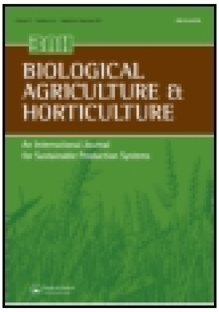

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Yield and water productivity of peach trees under continuous deficit irrigation and high evaporative demand

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Long-term effects of deficit irrigation on yield and water productivity of peach trees (*Prunus persica* L., cv. Carnival) grown in a semi-arid climate in northern Tunisia (36°41'N, 10°15'E) were investigated. Continuous deficit irrigation (Di I-II-III) was compared with the grower's irrigation programme (Control). The effects of Di I-II-III on yield and fruit quality were analysed. The benefit of deficit irrigation strategy in terms of water saving and agricultural water productivity (W_p) were estimated. Different relationships were investigated between yield, fruit quality, and W_p, and irrigation and total water supply. In reference to the high water needs of late cultivar Carnival for irrigation, Di I-II-III led to an important water saving (33%) with a yield reduction of 14%. Yield and fruit quality seemed to be related to watering regimes. Fruit dry matter (DM) decreased linearly with irrigation water supply for both Control and Di I-II-III. Unlike yield, Di I-II-III improved the dry weight of fruit. Consequently, W_p was enhanced to reach a mean value of 0.62 kg DM m^{-3} in contrast to 0.54 kg DM m^{-3} for the Control. Continuous deficit irrigation is a valuable tool for improving W_p in peach orchards, achieving significant water saving and maintaining sustainable production levels

Keywords: deficit irrigation; *Prunus persica*; water productivity; water saving; yield

Introduction

The growing water scarcity and poor management of the available water resources are the major threats to sustainable development of agriculture with competing demands from domestic and industrial sectors (Katerji et al. 2008). With less water available, agriculture faces the challenge to produce more food with less water by increasing water use efficiency or crop water productivity.

Irrigated crops in semi-arid regions of Mornag, northern Tunisia, consist mainly of fruit crops such as peach, apple, and pear. This production area has an average rainfall of 450 mm $year^{-1}$ with a rainy period concentrated from autumn to early spring and high evaporative demand (ET_o) of 1233 mm $year^{-1}$ (Ben Mechlia et al. 2002). Consequently, under high evaporative demand and low and irregular precipitation, irrigation becomes necessary for commercial orchards. Peach is considered a strategic fruit species in Tunisia. An important increase of the irrigated peach crop area has been recorded with a large extended ripening season from April to September. Peach cultivars were characterized by an important need of water, especially for late season ones (Ben Mechlia et al. 2002).

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These conditions make it imperative to develop new strategies to achieve an efficient water use and greater water saving in irrigated agriculture.

Effective use management is the only way to save water for the increasing irrigated agriculture (Mitchell et al. 1986; Pérez-Pérez et al. 2010). Applying deficit irrigation is considered an option and practice that can be adopted in fruit tree orchards to control vegetative growth and achieve water saving (Chalmers et al. 1981; Girona et al. 2003). Deficit irrigation has been used with success around the world for species such as peach and pear (Mitchell and Chalmers 1982; Mitchell et al. 1986). In Mediterranean regions, deficit irrigation strategies have been employed to save water and to improve the water use efficiency of various crops (Naor 2006; Egea et al. 2010; Garcia-Tejero et al. 2011). Under semi-arid conditions of Tunisia, irrigation deprivation at different stages of fruit growth of a late cultivar of peach was investigated in field experiments (Ghrab et al. 1998; Ben Mechlia et al. 2000, 2002). The use of deficit irrigation as a strategy in the irrigation of fruit trees under semi-arid conditions in Tunisia seems to be a relevant choice (Ben Mechlia and Masmoudi 2003).

