the lane and a third one in-between, as shown by the black open circles of Fig. 1. We compared the soil water measurements averaged over the eight tubes in Rep. 1 against those determined with the three tubes in the other three replicates, as shown in the Results Section. The rainfed plot was monitored with nine access tubes.

Seasonal change in SWC was calculated by addition of the SWC changes between measurement dates.

2.4.2. Effective precipitation (Peff)

Due to the relatively high soil infiltration rate and the flat field, 100% of the rainfall over 0.2 mm was considered as effective precipitation (Villalobos and Fereres, 2017).

2.4.3. Evaporation from soil (E_S)

Daily E_S was calculated following Bonachela et al. (2001), which divides orchard evaporation into two terms; one from emitters wetted surface and another from the rest of the soil surface. The percentage of emitter wetted soil surface ranged from 5% in the RDI_S during the severe deficit period to 25%, 35%, 40% in the FI in 2014,

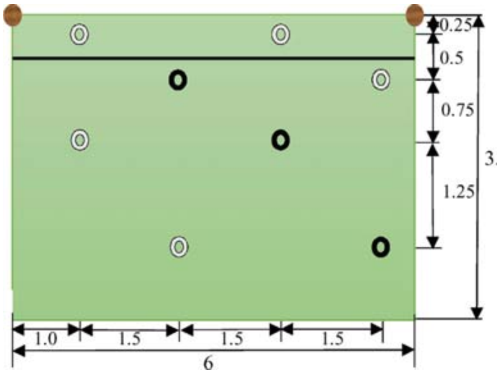

Fig. 1. Eight neutron probe access tube locations in the space between two experimental trees (full circles in the upper corners) in Block 1 plots. The three black rings indicate the locations of the three access tubes installed in the rest of blocks. Black line represents the drip lateral with emmiters a meter apart. Distances are in meters.

2015 and 2016 respectively. The Microadvective coefficient $kw = 1.0$ was taken throughout spring and after harvest against 1.2 during summer (Bonachela et al., 2001). In the RDI_S treatment, fallen leaves created a mulch above the surface wetted by the emitters, so a 50% reduction coefficient was used (Allen et al., 1998). Ritchie's model (1972) was used to calculate evaporation from the rest of the soil, which required intercepted radiation values.

2.4.4. Evapotranspiration (ET_{WB}) and transpiration (T_{WB})

ET_{WB} was calculated from water balance between SWC readings. T_{WB} came from subtracting E_S from ET_{WB}. Seasonal ET and T resulted from adding partial calculations. The DP component could not be measured or estimated by water balance, so it was not considered in our calculations.

$$ET_{WB} = Peff + Ir - \Delta SWC - DP \quad (5)$$

$$T_{WB} = ET_{WB} - E_S \quad (6)$$

Calculated T_{WB} for all the treatments in Replicate 1 was compared to the one measured with sap-flow, both seasonally and between SWC measurements.

2.5. Transpiration measurements with CHP sap-flow (T_{SF})

Two sap-flow probes were installed in a single tree per treatment in replicate 1 plus a second tree in RDI_S, as well as in two rainfed trees and in the lysimeter tree. The method used was the Compensation Heat Pulse (CHP) plus the Calibrated Average Gradient (CAG) for the hours of the day when the sap flow is very low (Testi and Villalobos, 2009).

The probes, designed and produced at the IAS-CSIC laboratory in Cordoba, Spain, are made of a 4.8 W 2 mm diameter stainless steel needle which emits heat pulses and two temperature sensors (protected by stainless steel). The upper temperature probe was 10 mm above the heater, while the lower was 5 mm below the latter. Each temperature probe has four thermocouple junctions along it, so heat pulse velocities can be known at different depths. Temperature difference (DT) between thermocouple junctions at the same depth was measured with less than 0.01 K error. Every 8 probes were connected to a multiplexer (AM16/32, Campbell Scientific Inc., Logan, UT, USA) controlled by a datalogger (CR10X or CR1000, Campbell Scientific Inc., Logan, UT, USA). At given intervals, the multiplexer triggers a measurement cycle along which DT is measured at 1-s intervals for 10 s, a 2-s heat beat (0.12 W/mm) is released, and DT is measured again at 1-s intervals for 3 min. DT

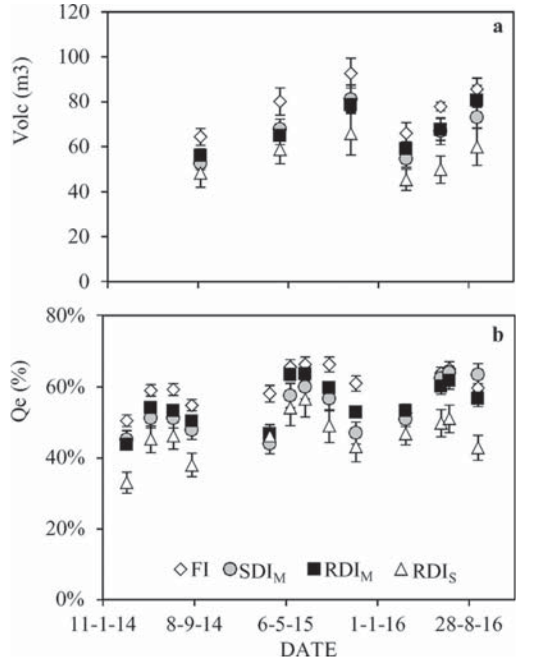

Fig. 2. **a**) Canopy volume (Volc, m^3) trends along the three-year study; and, **b**) Time course of the percentage of intercepted radiation (Qe, %). Points are average of four replicates. Vertical bars are standard error of the means. FI = Full Irrigation, SDI_M = Moderate Sustained Deficit Irrigation, RDI_M = Moderate Regulated Deficit Irrigation, RDI_S = Severe Regulated Deficit Irrigation.

readings are collected in the datalogger. The heat-pulse velocities had then to be checked for wounding effects (Green et al., 2003).

Sap-flow measurements were calibrated with transpiration data from the lysimeter, by covering the surface of the lysimeter with black plastic (a thin layer of straw was placed over the plastic not to change the albedo) thus avoiding soil evaporation in several 3–10 days' periods along the year. The rest of probes were calibrated, assuming a constant relation between their T and their GC at the start of the season, before any stress had taken place-. The seasonal evolution of the calibration coefficient for every probe was assumed to follow the same pattern as the lysimeter probes.

Sap-flow measured transpiration of only one out of four trees which were taken into account in the water balance of each experimental plot. To compare the two methods, we needed to estimate from the water balance the transpiration (T_{WB}) of the probed tree. For that purpose, we used a weighing factor that corrected for the specific canopy volume (Vol_C) of the probed tree.

3. Results

3.1. Canopy volume and radiation interception

Fig. 2 shows the time course of canopy volume (Vol_C) and percentage of intercepted radiation (Q_e) in the different treatments along the study. ANOVA and subsequent LSD test conducted for the indicated dates showed that FI trees were always significantly larger and intercepted more radiation than severely stressed ones, although 2016 winter pruning evened tree sizes somewhat. Regarding moderately stressed treatments, both SDI_M and RDI_M were smaller than FI at budburst, but did not differ significantly from FI trees later on in the seasons of 2015 and 2016. Average FI Vol_C achieved at the end of 2016 was 85.7 m^3, whereas RDI_S averaged 60.0 m^3. Q_e exceeded 60% of incoming radiation in FI, RDI_M

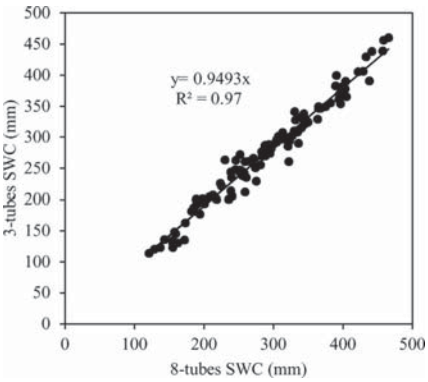

Fig. 3. Best-fit linear regression of total Soil Water Content (SWC, mm) measured with 8 neutron probes access tubes against 3 tubes in Replicate 1 for years 2014–2016. Points are individual SWC measurements of all treatments.

and SDI_M from 2015 onward. On the contrary, in the most stressed treatment, Q_e remained below 60% in 2015 and under 55% in 2016, respectively

3.2. Soil water dynamics

Fig. 3 presents the comparison between the 3-tubes weighed average SWC and the 8-tubes average SWC, taken at the same time, in the four treatment plots of Replicate 1. The excellent correlation obtained ($y = 0.949{\cdot}x$, $r^2 = 0.97$) indicates that SWC could be measured practically with three as well as with eight tubes. Therefore, SWC in replicates 2–4 could be well measured with just three tubes. Even though, the regression equation of Fig. 3 was reversely applied to the replicates 2–4 SWC measurements to correct the 3-tubes SWC data.

Fig. 4 presents the time course of SWC for the three seasons. Soil under FI trees had significantly higher soil moisture than in the other treatments at the end of 2014 and 2016, while no differences among treatments were found at the end of 2015 due to rainfall. In October 2016, a LSD test could also segregate RDI_M from RDI_S, and placed SDI_M in an intermediate group. Regarding the Rainfed plot, it can be observed that trees depleted the first 2.10 m of soil by early July 2014.

