Agricultural Water Management 97 (2010) 171–181

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Agronomic response and water productivity of almond trees under contrasted deficit irrigation regimes

Gregorio Egea [a], Pedro A. Nortes [a], María M. González-Real [a], Alain Baille [a,*], Rafael Domingo [b,c]

[a] Universidad Politécnica de Cartagena, Escuela Técnica Superior de Ingenieros Agrónomos, Área de Ingeniería Agroforestal, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain
[b] Universidad Politécnica de Cartagena, Escuela Técnica Superior de Ingenieros Agrónomos, Departamento de Producción Vegetal, Paseo Alfonso XIII, 48, 30203 Cartagena, Spain
[c] Unidad Asociada al CSIC de Horticultura Sostenible en Zonas Áridas (UPCT-CEBAS). 30203 Cartagena, Spain

ARTICLE INFO

Article history:
Received 16 April 2009
Accepted 7 September 2009
Available online 7 October 2009

Keywords:
Prunus dulcis
Regulated deficit irrigation
Partial root-zone drying
Water stress
Yield
Vegetative growth

ABSTRACT

We investigated the long-term effects of different deficit irrigation (DI) options on tree growth, shoot and leaf attributes, yield determinants and water productivity of almond trees (*Prunus dulcis*, cv. Marta) grown in a semiarid climate in SE Spain. Three partial root-zone drying (PRD) irrigation treatments encompassing a wide range of water restriction (30%, 50% and 70% of full crop requirements, ET_c) and a regulated deficit irrigation treatment (RDI, at 50% ET_c during kernel-filling) were compared over three consecutive growth seasons (2004–2006) to full irrigation (FI). The results showed that all deficit irrigation treatments have a negative impact on trunk growth parameters. The magnitude of the reduction in trunk growth rate was strongly correlated through a linear relationship with the annual volume of water applied (WA) per tree. Similarly, a significant relationship was found between WA and the increase in crown volume. In contrast, leaf-related attributes and some yield-related parameters (e.g., kernel fraction) were not significantly affected by the irrigation treatments. Except in PRD_{70}, individual kernel weight was significantly reduced in the deficit irrigated treatments. Kernel yield, expressed in percent of the maximum yield observed in the FI treatment, showed a linear decrease with decreasing WA and a slope of 0.43, which implies that a 1% decrease in water application would lead to a reduction of 0.43% in yield. Water productivity increased drastically with the reduction of water application, reaching 123% in the case of PRD_{30}. Overall, our results demonstrate the prevalence of direct and strong links between the intensity of the water restriction under PRD – i.e., the total water supply during the growing season – and the main parameters related to tree growth, yield and water productivity. Noteworthy, the treatments that received similar annual water volumes under contrasted deficit irrigation strategies (i.e., PRD_{70} and RDI) presented a similar tree performance.

1. Introduction

As drought resistant species (Torrecillas et al., 1996), almonds play an important role in fighting desertification (Rouhi et al., 2007) when cultivated in areas like the Mediterranean, where there is a shortage of water, scarce rainfall and high temperatures. However, the sustainability of almond orchards in dry-lands is compromised in years when winter and spring rainfalls do not occur, and it comes with the cost of causing low crop productivity (Girona and Marsal, 1995; Torrecillas et al., 1989). In arid and semiarid countries, various types of deficit irrigation (DI) strategies are practiced to increase crop productivity (Fereres and Soriano, 2007). Generally, DI is termed 'uncontrolled' when the water supply is constrained by the availability and amount of water delivered for irrigation at the farm. This situation frequently occurs in most Mediterranean regions because water agencies distribute water to farms based on random and unpredictable factors, such as droughts or political decision made at a regional or national level. Whenever irrigation water could be supplied in a rather continuous way to crops (e.g., using water stored in farm or collective irrigation reservoirs), controlled DI strategies could be applied, such as regulated deficit irrigation (RDI, Chalmers et al., 1981), sustained deficit irrigation (SDI, Goldhamer et al., 1987; Girona et al., 2005; Moriana et al., 2003) or partial root-zone drying (PRD, Dry et al., 1996; Dry and Loveys, 1999). These strategies are known to substantially reduce tree water consumption without inducing a significant negative impact on crop productivity (Fereres and Soriano, 2007).

It is well established that almond is a species that responds positively to DI practices, as reported in several experimental field studies dealing with the evaluation and management of RDI practices (Goldhamer and Viveros, 2000; Esparza et al., 2001a,b;

* Corresponding author. Tel.: +34 968 325658; fax: +34 968 327031.
E-mail address: alain.baille@upct.es (A. Baille).

0378-3774/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2009.09.006

Girona et al., 2005; Romero and Botía, 2006). A large body of work dealing with the application of RDI strategy to almonds in low water sensitive periods (i.e., dry weight accumulation in the kernel), has proved that this method has emerged as a possible way to increase water savings without excessively reducing kernel yield (Goldhamer, 1996; Romero et al., 2004; Girona et al., 2005).

In the last few years, the PRD strategy has raised interest among scientists because it allows the control of vegetative growth and leaf transpiration with no or subtle impact on fruit yield or quality (Dry et al., 1996; Dry and Loveys, 1999; de Souza et al., 2003; Wahbi et al., 2005; Fernández et al., 2006; De la Hera et al., 2007; Abrisqueta et al., 2008; Intrigliolo and Castel, 2009). Exposure of the root system to alternate drying and wetting cycles promotes the generation of the plant hormone abscisic acid (ABA), which, in combination with hydraulic signals (Tardieu and Davies, 1992), controls the leaf stomatal conductance and improves the transpirational water use efficiency (Dodd et al., 2006). The signal is triggered by the roots, which sense the water status of the soil (Dodd et al., 2008). However, to the best of our knowledge, no studies that analyse the long-term impact of PRD on the agronomic response and water productivity of almond trees are presently available.