Deficit irrigation has been widely studied but the profitability of these strategies in commercial orchards is largely unknown (Pérez-Pérez et al. 2010). The beneficial effect of deficit irrigation may be better understood in terms of the productivity of applied water. The meaning of water use efficiency (WUE) or water productivity (W_P) depends on the value or benefit derived from the use of water (Pereira et al. 2002; Zwart and Bastiaanssen 2004; Katerji et al. 2008). Many expressions have been proposed in relation to WUE and crop water productivity from an agricultural perspective (Garcia-Tejero et al. 2011). WUE is defined as the ratio between the amount of biomass production and water consumption by the crop (Turner 2004; Hsiao et al. 2007). An agricultural WUE is related to the ratio between crop yield and total water applied (irrigation + rain) and the financial WUE concept relates a profit to investment (Egea et al. 2010; Pérez-Pérez et al. 2010; Garcia-Tejero et al. 2011).

Water use efficiency is considered a critical factor in the determination of adaptation and productivity of crops in water-limited areas. It can be altered by water regimes, and deficit irrigation strategies are known to reduce tree water consumption without harmful impact on crop productivity (Fereres and Soriano 2007). These irrigation strategies seem to be a relevant choice for water saving in Mediterranean regions. This paper investigates the potential long-term effects of continuous deficit irrigation on water saving and productivity of peach tree orchards. It assesses the yield response and evaluates the water productivity of peach as harvested yield/total water supply during seven consecutive years under the semi-arid Mediterranean climate of Tunisia.

Material and methods

Plant material and experimental field

This study was conducted in a 2 ha commercial orchard of four-year old peach trees (*Prunus persica* L., cv. Carnival) grafted on GF677 rootstock, located in the region of Mornag northern Tunisia (36°41'N, 10°15'E). Trees were planted at a spacing of 3 × 6 m and drip irrigated. The experiment was started at the beginning of the 1996 growing season. The survey was carried out during 1996–2002 on a late cultivar of peach, Carnival, with flowering and fruit maturity dates observed in mid-March and the beginning of August, respectively. Pest control and fertilization practices were those commonly used by the peach growers, and no weeds were allowed to develop within the orchard.

Irrigation treatments

Three irrigation treatments were investigated with reference to the conventional irrigation programme applied by the farmer (Control): (i) water restriction during stages I and II of fruit growth (Di I-II), (ii) water restriction during stage III (Di III), and (iii) water restriction during all stages of fruit growth (Di I-II-III). Restriction of irrigation water was about 33% of the Control. Tree water status and yield were measured for all treatments during 1996–1998, whereas only the Control and the treatment Di I-II-III were applied during 1999–2001 (Ghrab et al. 1998; Sahli et al. 1999; Ben Mechlia et al. 2000, 2002). In this paper, the two extreme treatments, that is, the most watered (Control) and the least watered (Di I-II-III), are mainly considered. Irrigation reduction of 33% was achieved by replacing two of the three drippers of 4 l h^{-1}, placed under each tree, with ones giving 2 l h^{-1}. As a consequence, trees under continuous deficit irrigation received 8 l h^{-1}, instead of 12 l h^{-1} for the Control.

Climatic demand and water supply

Daily values of air temperature, relative humidity, and wind speed were obtained from the manual weather station of National Agronomic Institute of Tunisia located 15 km from the experimental orchard. The reference evapotranspiration (ET_o) was calculated from the daily climatic data according to the Penman-Monteith method (Allen et al. 1998). Precipitation (P) was recorded in the experimental field and irrigation water supplied (I) was monitored daily. These data were used to determine watering conditions during the four tree growth stages: initial, development, mid-season, and late season (Allen et al. 1998) by a coefficient K_{supply} defined as:

$K_{supply} = (I + P) / ET_o$ (Ben Mechlia et al. 2000)

Under standard conditions, crop evapotranspiration (ET_c) was determined by the single crop coefficient (K_c) method (Allen et al. 1998) and based on observed duration of tree growth stages: initial, development, mid-season, and late season. Phenological stages and vegetative and fruit growth were used to identify crop growth stages over the experimental period. Crop coefficient K_c values of 0.5, 0.9, and 0.65 were adopted by Allen et al. (1998) for initial, mid-season, and late season, respectively.