Fig. 5 depicts representative examples of volumetric soil moisture (Θ, cm^3 water/cm^3 soil) along 2016 at different depths in FI and RDI_S to illustrate the differences in soil water patterns. Data from two tubes per treatment are shown, one inside the drip-wetted area and the other in the middle of the lane. From the soil water content measurements, we presume that deep percolation may have occurred from 4th March to early August under the emitters in the FI treatment (Fig. 5a). Water extraction can also be seen at upper layers in FI, and soil water outside the influence of the dripper was consumed by the time of harvest (Fig. 5b). In the case of RDI_S, those treatments had depleted the monitored SWC inside and outside the

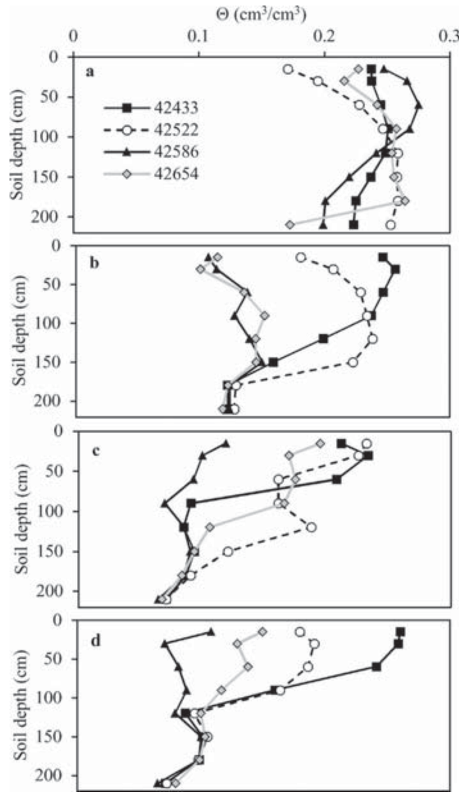

Fig. 5. Examples of volumetric soil moisture (Θ, cm^3/cm^3) seasonal evolution with depth (cm) along 2016 season in one neutron probe access tube nearby a dripper (**a** and **c**) and other in the middle of the lane (**b** and **d**), for both FI and RDI_S treatments. FI = Full irrigation, RDI_S = Severe Regulated Deficit Irrigation.

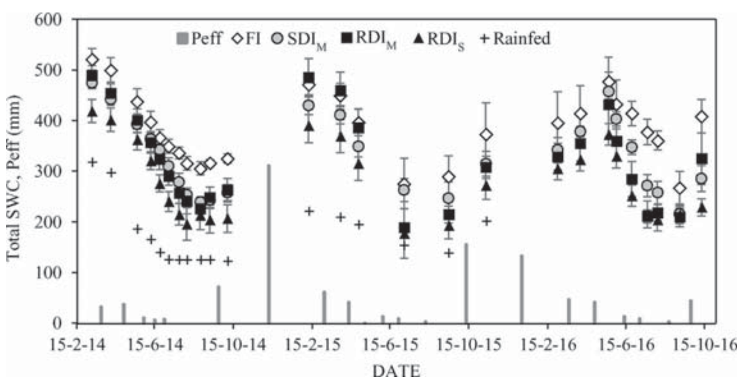

Fig. 4. Total soil water content (SWC, mm) evolution along the three years of study. Points are averages of the four blocks, but for the Rainfed treatment, which had no replicates. FI = Full Irrigation, SDI_M=Moderate Sustained Deficit Irrigation, RDI_M = Moderate Regulated Deficit Irrigation, RDI_S = Severe Regulated Deficit Irrigation. Vertical bars are standard error of the means. Grey bars show effective precipitation accumulated over the interval between two consecutive SWC measurements.

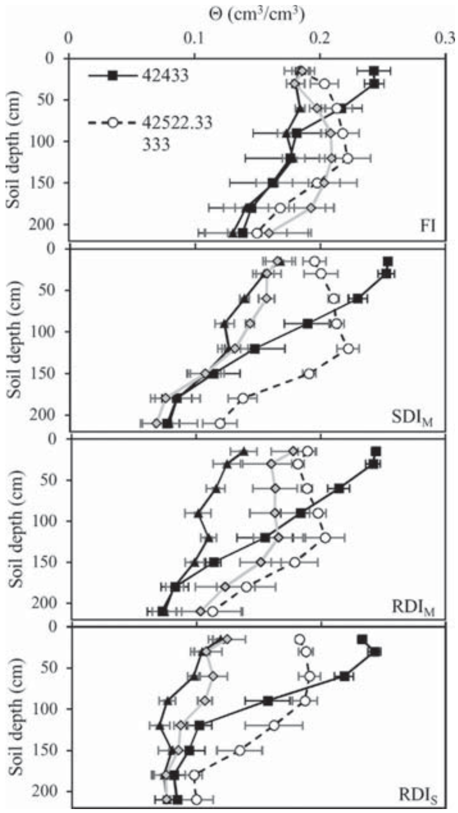

Fig. 6. Volumetric soil moisture (Θ, cm^3/cm^3) at different soil depths (cm) of the four treatments at four 2016 dates: budburst, start and end of Regulated Deficit Irrigation treatments and last soil moisture measurement. FI = Full Irrigation, SDI_M = Moderate Sustained Deficit Irrigation, RDI_M = Moderate Regulated Deficit Irrigation, RDI_S = Severe Regulated Deficit Irrigation. Points are means of the four replicates. Horizontal bars show standard error of the means.

influence of the emitters (Fig. 5c and d) and transpired just what was applied as irrigation.

Fig. 6 displays the time course of the average Θ for the four treatments. Summing up, FI profile remained wetter than the rest throughout the season; SDI_M depleted more soil water than RDI_M by the end of the season. Winter rains recharged the soil below 150 cm in RDI_S and spring rainfall was consumed completely by the end of the irrigation season in early autumn. A rainy spring in 2016 (see Table 2) filled all the treatments' profile from budburst to the start of RDI treatments.

3.3. *Crop evapotranspiration and transpiration coefficient*

Table 2 displays ET_O, calculated ET_C for irrigation scheduling, Peff, and actual irrigation and the actual ET calculated from the water balance for the four treatments. Average ET_O and Peff throughout the study were 1071 mm and 243 mm respectively. Average three years ET_C was 1134 mm for FI, of which 800 mm were contributed as irrigation. Moderate DI strategies averaged seasonal ETa of 897 mm (79.0% of FI) with 524 mm irrigation (65.5%). There were no significant differences in ETa between SDI_M and RDI_M. Besides, RDI_S treatment reduced ETa to 722 mm (63.6%) with 317 mm irrigation (39.6%).

For each season, data are presented as seasonal values and divided into three periods: spring, pre-harvest period (where the deficits are applied in RDI) and post-harvest.

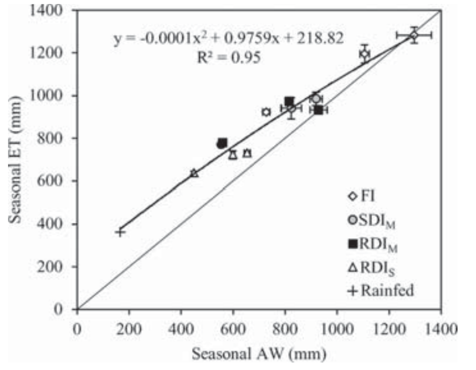

Fig. 7. Seasonal ET calculated from water balance (ET_{WB}) against seasonal applied water (AW, irrigation plus effective precipitation), both in mm. Points are averages of the four replicates each of three years (3 points per treatment), but for the Rainfed trees, which had no replicates, and was just measured in 2014. FI = Full Irrigation, SDI_M = Moderate Sustained Deficit Irrigation, RDI_M=Moderate Regulated Deficit Irrigation, RDI_S = Severe Regulated Deficit Irrigation. Vertical and horizontal bars show standard error of the means.

Randomized Complete Block ANOVA conducted on calculated ET showed no significant differences amidst treatments from budburst to the start of pre-harvest period in the first two years. In pre-harvest, FI had the highest ET values; the two moderately stressed treatments presented significantly lower values than FI and higher than the severely stressed one. After harvest, LSD test segregated FI from all deficit treatments in 2014, whereas in 2015 RDI_S ET values were significantly lower than those of the other treatments. Finally, in 2016 means were separated in three groups: FI, both SDI_M and RDI_M, and RDI_S.

On a seasonal scale, FI consumed more water than the rest, and the moderately stressed treatments consumed more than the severely stressed one. No differences were found between SDI_M and RDI_M.

Fig. 7 represents the calculated seasonal ET against AW (Ir + Peff) for the four treatments and the three study years. The 1:1 line represents a situation where all applied water is consumed by the crop ET and no SW depletion takes place. The vertical distance between the 1:1 line and the points above it represents the SWD. Points below the 1:1 line in Fig. 7 indicate that some deep percolation took place, as it must have happened in some FI replicates in 2016. From Fig. 7 it can be estimated that the maximum seasonal SWD was about 200 mm under the experimental conditions.

The time course of the transpiration coefficient (K_T) calculated with water balance in the first and the last study years is shown in Fig. 8. Maximum K_T values for FI were 0.87 and 1.16 in 2014 and 2016, respectively. In the RDI_S treatment, K_T dropped to minimum values of 0.14 and 0.33 in 2014 and 2016, respectively. Regarding the moderate deficit treatments, the K_T of RDI_M was lower than in SDI_M during summer, but recovered after harvest, and both treatments showed similar values at the end of the season, around 0.46 in 2014 and 0.59 in 2016.