This paper deals with the characterisation and analysis during three growing seasons of almond trees' seasonal patterns of growth and yield determinants when subjected to two different types of deficit irrigation strategy (RDI, PRD) and to three levels of water applied under PRD. It should be stressed that our goal mainly focuses on the agronomic assessment of different DI management options, without entering in a detailed comparative study of the respective responses of almond tree to PRD and RDI. The main objectives of the study are (i) to confirm if water productivity of almond trees could be described by a unique relationship linking yield reduction to soil water deficit independently of the irrigation strategy (RDI, PRD) applied and (ii) to provide some elements allowing the assessment of the agronomic response of almond trees to PRD under contrasted soil water deficits.

2. Materials and methods

2.1. Plants and experimental conditions

The experiment was conducted at the Agricultural Experimental Station of the Technical University of Cartagena (37°35′N, 0°59′W) in an experimental orchard of 4-year-old almond trees (*Prunus dulcis* (Mill.) D.A. Webb cv Marta) grafted on 'Mayor' rootstock and planted at a spacing of 6 m × 7 m in December 1999. The period of observation and measurement reported in this study was from November 2003 to December 2006, albeit the irrigation regimes detailed below were started at the beginning of the 2003 growing season.

The soil was a deep silt–clay–loam with low available potassium and organic matter content and high phosphorous content. The bulk density varied within the range 1.3–1.55 g cm^{-3}, and the soil's water-holding capacity was about 0.18 m m^{-1}. The electrical conductivity (EC) of the irrigation water was 1.2 dS m^{-1}, with a content of chloride and sodium of 4.6 and of 5.4 meq L^{-1}, respectively.

The trees were fertilised with 35–35–57 kg ha^{-1} $year^{-1}$ of N, P_2O_5 and K_2O and managed following current commercial practices (a routine pesticide program was maintained, pruning was applied manually in December, and no weeds were allowed to grow within the orchard).

2.2. Irrigation treatments

Five irrigation treatments were applied in the experimental plots: full irrigation (FI), regulated deficit irrigation (RDI), and three treatments under partial root-zone drying (PRD) following a randomised block statistical design with three blocks, one replicate per block and twelve trees per replicate. A single pipe per row with six 4 L h^{-1} drippers per tree was used for FI and RDI irrigation. In PRD treatments, two laterals per tree row were used, each equipped with six 4 L h^{-1} drippers per tree. The drippers of each lateral were at a different side of the tree (east and west) in order to allow independent water supply on each side of the root system. In FI, the trees were managed through full root-zone irrigation to satisfy crop water requirements (ET_c) throughout the whole growing season. ET_c was determined by means of six drainage lysimeters located in the FI plots. An extra amount of water equivalent to 20% of ET_c was applied to guarantee well-watered conditions. In RDI, the trees were also irrigated through full root-zone irrigation at 50% ET_c during kernel-filling (stage IV) and at 100% ET_c throughout the remainder of the growth period (Girona et al., 2005). In PRD, the irrigation was supplied at 70%, 50% and 30% ET_c (PRD_{70}, PRD_{50} and PRD_{30}, respectively) during the whole growth season, as usually practiced in other fruit tree species (Wahbi et al., 2005). In all the PRD treatments, only one side of the row received water while the other was left dry. Assuming that the physiological benefits of PRD are likely to disappear at completion of the soil drying process (Dry et al., 2000), water supply was switched between sides of the PRD treatments on a variable time basis (6–9 days) once the soil drying process was about finishing. Volumetric soil water content (θ_v) was measured from 0.1 to 1 m depth every 0.1 m with an *in situ* calibrated frequency domain reflectometry (FDR) probe (Diviner 2000®, Sentek Pty. Ltd., South Australia). More details on soil water status and its seasonal dynamics in the five irrigation treatments can be found in Egea et al. (2009).

2.3. Tree water status

Predawn leaf water potential (Ψ_{pd}) was monitored fortnightly with a pressure chamber (Model 3000, Soil Moisture Equipment, Santa Barbara, CA) on nine leaves per irrigation treatment during 2004 and 2005 growing seasons. Measurements of Ψ_{pd} were carried out before dawn on mature leaves taken from the middle third of the branches.

2.4. Tree growth pattern

Tree growth measurements were carried out during the experimental period to evaluate the influence of the irrigation treatments on plant vegetative behaviour. Trunk circumference and diameter (TD) were measured by tape-measure at the end of each year during winter dormancy on ten trees per replicate ($n = 30$). The absolute trunk growth rates (TGR, cm $year^{-1}$) were derived from these data. In addition, six trees per treatment were equipped with linear variable displacement transducers (LVDT; Solartron Metrology, Bognor Regis, UK, model DF ± 2.5 mm, precision ± 10 μm) for continuous trunk growth monitoring. LVDT were installed on the trunks' northern side at 40 cm above ground and mounted on holders built of aluminium and invar (alloy of 64% Fe and 35% Ni). Measurements were taken every 30 s, and four data loggers (Mod. MicroIsis®, Sistemes Electronics-Progrés, S.A., Spain) were programmed to record 10-min means.

Tree canopy height and diameters (across and within rows) were measured annually once shoot growth had ceased (late in the season) on four trees per replicate ($n = 12$). Tree crown volume (V_c) was calculated according to Hutchinson (1978) as $V_c = (\text{width}^2 \times \text{height})/2$. At the beginning of the 2004 and 2005 growing seasons, twelve 1-year-old branches per treatment (four per replicate) were selected to monitor basal branch diameter and the growth of new shoots. Measurements were conducted every 7–10