Yield and fruit dry matter

Individual yield per tree was determined annually in five trees per treatment during the period of 1996–2002. Fruits were harvested at commercial maturity. Thirty fruits per treatment, six fruits per tree, were sampled at mid-harvest and used to determine fruit dry matter. Fresh weight (FW) was determined and then fruits were dried at 75°C until a constant dry weight (DW) was achieved. The percentage of fruit dry matter was calculated as %DM = (DW/FW)*100.

Water saving and water productivity

For comparison of the impact of deficit irrigation strategies on water saving and water productivity, taking into account the total water applied, an agricultural or a farmer water productivity (W_P) term was considered. The evaluation of the W_P was based on the ratio between dry matter crop yield and the total water applied:

W_P (kg DM m^{-3}) = (fruit yield * %DM) / (I + P)

Statistical analysis

Data were subjected to analysis using a one-way analysis of variance with the SPSS statistical package, using Duncan's test for mean separations ($p < 0.05$).

Results and discussion

Watering conditions

The experimental site was characterized by a high climatic demand (ET_o) with an annual average of 1246 mm (Table 1). Annual precipitation was 468 mm with important yearly variation ranging between 306 and 685 mm. The greatest rainfall occurred during the autumn and winter seasons. The grower's conventional irrigation programme supplied between 533 and 880 mm. The late cultivar Carnival needs a water supply by irrigation of an average of 727 mm (Table 1). Continuous deficit irrigation (Di I-II-III) permitted significant water saving of 33%, which computed an annual average of saved water of 242 mm over seven years of study. This is considered to be a good irrigation practice known as regulated deficit irrigation (RDI), which has been successfully applied on prune and peach (Shackel et al. 2000; Girona et al. 2003).

The farmer irrigation management is reported at the growth stages defined by Allen et al. (1998). For each crop growth stage, watering conditions were scaled using K_{supply} as the ratio between the total water supply and ET_o. Average values of K_{supply} were 0.98, 0.78, 0.98, and 1.11 for initial, development, mid-season, and late-season growth stages, respectively, under the grower's conventional irrigation programme considered as the Control (Table 2). Continuous deficit irrigation (Di I-II-III) reduced the irrigation water supply by 33% and consequently K_{supply} values were 0.87, 0.57, 0.67, and 1.01 over the four crop growth stages.

Under standard conditions, cultural coefficient K_c considered for peach was 0.5, 0.9, and 0.65 for initial, mid-season, and late-season stages, respectively (Allen et al. 1998). The higher values of K_{supply} in comparison to K_c for initial and late-season growth stages can be explained by the higher precipitation and reduced ET_o. Irrigation scheduling during development and mid-season stages reflected the approximate increased water requirements of peach trees. As regards to K_c values, continuous deficit irrigation allowed a reduction of irrigation water requirements mainly in the development and mid-season growth stages.

Table 1. Annual applied water for each irrigation treatment, annual precipitation, and reference evapotranspiration (ET_o) at the commercial orchard during the seven-year period, 1996–2002.

	Water applied (mm)				
	Control	Di I-II-II	Water saving (mm)	Precipitation (mm)	ET_o (mm)
1996	786	524	262	685	1207
1997	686	457	229	593	1292
1998	749	499	250	306	1387
1999	721	480	241	631	1125
2000	533	356	177	450	1212
2001	733	488	245	378	1287
2002	880	587	293	306	1211
Mean	727	485	242	468	1246
Reduction (%)	0	33			

Note: ET_o = reference evapotranspiration; Di I-II-III = continuous deficit irrigation.

Table 2. Mean values of ET_o, precipitation, irrigation, and K_{supply} at different crop growth stages during the seven-year monitoring period, 1996–2002.