3.4. *A comparison of water balance estimates of ta against sap-flow Ta measurements*

Fig. 9 presents the comparison between the two methods of determining Ta for every period between two SWC measurements. Generally, both methods agreed in the estimates of Ta for RDI_S, whereas there were some discrepancies in the other treatments. In 2014 (Fig. 9a), the sap-flow measurements of Ta were lower than those obtained with the WB method in the period when irrigation was resumed after harvest in both RDI_M and FI. During summer,

Table 2
Seasonal and per-periods (spring, pre-harvest and post-harvest period) reference evapotranspiration (ET_O), effective precipitation (Peff), irrigation and evapotranspiration (ET_{WB}), all in mm. Treatments: FI = Full Irrigation, SDI_M = Moderate Sustained Deficit Irrigation, RDI_M = Moderate Regulated Deficit Irrigation and RDI_S = Severe Regulated Deficit Irrigation Different letters within the same time period indicate statistically significant differences (P < 0.05) among treatments according to LSD test.

	ETo	ETc	Peff	Treatments							
				FI		SDI_M		RDI_M		RDI_S	
				Irrigation	ET_{WB}	Irrigation	ET_{WB}	Irrigation	ET_{WB}	Irrigation	ET_{WB}
2014											
Spring (10 March-18 May)	274.8	160.3	73.3	94.3	250	96.1	251	97.2	259	112.5	241
Pre-harvest (19 May-3 Aug)	457.1	422.9	22.3	270.7	416a	177.9	340b	153.3	334b	52.6	234c
Post-harvest (4 Aug-5 Oct)	304.2	249.4	72.1	194.7	257a	112.2	180b	147.0	198b	117.2	178b
Seasonal	1036.1	832.6	167.7	559.7	923a	386.3	771b	393.1	779b	281.4	647c
2015											
9 Feb-27 April	192.9	119.6	103.3	5.5	184	1.7	186	7.3	202	3.9	182
28 April-13 Sept	810.0	726.5	29.1	715.6	851a	483.1	614b	451.9	629b	288.9	441c
14 Sept-8 Nov	127.6	116.8	152.4	99.7	160a	54.1	139a	76.3	136a	24.1	97b
Seasonal	1130.5	962.9	284.8	820.8	1195a	538.9	939b	532.0	972b	314.0	722c
2016											
Spring (1 March-30 May)	272.6	211.7	270.1	109.8	343a	90.0	313ab	98.3	323.6a	60.1	305ab
Pre-harvest (31 May-2 Aug)	424.9	457.0	1.3	487.6	561a	301.7	448b	234.2	389.7b	131.7	258c
Post-harvest (3 Aug-9 Oct)	348.5	378.9	5.9	421.9	380a	239.7	218b	334.0	233.8b	185.0	166c
Seasonal	1046.0	1047.6	277.3	1019.4	1284a	642.1	984b	651.2	932b	376.8	730c

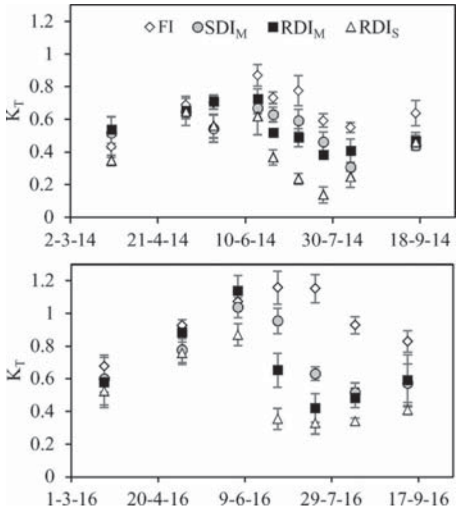

Fig. 8. Seasonal evolution of the relation between transpiration and reference evapotranspiration ($K_T = T/ET_O$) for years 2014 (**a**) and 2016 (**b**). Points are averages of the 4 blocks over periods between two consecutive SWC measurement dates and vertical bars are standard error of the means.

T_{SF} was greater than T_{WB} in RDI_M. Whereas, in 2015 (Fig. 9b), the same happened in SDI_M. Again, FI showed T_{SF} lower than T_{WB} after harvest. In 2016 (Fig. 9c), some points over the 1:1 line can be seen in FI and RDI_M, obtained during spring and autumn, while before harvest, T_{SF} of RDI_M was greater than T_{WB}. Fig. 9d shows data of the four treatments and three years. Overall, the correlation was very good with a linear regression: y = 0.90x + 4.23, (r^2 = 0.81).

4. Discussion

In our three-year study, a DI regime that applied 39.6% of FI irrigation (RDI_S) resulted in a much higher relative consumptive use, equivalent to 63.6% of ET_C (ETa of 722 mm). Our results contrast with those of Spinelli et al. (2016), that measured ETa of a deficit irrigated almond orchard with eddy covariance and found no decrease in comparison with the well irrigated treatment. Other DI works on almonds (Egea et al., 2013, 2010; Girona et al., 2005) reduced irrigation to 40% and 28% of their control treatments in their most severely stressed treatment. However, they did not take into account either precipitation or changes in SWC when establishing relations between irrigation regimes and crop response. If we consider the large climatic and soil variability throughout the almond growing areas, it would be difficult to extrapolate tree responses to irrigation amounts to conditions other than those where they were obtained. In Fig. 7, it can be seen that the intersection point between almond ET and AW was around 1200 mm, and maximum seasonal SWD, observed in the rainfed plot in 2014 as well as in deficit irrigated trees, was near 200 mm, which is 27.7% of the three-year average ETa of RDI_S, in the experimental conditions. This is particularly important if mild stressed or over-irrigated treatments are chosen to analyse the effects of irrigation on crop response, since different irrigation regimes could result in the same ETa. This is because the mild stressed tress would extract more water from the soil, while the over-irrigated treatments would have percolation losses below the root zone.

Along with canopy size and ET_{WB}, T and K_T increased from the first to the last study year too. On the one hand, FI K_T pattern reveals some sustained stress in 2014, possibly because of insufficient irrigation. On the other, the highest average K_T obtained (1.16) can be overestimated due to percolation, but experimental plots without percolation gave K_T values between 0.99 and 1.08 along the summer, leading to corresponding K_C values from 1.10 to 1.27 which is in accordance with recently published K_C values for almond (Espadafor et al., 2015; García Tejero et al., 2015; Goldhamer and Fereres, 2016; Stevens et al., 2012). The RDI_S made K_T drop to 0.14 in 2014 and 0.33 in 2016 during the pre-harvest period. Stress was too severe in 2014, and this treatment was increased in the deficit period from. 280 mm up to 370 mm to avoid too severe stress. When comparing SDI_M with RDI_M, both reduced transpiration along summer, but K_T of SDI_M remained higher until full irrigation was resumed in RDI_M after harvest. Thus, SDI_M got minimum values of 0.31 and 0.48 by early August 2014 and 2016, respectively, while RDI_M reached minimum values of 0.38 and 0.42 by late July 2014 and mid July 2016, respectively. Nonetheless, there were no differences in ET_{WB}: smaller drip-wetted surface in RDI_M made E_S relatively lower during the months of highest ET_O. Both treatments had recovered transpiration by mid-September.

In Table 2 and in Fig. 7 we can appreciate that ET of FI treatment increased noticeably from 2014 to 2015. There are a couple of possible explanations for this. Firstly, Vol_C and Qe increased from

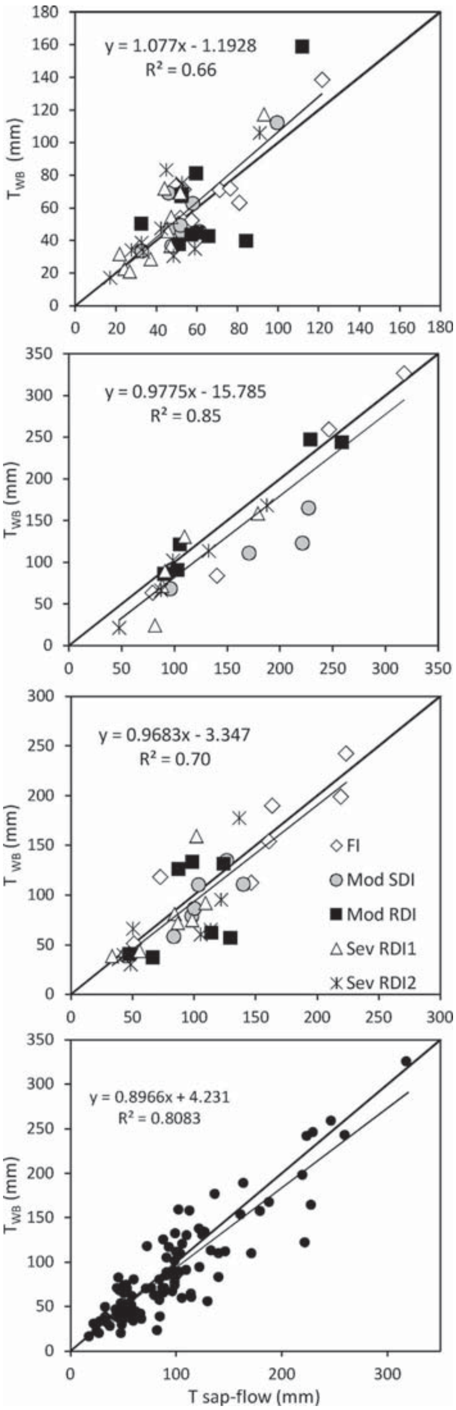

Fig. 9. Transpiration calculated with water balance (T_{WB}) against transpiration measured with sap-flow (T_{SF}), both in mm. Each point corresponds to a period of time between two consecutive measurements of SWC with the neutron probe: **a**) 2015, **b**) 2015, **c**) 2016 and **d**) all five probed trees and three years are included. FI = Full Irrigation, SDI_M = Moderate Sustained Deficit Irrigation, RDI_M = Moderate Regulated Deficit Irrigation, RDI_S = Severe Regulated Deficit Irrigation.

2014 to 2015 (Fig. 2), so growth had not finished yet. Secondly, predicted ETc for irrigation scheduling was lower than actual ET_{WB}, so the Kc used in 2014 may have been underestimated. As well, red leaf blotch was not under total control in 2014, and it reduced leaf area density and hence Qe. Trees were much healthier the following seasons. On the other hand, percolation events due to the rainy spring together with the need to irrigate for fertilizing rose 2016 ET values of FI. Therefore, the shape of the regression line in Fig. 7 should be blunter at the upper extreme. We can observe that the 2016 rainy spring after a dry winter brought points corresponding to the rest of the treatments under the regression line as well: there was not so much SWC available at the beginning of this season (Fig. 4), and subsequent rainfall was already computed as AW instead of SWD.

If we think of carryover effects of DI on SWC, the most severe treatment kept similar values of total SWC throughout the three years (Fig. 4). However, no recharge of the deepest layers was observed after winter and spring rains (Fig. 5c and d) as in moderately stressed treatments and FI (Figs. 6, 5a and b), which may entail a change in the relation between AW and ET on a longer term by reducing SW reservoir, or after particularly dry winters.

Regarding water balance limitations, such as soil variability within an irrigated tree orchard, our SWC estimation with 3 neutron probe access tubes (one nearby the irrigation lateral, one almost in the middle of the lane and a third one in-between) resulted a good representative of the SWC (Fig. 3). However, the water balance method overestimated ET when DP is significant and underestimates it when SWD occurs outside the monitored soil volume, in this case below the 2.1 m depth. We delayed irrigation until late spring to prevent applying water to the soil at field capacity after the winter rains, and thus have the trees consumed part of the SW reservoir. However, we cannot rule out the possibility that DP events may have occurred in the FI treatment which received the highest irrigation depths. This would make the, ET of the FI treatment overestimated. In the case of DI treatments, the dryness of the soil (consequently with very low hydraulic conductivity) should have prevented DP, leading to more precise estimates of almond ETa values.

The use of the CHP-CAG sap-flow technique allowed to detect these events in one of the replicates. Thus, in 2014 (Fig. 9a), RDI_M must have extracted water below 2.10 m, since the sap-flow measurements led to Ta values greater than those of the WB method. On the contrary, there must have been some deep percolation in the period when irrigation was resumed after harvest in both RDI_M and FI. In 2015 (Fig. 9b), it is SDI_M which seemed to have extracted water beyond 2.10 m deep. Again, FI showed deep percolation after harvest that year. In 2016 (Fig. 9c), it seems that deep percolation occurred in spring and autumn in FI and RDI_M, while extraction below 2.10 m took place during the deficit period in the latter. This all seems consistent with the irrigation schedule and the treatments applied.

We found other three works in which water balance and sap-flow methodologies were combined (Gong et al., 2007; Kang et al., 2003; Oren et al., 1998), but not contrasted, because E_S was not estimated independently, as in our case. The comparison presented in this work is therefore the first that presents three years of data and different levels of water status and time periods (Fig. 9d), and demonstrates a robust correlation between the two methodologies. Nonetheless, there were also limitations in the sap-flow technique. One is the gum exudation in almond due to needle wounds that altered the calibration coefficient during the season, which was corrected just in the FI tree, when it was compared to the lysimeter tree. In the case of the DI treatments, a different calibration approach would be required for greater accuracy.

Finally, as in other studies where deficit irrigation was applied to almond trees, water shortage resulted in reduced canopy size (Egea et al., 2010; Goldhamer and Viveros, 2000; Hutmacher et al., 1994; Romero et al., 2004). Although this could have negative effects on production, Goldhamer et al. (2006) pointed it as a chance to increase yield via increased plantation density, while consuming less water. More years of study may be needed to assess the performance of DI throughout the functional duration of a commercial almond plantation.

5. Conclusions

Moderate deficit irrigation strategies averaged a seasonal ETa of 897 mm (79.0% of FI) with 524 mm of irrigation (65.5% of FI). There were no significant differences in ETa between Sustained Deficit Irrigation and Regulated Deficit Irrigation strategies. By contrast, a more severe Regulated Deficit Irrigation treatment reduced ETa to 722 mm (63.6%) with 317 mm of irrigation (39.6%). As a consequence of the reduced water application, the SWC in the DI treatments was much less than in FI at the end of the season, with the risk of incomplete soil profile recharge, particularly in dry winters.

The intersection point between almond ET and Applied Water was somewhat lower than 1200 mm, and maximum seasonal SWD was near 200 mm in our soil and climate conditions. Furthermore, sap-flow measurements revealed that almond trees of some treatments extracted water from depths below the lowest measuring depth of 2.1 m. Therefore, depending on rainfall distribution and soil water holding capacity, both precipitation and SW extraction may play an important role in seasonal crop water consumption and should be considered when analysing the effects of watering regimes on other crop features such as vegetative growth and yield.

Both techniques CHP-CAG sap-flow and water balance presented limitations for the accurate estimation of ETa and Ta. However, the combination of both methods reduced the uncertainty in the determination of orchard ET, caused either by an unknown deep percolation and/or by soil water depletion outside the monitored soil volume. Improvements in the calibration of the sap-flow technique should enhance the accuracy of the determination of Ta in almond trees under variable irrigation supply.

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ORIGINAL PAPER

Yield response of almond trees to transpiration deficits

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Abstract

Irrigation optimization under limited water supply requires knowledge of the relation between consumptive use and production. The recent expansion of almond production is highly dependent on irrigation which may be limited by water scarcity in the future. A 3-year experiment was conducted in Cordoba, Spain, to determine the yield and water productivity (WP) responses of almond (cv. Guara) to irrigation deficits. Maximum yields of 2508.4 kg/ha (3-year average) were obtained when the crop evapotranspiration (ET_C) was fully met. Three deficit irrigation treatments that supplied 66.9, 69.7 and 43.2% of the full irrigation requirements yielded 2147.5, 2038.2, and 1496.9 kg/ha, respectively. Assessment of the consumptive use (ET_C) and its components, E_S and T, yielded seasonal values of 1088, 887, 894 and 699 mm of ET_C, of which T represented 831, 640, 648 and 479 mm, for the four different treatments, respectively. The relations between yield and irrigation, ET_C, and T were used to determine the WP values as affected by water. Although values varied from year to year, the WP_{ET} averaged 0.23 kg/m^3 for the 3 years and did not differ among treatments. The transpiration efficiency (WP_T) had a value of 0.32 kg/m^3 and was roughly the same for all treatments.

Introduction

Spain is the third almond-producing country in the world, after Australia and USA, 5, 8 and 80% of total world production, respectively (Californian Almond Board 2015). In terms of cultivated area, almond is the third tree crop in Spain (nearly 736,000 ha; MAGRAMA 2016). Most of the area is devoted to traditional rainfed production, but recently, newly planted almond orchards are undergoing a fast intensification process. Attractively high international prices are pushing farmers in Spain to shift from the extensive, low-input management in marginal soils (with yields of less than 200 kg/ha) to high-yielding plantations that receive high levels of irrigation and fertilization. However, there are water supply restrictions for new plantations in many areas, so deficit irrigation (DI; Fereres and Soriano 2007) strategies are necessarily adopted.

When a crop is subjected to DI, it is necessary to know the possible long-term effects of water stress on crop growth and production. Almond growers need to understand the relation between water use and yield and its components, and thus income, to make appropriate management decisions (such as allocating limited water to various crops). Also, public institutions need this basic information to assign water allocation for the new intensive and more demanding plantations.

Plant–water relations in almond have been thoroughly studied, and water stress is known to affect stomatal conductance and photosynthetic assimilation at leaf level (Castel and Fereres 1982; Romero et al. 2004b; Romero and Botía 2006; Nortes et al. 2009; García-Tejero et al. 2011), and provokes premature defoliation (Goldhamer and Viveros 2000; Klein et al. 2001; Romero et al. 2004a). The effects of water stress on growth and yield, and its components, of almonds of different ages and at different stages of the crop cycle (generated by a variety of DI strategies), have also been examined in several multi-year experiments. Summing up, water stress diminishes vegetative growth and hence canopy size and affects the accumulation of reserves. During kernel-filling stage, water stress can reduce nut weight, while when it occurs

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after harvest, it lessens the crop load of the next season (Hutmacher et al. 1994; Goldhamer and Viveros 2000; Esparza et al. 2001; Girona et al. 2005; Egea et al. 2010, 2013; Mousavi et al. 2015).