Crop growth stage	ET_o (mm)	Precipitations (mm)	Irrigation Control	(mm) Di I-II-III	K_{supply} Control	Di I-II-III
Initial	131.5	82.1	42.9	28.6	0.98	0.87
Development	374.1	68.5	221.0	147.3	0.78	0.58
Mid-season	411.9	12.2	388.3	258.9	0.98	0.67
Late-season	246.3	194.4	73.5	49.0	1.11	1.01

Note: ET_o = reference evapotranspiration; K_{supply} = ratios between total water supplied and reference evapotranspiration [(I + P) / ET_o]; Di I-II-III = continuous deficit irrigation.

Yield and fruit dry matter

In previous research, the response of peach trees to deficit irrigation clearly showed that fruit yield and fruit dry matter were greater under continuous irrigation restriction than with restriction during only stage I-II or stage III (Ghrab et al. 1998; Sahli et al. 1999; Ben Mechlia et al. 2000, 2002), which agreed with earlier work (Chalmers et al. 1981; Mitchell and Chalmers 1982). With deficit irrigation strategies, water stress tolerated by the crop depends mainly on the crop phenology, and the different effects are closely related to the timing, duration, crop physiological status, and the stress endured by the crop (Chalmers et al. 1981; Johnson et al. 1992; Ghrab et al. 1998; Johnson and Handley 2000). Fruit trees can benefit from moderate water stress during the post-harvest period for early-maturing cultivars (Larson et al. 1988; Johnson et al. 1992; Johnson and Handley 2000) and during the lag phase (stage II) of peach fruit growth for late ripening cultivars (Chalmers et al. 1981). It has been hypothesized that water stress imposed during an early stage of stone fruit growth had a much greater effect on reducing vegetative growth than reproductive growth (Chalmers et al. 1981, 1984; Mitchell and Chalmers 1982). However, continuous deficit irrigation gave the highest yield of the three treatments with water restriction (Ben Mechlia et al. 2000, 2002). This could be explained by better trend of K_{supply}, which increases steadily as the tree requirements increase (Ben Mechlia et al. 2000). As a consequence, the long-term effects of continuous deficit irrigation were investigated for the period of 1999–2002 and variable fruit yields were obtained (Table 3). The highest overall yield was obtained for the Control and ranged between 48 and 109 kg tree^{-1}. Continuous deficit irrigation treatment (Di I-II-III) gave a significantly lower yield in five of the seven years, which ranged between 35 and 103 kg tree^{-1}.

Table 3. Fruit yield and fruit dry matter of peach trees under the grower's conventional irrigation programme (Control) and continuous deficit irrigation (Di I-II-III).

	1996	1997	1998	1999	2000	2001	2002	Average
Yield (kg tree^{-1})								
Control	109^a	81^a	64^a	109^a	74^a	48^a	80^a	82
Di I-II-III	99^b	78^a	53^b	103^a	66^b	35^b	68^b	73
Fruit dry matter (%)								
Control	13.0^b	15.3^b	14.5^b	15.6^a	16.7^b	14.3^a	11.8^b	14.5
Di I-II-III	14.0^a	16.1^a	15.7^a	15.0^b	17.7^a	14.7^a	13.6^a	15.3

Note: Di I-II-III = continuous deficit irrigation. Values with different letters (^{a,b}) within columns are significantly different according to Duncan's test at $p < 0.05$.

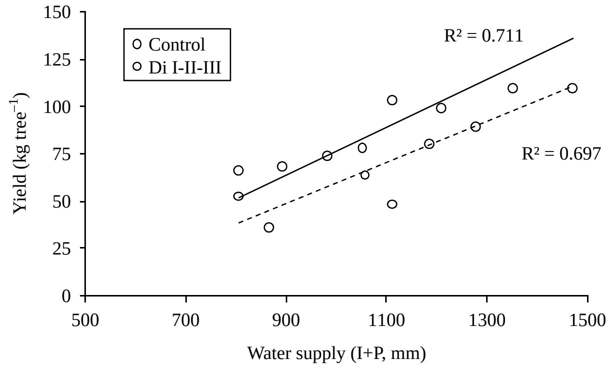

Figure 1. Relationships between total water supply (I + P, mm) and fruit yield under the conventional irrigation programme (Control) and continuous deficit irrigation (Di I-II-III).