It is known that DI can increase water use efficiency (WUE; Howell 2001; Fereres and Soriano 2007). Some authors have reported values of water productivity (WP) around 0.17–0.22 kg/m^3 and 0.30–0.34 kg/m^3 for well-watered and water-stressed almonds, respectively (Hutmacher et al. 1994; Romero et al. 2004a; Goldhamer et al. 2006; Egea et al. 2013). Conversely, Egea et al. (2010) presented much higher values: 0.32 kg/m^3 for the fully irrigated treatment and 0.71 kg/m^3 for the stressed one. Phogat et al. (2013) calculated water productivity in terms of irrigation (IR), evapotranspiration (ET_C) and transpiration (T), showing that while IR–WP varied noticeably from fully irrigated trees to deficit-irrigated ones, ET_C–WP and T–WP differed less regardless of the irrigation regime. This highlights the need to generalize WP assessments by measuring the amount of water that the crop actually consumes.

Goldhamer and Fereres (2017) recently published an applied-water production function for almonds in California, with data from a 5-year experiment. Their research was conducted in an environment of very low rainfall and in a soil with low water-retention capacity, thus one would expect very small differences between IR and ETC under those conditions. However, this is not the case in many other areas, including the Mediterranean Basin, where intensive almond orchards are being planted. There are almond-growing environments with substantial in-season rainfall as well as with soils of high water storage capacity. In those locations, soil water depletion can represent an important percentage of seasonal ETC. Also, the minimum irrigation treatment applied by Goldhamer and Fereres (2017) was 1000 mm, thus there is a need to investigate the response at lower irrigation levels, which would be required in conditions of lower water availability for irrigation. Finally, Goldhamer and Fereres (2017) worked on ‘Nonpareil’, a soft-shell almond cultivar, while hard-shell cultivars are more commonly grown in other areas of Europe. All of these differences justify the need to develop a consumptive-water production function which considers lower levels of applied water in the hard-shell cultivar ‘Guara’, which is commonly grown in Spain.

Therefore, the objectives of the present study were: (a) to determine a functional relationship between yield and its components and the consumed water, and (b) to analyse the effect of different water regimes on transpiration efficiency and on the marginal productivity of irrigation water in almond trees.

Materials and methods

Experimental site

The experiment was carried out in a 5.5-ha almond orchard located at the Research Centre of IFAPA-Alameda del Obispo, in Cordoba, Spain (37.8°N, 4.8°W) from 2014 to 2016. The climate is typical Mediterranean, with hot and dry summers, mild winters and average annual rainfall of around 600 mm. The soil of the experimental field is of alluvial origin, and more than 200 cm deep. Soil texture is sandy loam in the first 150 cm depth and lighter in the deeper layers. The typical upper and lower limits of soil water storage are 0.23 and 0.08 cm^3/cm^3, respectively.

Almond trees (cv. *Guara*) were grafted on GF-677 rootstock and planted in 2009 in a 6 × 7 m grid (238 trees/ha). Pruning was done during the two first years for scaffold formation and only again in January 2016 to ease machinery traffic. A treatment calendar was followed for the chemical control of pests and diseases. This calendar was adjusted according to each season conditions. Weeds were controlled by combining mowing and herbicide applications. Mineral fertilization was calculated according to University of California guidelines (http://apps.cdfa.ca.gov/frep/docs/Almonds.html), and its application followed the recommendations by Muncharaz (2004).

Two drip irrigation laterals were placed 80 away from tree rows in 2014–2015, and 100 cm in 2016, with a total of 12, 4 l/h-pressure-compensating emitters per tree. The control treatment and the non-experimental trees were irrigated to cover their full requirements, though allowing some soil water depletion in spring to avoid deep percolation. The rest of the experimental trees were fully irrigated until the start of differential irrigation treatments in 2013.

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

Experimental design

Four differential irrigation treatments (three DI levels and one control) started in 2013. Irrigation was scheduled on a biweekly basis to match the net water requirements (pre-estimated ET_C minus P_{eff}). All treatments had the same number of emitters and irrigated daily, differing in the duration of irrigation. Afterwards, actual ET_C was calculated by water balance. Irrigation amounts for the 3 years are presented in the third column of Table 1 in mm and in the sixth column as percentages of the control treatment.

Table 1 Seasonal irrigation (IR), crop evapotranspiration (ETc), soil evaporation (E_S) and transpiration (T) of the four treatments over the 3 years of study (2014–2016) and their average

Year	Treat.	Absolute values (mm)				% of T1			
		IR	ETc	Es	T	IR	ETc	Es	T
2014	T1	559.7	923a	236a	687a				
	T2	386.3	771b	230b	541b	69.0	83.5	97.4	78.8
	T3	393.1	779b	232b	547b	70.2	84.4	98.3	79.6
	T4	281.4	648c	216c	432c	50.3	70.2	91.5	62.9
2015	T1	820.5	1125a	275a	847a				
	T2	538.9	939b	279a	660b	65.7	83.5	101.4	77.9
	T3	530.6	975b	272a	699b	64.7	86.7	98.9	82.6
	T4	314.0	722c	254b	468c	38.3	64.2	92.3	55.3
2016	T1	904.5	1220a	278a	961a				
	T2	642.1	984b	231b	754b	71.0	80.7	83.1	78.4
	T3	651.2	932b	234b	698b	72.0	76.4	84.2	72.6
	T4	376.8	730c	189c	541c	41.7	59.8	68.0	56.2
Average	T1	754.2	1088a	263a	831a				
	T2	504.3	887b	247b	640b	66.9	81.5	93.9	77.0
	T3	525.5	894b	246b	648b	69.7	82.2	93.9	78.1
	T4	325.7	699c	220c	479c	43.2	64.2	83.6	57.7

Values are expressed in mm and as % of every season control treatment (T1)

Different letters in the same column indicate different homogenous groups according to LSD test after randomized complete block ANOVA at $P<0.001$

Control (T1)

These trees received the irrigation amount required to allow application of the full pre-estimated ETc, which was calculated in 2014 as in Fereres et al. (2012). From 2015 onwards, we used the relation between transpiration coefficient ($K_T = T$/ETo) and ground cover (GC), K_T/ GC = 1.2 (Espadafor et al. 2015), plus 15% more to account for the evaporation from the emitters' wet surfaces to estimate previous ET_C, to schedule irrigation. This 15% was calculated according to Bonachela et al. (2001) for 25% of wetted surface and 60% of intercepted radiation, which were the average values for the control treatment in 2014. To avoid deep percolation as much as possible, 75–125 mm of soil water content (SWC) depletion was allowed early in the season by postponing the start of irrigation, except in the last year when, despite the rainy spring, we still had to apply the fertilizers via irrigation, and SWC was not depleted.

Moderate sustained DI (T2)

T2 received 75% of T1 (75% of ETc) steadily throughout the irrigation season.

Moderate regulated DI (T3)

T3 was irrigated as T1 in spring and after harvest, but only 40% of T1 was applied during the kernel-filling stage (pre-harvest period, usually occurring from mid-June to late-July in the area). The cumulative irrigation amount at the end of the season was targeted equal to that of T2.

Severe regulated DI (T4)

T4 was given the same irrigation as T1 in spring and after harvest, and only 15% of T1 during the kernel-filling stage in 2014. However, trees underwent severe stress in 2014, and some of them dropped all their leaves. In 2015 and 2016, we reconsidered treatment T4 to avoid severe stress. We increased the total water allocation and redistributed the water deficit as follows: 60% of T1 was applied in spring and after harvest, and 20% of T1 during kernel filling.

The experiment had a randomized complete block design with four replications, each experimental plot being composed of four central experimental trees plus their borders (4 × 4). Irrigation of the whole orchard was withdrawn 10–15 days previous to harvest to minimize the risk of tree debarking by the mechanical shaker.

Evapotranspiration (ET_C) and transpiration (T)

ET_C was calculated using the soil water balance method. For the calculation of ET_C, we needed to measure or estimate the rest of fluxes involved in the soil water balance as follows:

Irrigation (IR)

One water meter was installed per experimental plot, from which readings were taken every fortnight.

Effective precipitation (P_{eff})

Precipitation data from the first SWC measurement to the last one were collected from the automated weather station nearby. Since the soil has a high infiltration rate and null slope, runoff was assumed to be zero and, therefore, P_{eff} was considered 100% of precipitation. The proportion of rain directly intercepted by the plant canopies was neglected in this work, basically because the rainy season coincides with winter, when almond trees have no leaves. Events smaller than 0.2 mm were not taken into account (Villalobos and Fereres 2017).

Change in soil water content (ΔSWC)

A neutron probe (Campbell Pacific Nuclear Scientific, Model 503) was used to measure SWC down to 210 cm in different locations within the experimental plots. There were three tubes per replicate, one in the emitter-wetted area, a second in the middle of the lane, and a third in an intermediate location. A sketch of the layout of access tubes can be found in López-López et al. (2018). The neutron probe was calibrated for the experimental soil by taking soil samples for volumetric moisture content (Θ, cm^3 of water/cm^3 of soil) when the access tubes were installed. One calibration line was used for the first 15 cm of soil and another for the rest of the profile down to the 210 cm depth. The SWC of the 0–30 cm depth was characterized with two readings at 7.5 and 22.5 cm depth. Then, readings were taken at 30 cm intervals down to 210 cm.

SWC was measured at budburst, 1 week before and one after the differential treatments started, 1 week before and one after irrigation resuming, and one last time in early October. The deep percolation (DP) component was considered negligible based on the SWC readings of the deeper depths (López-López et al. 2018). The ET_C of every interval was computed as:

$$ET_c = IR + P_{eff} - \Delta SWC - DP. \tag{1}$$

Evaporation from soil (E_S)

The calculation of daily E_S was performed by separating evaporation into two components: one from the surface wetted by the emitters (E_{SW}), and the other as the evaporation from the rest of the soil surface (E_{SO}) (Orgaz et al. 2006).