The yearly variations seem to be mostly linked to climatic conditions and to a changing tree load. The lower yields obtained in 1998 and 2001 were, in part explained, by low chilling accumulation and severe winter pruning. Insufficient winter chill severely reduces yield and fruit quality of fruit trees (Campoy et al. 2012; Luedeling et al. 2009). Furthermore, water supply had an impact on the total yield related to precipitation, with1998 and 2001 having the lowest rainfall. The relationship between total water applied and fruit yield showed that the yield response was strongly influenced by the irrigation management (Figure 1). For both irrigation treatments (Control and Di II-I-III), a positive correlation between yield and total water supply was obtained. However, for similar water amounts, deficit irrigation treatment gave higher fruit yield than the conventional irrigation programme (Control).

Continuous deficit irrigation treatment (Di I-II-III) permitted significant improvement of fruit quality. A significant increase of fruit dry matter percentage was achieved in five of the seven years (Table 3). Mean values were 14.5 and 15.3% for the Control and continuous deficit irrigation treatment (Di I-II-III), respectively, over seven years of study. Fruit quality seemed to be closely related to watering regimes (Figure 2). Fruit dry matter decreased linearly with irrigation water supply for both Control and Di I-II-III. Unlike yield, continuous deficit irrigation (Di I-II-III) improved the dry weight of fruit over the

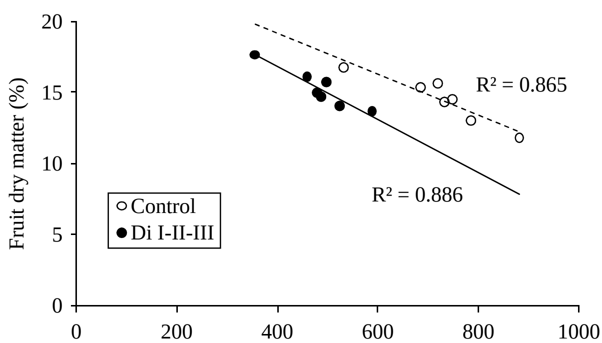

Figure 2. Relationships between irrigation (mm) and fruit dry matter measured over seven years for the conventional irrigation programme (Control) and continuous deficit irrigation (Di I-II-III).

seven years of study, confirming previous results (Ghrab et al. 1998; Ben Mechlia et al. 2002). However, it has been shown that fruit dry matter accumulation was more greatly affected by water stress during the third stage (Bertman and DeJong 1996) and leads to a reduction of yield and fruit size (Chalmers et al. 1981; Ben Mechlia et al. 2002). A typical seasonal pattern of fruit growth presented the highest accumulation of dry matter (50%) during stage III (Girona et al. 2004). Continuous irrigation restriction seems to induce adaptation of trees to water deficit.

Water productivity

Agricultural water productivity (W_P) was considered as fruit dry matter produced per m^3 of total water supply (I + P). During the first three years, W_P was computed for all the deficit irrigation strategies (Table 4). The results showed that during the first three years, continuous deficit irrigation Di I-II-III gave W_P significantly higher than all other irrigation regimes. W_P was significantly lower than with the Control treatment for Di III in 1996 and 1998 and for Di I-II in 1997. As previously reported, Di I-II-III gave the second highest yield after the Control and had a higher yield than Di III and Di I-II while receiving less water (Ben Mechlia et al. 2002).

The long-term effects of the continuous deficit irrigation were evaluated. The grower's conventional irrigation programme (Control) gave a W_P between 0.35 and 0.70 kg DM m^{-3}. With continuous deficit irrigation (Di I-II-III), W_P was significantly improved except in 2000 and 2002 (Table 4). It varied from 0.34 to 0.80 kg DM m^{-3}. Inter-annual variation of W_P was related to irregularity of precipitation and irrigation water supply and high fluctuations of fruit yield. The lowest W_P values reached in 2001 for both the Control and Di I-II-III were the result of low yields achieved as a consequence of low chill accumulation and precipitations and high ET_o.