The model developed by Bonachela et al. (2001) was used to calculate E_{SW} as follows:

$$E_{SW} = f_w \cdot K_{sw} \cdot (\mathrm{Rad} \cdot (1 - \mathrm{Qe}) + \mathrm{Aer}), \tag{2}$$

where f_w (0–1) is the fraction of soil wetted by the emitters. Rad and Aer are the radiative and the aerodynamic terms of the Penman-FAO ET_O equation, as described in Bonachela et al. (1999). K_{sw} is a microadvective coefficient that accounts for the enhancement of evaporation from the emitter-wetted soil surface due to being surrounded by a drier area (adimensional). The relation between this coefficient and the microadvective conditions of the orchard was empirically determined by Bonachela et al. (2001), from $K_{sw} = 1.0$ when advection is not present (that is when the soil apart from the emitters is not completely dry) to $K_{sw} = 1.6$ for highly microadvective conditions (small surface wetted by emitters surrounded by a very dry soil, and a very high fraction of direct radiation reaching the soil). According to our conditions, we considered $K_{sw} = 1.0$ in spring and after harvest, and $K_{sw} = 1.2$ during summer. Finally, Qe is the fraction of radiation intercepted by the canopies, which was reported for this experiment in López-López et al. (2018). Thus, 1 − Qe represents the fraction of radiation reaching the soil surface. Qe is determined by tree canopy size and GC% (Bonachela et al. 2001).

Measurements of f_w were taken every time irrigation scheduling was modified with the help of a measuring tape. Also, a 50% reduction was applied to the evaporation from emitter-wetted surface in T4, to account for the mulch created by the fallen leaves due to severe water stress (Allen et al. 1998).

For the rest of the soil, Philip (1957) described the E_s process in three stages. After a rainfall event, the soil is completely wet, and E_{SO} is limited by incoming radiation. E_{SO} during Stage I was calculated as described in Bonachela et al. (1999) (Eq. 3). Once accumulated E_{SO} reaches a certain value U (mm), E_{SO} enters a falling rate stage (Stage II), in which it is determined by soil hydraulic properties and time (t) since the end of Stage I. We used Ritchie's model (1972) to calculate E_{SO} at Stage II (Eq. 4). Finally, Philip described a third stage at which E_{SO} reached a steady state at a very low value.

$$E_{SOi} = (1 - f_w) \cdot (\mathrm{Rad} \cdot (1 - \mathrm{Qe}) + \mathrm{Aer}), \tag{3}$$

$$E_{SOii} = (1 - f_w) \cdot \alpha \cdot t^{0.5}. \tag{4}$$

The values of U and α for our soil are 8 and 4 mm·$day^{-0.5}$ (Bonachela et al. 1999), where t is the time (days) since the end of Stage I. According to Ritchie's expression, E_S from our soil reaches $E_{SOiii,}$ after 1 month following wetting. This value was kept until a new rainfall returned soil to Stage I. Unpublished data collected in our conditions suggest that the E value at Stage III (E_{SOiii}) is between 0.3 and 0.5 mm·day^{-1} (FJ Villalobos, personal communication), thus we assumed $E_{SOiii} = 0.4$ mm·day^{-1}. Note that whether we choose 0.3 or 0.5 mm·day^{-1} for Stage III (enduring about 3 months in our conditions), the seasonal E would differ by 18 mm, a small amount considering the value of ETc. Isolated rains in the middle of summer were considered to evaporate directly, without resetting to Stage I and without interrupting the value of *t*.

$$E_S = E_{SW} + E_{SO}. \quad (5)$$

Tree transpiration

T was calculated as

$$T = ET_c - E_S \quad (6)$$

Seasonal ET_C, E_S and *T* values were calculated by adding the partial values corresponding to the periods between two consecutive SWC measurements, from leafing out to leaf fall.

Plant water status

Tree water stress caused by the DI regimes was monitored by measuring midday stem water potential (Ψ, MPa) before and after the onset of DI treatments in early June and before and after resuming irrigation at post-harvest (in mid-August), respectively. Measurements were taken on two covered leaves per tree with a Scholander-type pressure chamber (Model 3005F01, Santa Barbara, CA, USA). Leaves were selected near the trunk or a scaffold-branch and were covered with aluminium foil for at least 30 min before measuring.

Yield and yield components

Harvest took place around the second week of August. All four experimental trees of every plot were manually harvested and mechanically de-hulled. Then, field fruit weight (FW, kg) was measured. A 1–2 kg sample was taken per tree (FW_{SAMPLE}). Almonds in the sample were counted (N_{SAMPLE}) to estimate fruit load as:

$$\text{Fruit load}\,(N/\text{tree}) = FW \cdot N_{SAMPLE}/FW_{SAMPLE}. \quad (7)$$

Afterwards, a subsample of 100 almonds was oven-dried at 70 °C until constant weight and de-shelled. Kernels were weighed to calculate unit kernel weight (g/almond).

Finally, kernel yield, in terms of dry weight per hectare (Y_{DW}, kg/ha) was calculated as:

$$Y_{DW}\,(\text{kg/ha}) = \text{Fruit load} \cdot \text{unit weight(g)} \cdot 238(\text{trees/ha})/1000\,(\text{g/kg}). \quad (8)$$

Yield and yield components were averaged per treatment and subjected to randomized complete block ANOVA and subsequent LSD test.

Water production functions

Three-year-average Y_{DW} was related to the seasonal IR, ET_C, and T of each experimental plot. Best-fit regression analysis was conducted with the software Statistix 10.0.

Water productivity (WP_{ET}), transpiration efficiency (WP_T) and irrigation water marginal productivity (IWMP)

WP_{ET} and WP_T (kg/m^3) were calculated as Y_{DW}/ET_C and Y_{DW}/T, respectively. ANOVA and subsequent LSD test were conducted on seasonal and 3-year-average WP_{ET} and WP_T data. The IWMP is defined as the infinitesimal increments or reductions in yield caused by infinitesimal increments or reductions in irrigation, respectively. An IWMP (kg/m^3) function was obtained as the derivative of the Y_{DW}–IR expression fitted, as in Goldhamer and Fereres (2017).

Results

Evapotranspiration and transpiration

Calculated ET_C, E_S and *T* values are presented in Table 1. ET_C and *T* of T1 increased every year, and were significantly higher than the values of the rest of treatments. There were no ET_C or *T* differences between T2 and T3, which had average ET_C values of 887 and 894 mm (81.5 and 82.2% of T1), and *T* values of 640 and 648 mm (77.0 and 78.1% of T1), respectively. T4 had significant lower ET_C and *T* than the rest of treatments, with an average ET_C of 699 mm and average *T* of 479 mm (64.2 and 57.7% of T1, respectively). ETo and P_{eff} from the automated weather station are summarized in Table 2, from the first to the last SWC measurement dates. Daily values of ET_O and monthly values of P_{eff} are presented in Fig. 1.

The fraction of the total soil surface wetted by the emitters varied with the irrigation treatment. It went from 0.05 in T4 to 0.25, 0.30 and 0.4 in T1 in 2014, 2015 and 2016, respectively. The calculation method is very sensitive to this variable. The time course of GC along the study can be seen in Fig. 2. Average E_S was 263, 247, 246 and 220 mm in T1,

Table 2 Seasonal reference evapotranspiration (ETo) and effective precipitation (P_{eff}), in mm, from 2014 to 2016 and their average

Year	ETo (mm)	P_{eff} (mm)
2014 (10 March–5 Oct)	1036.1	167.7
2015 (9 Feb–8 Nov)	1130.5	284.8
2016 (1 March–9Oct)	1046.0	277.3
Average	1070.9	243.3

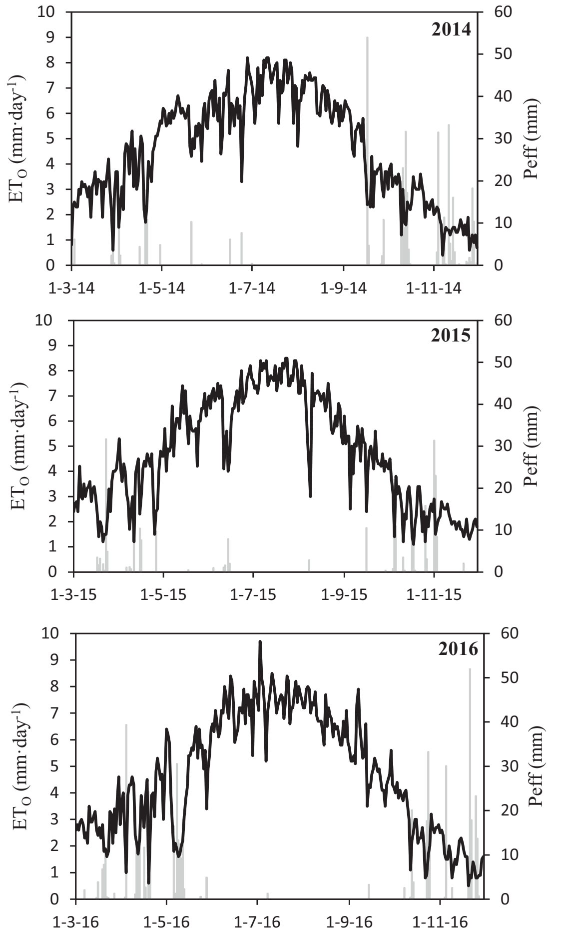

Fig. 1 Daily reference evapotranspiration, ETo (black line) and effective precipitation, P_{eff} (grey bars), both in mm, of the three seasons, 2014–2016, from budburst (early March) to leaf fall (November)

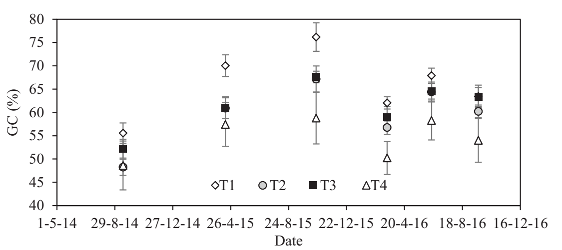

Fig. 2 Time course of ground cover percentage (GC%) along the 3 years of study

T2, T3 and T4, respectively. The depth of E_S from the emitter-wetted area only for T1 was 25, 20 and 94 mm more than that of T4 in 2014, 2015 and 2016, respectively. In terms of E_S for the entire orchard floor, these differences were 15, 20 and 88.5 mm. Figure 3 depicts the average monthly distribution of the two E_S components in the four treatments.

Plant water status

The differential irrigation treatments resulted in different patterns of stem water potential (Ψ) along the season. T1 stayed between − 1.0 and − 1.2 MPa. T2 and T3 had lower Ψ than T1 in the mid-July measurement, − 1.9 and − 2.1 MPa, respectively, and reached − 1.6 and − 2.0 MPa. After harvest, they both had − 1.3 MPa, a similar value to that of T1. Regarding T4, it already had lower Ψ than the other three in mid-June (− 1.4 MPa), reaching a minimum of almost − 3.0 MPa in mid-July. T4 stayed somewhat lower after irrigation resumption, around − 1.7 MPa. Time course of stem Ψ in 2016, presented as an example year, can be seen in Fig. 4.

Yield and yield components

The highest yields were observed in 2014 (2678.2 kg/ha in T1), while 2015 had the lowest yields (2093.1 kg/ha in T1, see Table 3). During 2014 and 2016, the yield of T2 and T3 did not differ significantly from that of T1. However, in 2015, lower nut loads in T2 and T3 led to significantly lower yields than T1, but not significantly different from T4. The more severely stressed treatment (T4) had always lower yields than T1. The interplot coefficients of variation (COV) for yield varied between 0.1% and 23.6% (corresponding to T1 in 2016 and T4 in 2015, respectively), the average value for the 3 years and four treatments being 11.5%. The intraplot COV varied between 0.4 and 39.8% (values of T3 and T4 in 2014), with an overall average of 19.4%.

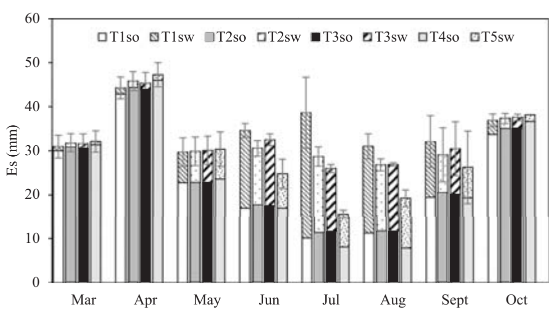

Fig. 3 Average monthly total soil evaporation, E_s (full height of the columns) separated into evaporation from the emitter-wetted zone, E_{sw} (woven part of the column), and evaporation from the rest of the soil, E_{so} (full part of the columns) for the three seasons, 2014–2016, of the four treatments. Vertical bars correspond to standard error of total E_s among years

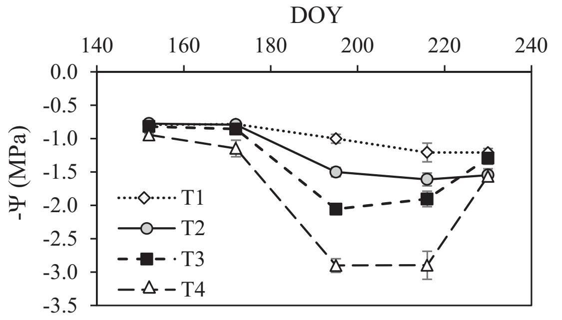

Fig. 4 Time course of stem water potential (-Ψ, MPa) in 2016, taken as an example year. Each point is the average of four treatment replications, and vertical bars are standard error of the means. In each experimental plot, two leaves were measured in all four experimental trees, so each point is an average of 32 leaf measurements. The five presented dates correspond to 1 week before and 1 week after reducing irrigation to RDI treatments, mid-July, and 1 week before and after resuming full irrigation after harvest

Regarding nut loads, T1 and T2 had similar values in 2014, T4 had significantly lower fruit loads and T3 had an intermediate value. In 2015, T1 had higher nut load than the rest of treatments, with no differences between them. In 2016, there were no significant differences among treatments, although T4 trees bore an average of about 1000 almonds less than T1 (a difference of 12%, which was not statistically significant). On average, T1 had higher nut loads than T4 (7830 vs 5933), and T2 and T3 had intermediate values (6823 and 6490, respectively).

Unit kernel weight was significantly reduced by severe stress during kernel-filling stage all the 3 years (1.08 vs 1.34 g, on average for T4 and T1, respectively), while moderate stress only affected it in 2016. On average, there were not significant differences in kernel weight among T1, T2 and T3.

Water production functions

Y_{DW}–IR was adjusted to a quadratic expression: $Y_{DW} = -0.0025 \cdot IR^2 + 4.87 \cdot IR + 243$ ($r^2 = 0.72$, $P = 0.0001$). On the other hand, Y_{DW}–ET_C and Y_{DW}–T were best-fitted by logarithmic expressions: $Y_{DW} = 2220.2 \cdot \ln(ET_C) - 13000$ ($r^2 = 0.78$, $P = 0.0001$) and $Y_{DW} = 1801.3 \cdot \ln(T) - 9574$ ($r^2 = 0.79$, $P = 0.0001$), respectively. Average values for each experimental plot together with the fitted expressions are shown in Fig. 5.

Water productivity (WP_{ET}), transpiration efficiency (WP_T) and irrigation water marginal productivity (IWMP)

WP_{ET} and WP_T averaged 0.23 and 0.32 kg/m^3, respectively, with noticeable variability among the three seasons. Our differential irrigation treatments did not affect significantly WP_{ET} and WP_T in any of the study years (Table 4).

The derivative of the quadratic curve fitted to Y_{DW}–IR is equivalent to the IWMP (kg/m^3) = $-0.00005 \cdot IR$ (m^3/ha) + 0.49. According to this expression, IWMP takes a value of 0.11 kg/m^3 for the average irrigation amount of T1, and values of 0.24, 0.23 and 0.33 kg/m^3 for T2, T3, and T4, respectively. IWMP becomes zero when IR reaches a value of 10,000 m^3/ha.

Table 3 Dry weight kernel yield (kg/ha) and yield components (nut load and unit weight) over the 3-year study (2014–2016) and their average

Yield and yield components	Treat.	Year			Average
		2014	2015	2016	2014–2016
Kernel yield (kg/ha)	T1	2678.2a	2093.1a	2552.1a	2508.4a
	T2	2573.6a	1506.0b	2380.2a	2147.5a
	T3	2414.9ab	1565.7b	2236.0a	2038.2a
	T4	1659.6b	1248.5b	1579.1b	1496.9b
	P value	0.0593	0.0499	0.0006	0.0197
Fruit load (*N*/tree)	T1	7109a	8209a	7804a	7830a
	T2	6929a	5826b	7692a	6823ab
	T3	6283ab	5770b	7959a	6490ab
	T4	4971b	5930b	6870a	5933b
	P value	0.0641	0.0594	0.3576	0.1310
Unit weight (g)	T1	1.55a	1.09ab	1.37a	1.34a
	T2	1.56a	1.10a	1.30a	1.31a
	T3	1.62a	1.13a	1.18b	1.34a
	T4	1.38b	0.88b	0.98c	1.08b
	P value	0.0152	0.0226	0.0005	0.004

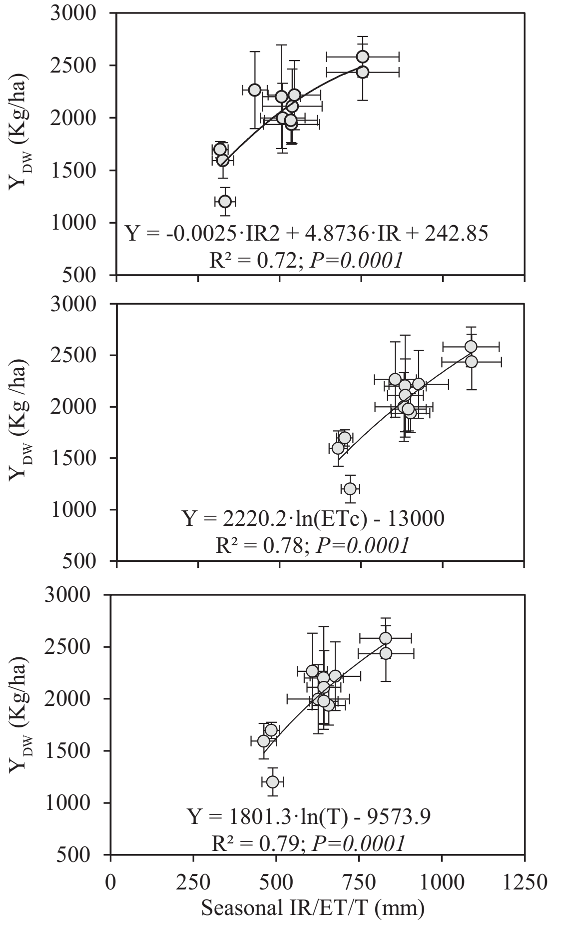

Fig. 5 Average kernel yields expressed as dry weight (Y_{DW}, kg/ha) against seasonal irrigation (IR), crop evapotranspiration (ET_C) and transpiration (*T*). Points are 3-year averages of individual replicates. The best-fit expressions obtained are presented under the corresponding lines. Error bars represent standard error of the means among different years

Discussion

In this 3-year-long study, we determined water production functions not only for IR but also in terms of ET_C and *T*.