Agricultural water productivity (W_P) was strongly influenced by the irrigation water supply. It increased with the reduction of water application (Figure 3). Similar trends of W_P with irrigation water supply were observed for the Control and Di I-II-III. Similarly, Egea et al. (2010) found that water productivity of almond trees increased drastically with the reduction of water application. However, Garcia-Tejero et al. (2011) indicated that agricultural water use efficiency (WUE_{agr}) and financial water use efficiency (WUE_f) were more strongly

Table 4. Agricultural water productivity (W_p) of different deficit irrigation strategies for the late cultivar of peach Carnival during the period 1996–2002.

	W_p (kg DM m^{-3})			
	Control	Di III	Di I-II	Di I-II-III
1996	0.54^b	0.49^c	0.51^{bc}	0.63^a
1997	0.59^b	0.59^{bc}	0.52^c	0.66^a
1998	0.49^b	0.40^c	0.44^{bc}	0.57^a
1999	0.70^a	–	–	0.77^a
2000	0.70^b	–	–	0.80^a
2001	0.35^a	–	–	0.34^a
2002	0.44^b	–	–	0.58^a
Average	0.54	0.49	0.49	0.62

Note: W_p = agricultural water productivity as the ratio between dry matter crop yield and total water applied [(fruit yield * % DM) / (I + P)]; Di III = water restriction during stage III of fruit growth; Di I-II = water restriction during stages I and II of fruit growth; Di I-II-III = continuous deficit irrigation. Values with different letters within rows are significantly different according to Duncan's test at $p < 0.05$.

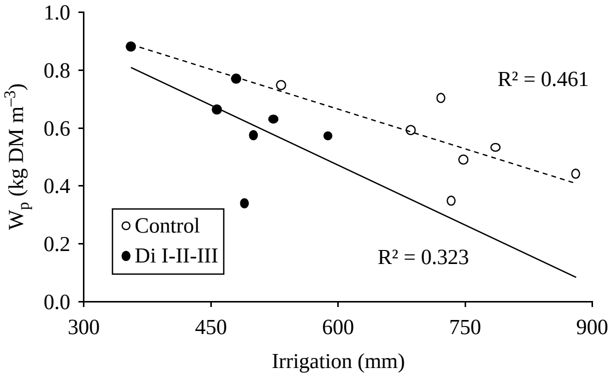

Figure 3. Relationships between irrigation (mm) and agricultural water productivity (W_p) for the grower's conventional irrigation programme (Control) and continuous deficit irrigation (Di I-II-III) over seven years of study, 1996–2002.

affected by a deficit irrigation strategy than by the total water applied. Thus, the amount of irrigation water would have importance but other variables, such as the irrigation strategy, would decidedly influence prudent water management in semi-arid areas.

Assessment of the effects of deficit irrigation strategies based exclusively on yield and water saving is difficult because the crop response depends not only on irrigation but also on climate, soil, and plant materials (Garcia-Tejero et al. 2011). For deficit irrigation strategies, the highest W_p values were recorded in the continuous deficit irrigation treatment. The improvement of water saving and fruit quality under continuous deficit irrigation may economically compensate for loss of yield. For citrus orchards, agricultural water use efficiency (WUE_{agr}) and financial water use efficiency (WUE_f) were significantly improved by deficit irrigation strategies (Garcia-Tejero et al. 2011). Moreover, with similar management, citrus orchards were more profitable under deficit irrigation conditions (Pérez-Pérez et al. 2010). The long growing season of late cultivar of peach needs significant amounts of irrigation water. With water scarcity, continuous deficit irrigation was demonstrated as an interesting tool for improving agricultural water productivity in the semi-arid region of Tunisia. It achieved significant water saving and maintained sustainable production levels.

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