The Y_{DW}–IR expression obtained gives $Y_{DW}=243$ kg/ha at no irrigation. Regarding Y_{DW}–ET_C and Y_{DW}–T expressions, yield would be reduced to 0 when ET_C is lower than 349 mm or *T* is below 203 mm.

In Fig. 5, the *x*-axis distance between Y_{DW}–IR and Y_{DW}–ET_C curves indicates that the combined contribution of P_{eff} and ΔSWC was, on average, around 350 mm. This amount is 30% of the ET_C of T1 and 50% of the ET_C of T4. These numbers highlight the importance of considering ET_C instead of IR as the driving variable in conditions of soils with high water-holding capacity or significant in-season rainfall.

Table 4 Water productivity (WP_{ET}) and transpiration efficiency (WP_T) in kg/m^3

	Treat.	Year			Average
		2014	2015	2016	2014–2016
WP_{ET} (kg/m^3)	T1	0.29	0.19	0.21	0.24
	T2	0.33	0.16	0.24	0.25
	T3	0.31	0.16	0.24	0.23
	T4	0.26	0.17	0.22	0.22
	P value	0.3617	0.5983	0.4397	0.1270
WP_T (kg/m^3)	T1	0.39	0.25	0.27	0.31
	T2	0.47	0.23	0.32	0.35
	T3	0.44	0.22	0.32	0.32
	T4	0.39	0.27	0.29	0.32
	P value	0.4211	0.3603	0.4451	0.7070

ANOVA *P* values are shown

Moreover, the model developed by Bonachela et al. (1999, 2001) allowed us to calculate E_S and detract it from ET_C to obtain *T* values (see Table 1). In our study, the frequency of irrigation was maintained even though the IR declined in the deficit treatments. This makes the values of *E* relatively higher as ET_C declines due to lower *T* values. Under deficit irrigation, it would be desirable to decrease irrigation frequency leading to lower *E* rates from the emitter-wetted areas, which represented, on average, 34.3 and 19.6% of total E_S in T1 and T4, respectively. Meanwhile, E_S accounted for 23.6% of ET_C in T1, on average, and around 30.0% in T4. It seems that although T1 had higher E_S from wetted areas due to higher IR, larger canopies compensated slightly by reducing E_S from the rest of the soil in spring and autumn. The difference in E_s between the two treatments, T1 and T4, was more pronounced in 2016, both in terms of *E* from the emitter-wetted areas and for total E_s because fw of T1 was also the greatest (0.4). Other studies which have estimated E_s are reported in Orgaz et al. (2006) in olive trees and Iniesta et al. (2008) in pistachios. In the first one, the Es of a drip-irrigated olive orchard with GC% of 65% and $f_w=0.1$ accounted for 21% of ETc during the irrigation season. Iniesta et al. (2008) reported Es between 35 and 41.3% of ETc of full-irrigated and deficit-irrigated pistachios. These high values correspond to a $f_w=1$ due to the use of sprinklers.

Since E_S depends on irrigation system (sprinklers or drippers), irrigation frequency (daily or otherwise) and soil infiltration rate (affecting the size of the emitter-wetted areas), Y_{DW}–T relations would be more easily transferrable than Y_{DW}–ET_C relations to conditions other than those where they were obtained. Growers and public institutions should afterwards convert the proposed Y_{DW}–T relationship to a specific

Y_{DW}–IR relation according to their own conditions of climate, soil and irrigation system. Nevertheless, more accurate methods for measuring the percentage of soil surface wetted by the emitters would be necessary to get better estimates of E_S, which has proven to be an important component of ET_C in this study. Our T calculations were compared with direct T estimates of sap-flow in López-López et al. (2018), which made us feel confident about our E_S estimates.

Actually, the relationship between Y_{DW} and T varies according to each season particular conditions as well as depending on previous seasons' carry-over effects. Both in Table 3 and Fig. 5 (error bars) we can appreciate the great variability among years. In our orchard, 2013 had a very low harvest due to rainy weather during flowering, so vegetative growth was promoted, and lots of flower buds developed for 2014 season. On the other hand, in 2014 red leaf blotch could not be controlled properly and it caused reduced leaf area and consequently, transpiration. The combination of an exceptionally high number of fruiting positions determined during the previous season and an uncommonly lower T resulted in high WP_{ET} and WP_T values in 2014. By contrast, healthy trees transpired more in 2015 and 2016, and WP decreased. The year 2016 showed an intermediate behaviour in ET_C, T and thus WP_{ET} and WP_T.

Regarding yield and its components (Table 3), T4 had always a lower kernel yield than T1, while the response of T2 and T3 depended on the season. The yield found here for the well-irrigated treatment (2508 kg/ha on average) is higher than those reported in the rest of experiments conducted on hard-shell almond varieties (Romero et al. 2004a; Girona et al. 2005; García-Tejero et al. 2011; Egea et al. 2013; Mousavi et al. 2015), while it is still lower than those of soft-shell almonds (Goldhamer et al. 2006; Stevens et al. 2012; Phogat et al. 2013; Goldhamer and Fereres 2017; Naor et al. 2017). The explanation of the differences among yields of hard-shell varieties may be related to not meeting the full water requirements in some of the experiments, but there is insufficient information in most of the reports to make a detailed assessment of ETc and IR. The yield difference between hard- and soft-shell cultivars may be related to differences in fruit load. Some examples of fruit load values reported in soft-shelled varieties averaged 9400 (Goldhamer et al. 2006); 14,700 nuts/tree (Goldhamer and Fereres 2017) and 11,600 (Naor et al. 2017), against 7800 nuts/tree in T1 here; 5400 (Egea et al. 2013) and around 6000 (Girona et al. 2005).

T1 had also the highest fruit load, T4 the lowest one and T2 and T3 were similar and had intermediate values. However, reductions in yield were mainly due to smaller nuts, in line with Egea et al. (2010) and Goldhamer and Fereres (2017). Kernel unit weight was significantly affected by severe stress at the kernel-filling stage (T4 trees reached a SWP of almost − 3.0 MPa before harvest) in the three study seasons: on average, 1.08 g/kernel in T4 against 1.34 g/kernel in T1. Similar results were reported by Hutmacher et al. (1994) and Mousavi et al. (2015). T3 had statistically significant smaller nuts than T2 in 2016. This was the only noticeable difference we found between applying a regulated or a sustained deficit irrigation strategy. Therefore, one should be careful when applying stress during the kernel-filling stage. Our T2 did not present a lower nut load as a result of water deficit after harvest as it would have been expected (Goldhamer and Viveros 2000; Goldhamer et al. 2006), but we believe stress was not sufficiently severe to provoke this effect (Fig. 4): the RDI treatment with post-harvest stress and the lowest irrigation amount reached predawn leaf water potential values of − 3.0 MPa, and the most severe SDI treatment reached predawn leaf water potential of − 1.6 MPa (Goldhamer et al. 2006). In fact, ET_O usually decreases in late-August, and storms become frequent in the location where our study was conducted.

Goldhamer and Fereres (2017) applied all their DI treatments biased towards the kernel-filling stage to avoid the known effects of post-harvest stress on kernel number (Goldhamer and Viveros 2000), and they found a tight relation between applied water and unit kernel weight, as Naor et al. (2017) confirmed recently.

The derivative of Y_{DW}–IR function, IWMP, has a constant negative slope. This indicates that a given reduction in irrigation amount causes a proportionally larger drop in yield as IR decreases from the amount required for maximum transpiration. A similar behaviour was found in olive trees (Moriana et al. 2003). One can look at this from two points of view: on the one hand, starting from a fully irrigated orchard, DI could be applied to reduce irrigation amount without large impacts on yield. On the other hand, starting from a rainfed crop, small increases in water application will cause proportionally larger increases in yield. By contrast, the WP_T of a given year was largely unaffected by the irrigation regime, supporting the conservative behaviour observed in the relation between T and crop productivity (Steduto et al. 2007). Nevertheless, WP_T values were found to differ from year to year which must be related to variations in climatic conditions among seasons (occurring at flowering and pollination) determining different levels of fruit load, as well as to the physiological responses of the different treatments in reaction to stress (Table 4).

Finally, given that a commercial plantation has a life cycle of 20 years or more, the conclusions of this 3-year study must be supported by longer term observations that will document the carry-over effects of persistent water stress, where both acclimation and the depletion of carbohydrate reserves would play a role in determining the response of almond orchards to deficit irrigation throughout the life of the orchard.

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Compliance with ethical standards

Conflict of interest Authors declare no conflicts of interest.

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