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Water relations and yield of lysimeter-grown strawberries under limited irrigation

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Abstract

The effects of partial root-zone drying (PRD), as compared to deficit irrigation (DI) and full irrigation (FI), on strawberry (cv. Honeoye) berry yield, yield components and irrigation water use efficiency (WUE_I) were investigated in a field lysimeter under an automatic rain-out shelter. The irrigation treatments were imposed from the beginning of flowering to the end of fruit maturity. In FI the whole root zone was irrigated every second day to field capacity viz. volumetric soil water content (u) of 20%; while in DI and PRD 60% water of FI was irrigated to either the whole or one-half of the root system, respectively, at each irrigation event. In PRD, irrigation was shifted from one side to the other side of the plants when u of the drying side had decreased to 8–11%. Compared to FI plants, leaf water potential was significantly lower in DI and PRD plants in 3 out of 10 measurement occasions, while stomatal conductance was similar among the three treatments. Leaf area, fresh berry yield (FY), individual berry fresh weight, berry water content, and berry dry weight (DW) were significantly lower in DI and PRD plants than those of FI plants; whereas the total number of berry per plant was similar among treatments. Compared with FI, the DI and PRD treatments saved 40% of irrigation water, and this led to a 28 and 50% increase of WUE_I based on berry FY and DW, respectively, for both DI and PRD. Conclusively, under the conditions of this study PRD had no advantage compared to DI in terms of berry yield and WUE_I. DI and PRD similarly decreased berry yield and yield components and thus cannot be recommended under similar conditions.

Keywords: *Fragaria* × *ananassa* Duch.; Deficit irrigation; Irrigation water use efficiency; Partial root-zone drying

1. Introduction

Strawberry is among the most widely consumed fruits throughout the world. In 2003 the world strawberry harvested area was 207,000 ha and the cultivation area is increasing significantly in recent years (Today's Market Prices Reports, 2004). Strawberry is a shallow-rooted crop that is very sensitive to soil water deficits (Krüger et al., 1999). Berry yield and size are significantly reduced under drought stress during flowering and fruit maturing stages (Blatt, 1984). Therefore, in order to achieve acceptable yield and quality irrigation is generally needed in strawberry production. However, the worldwide decline in irrigation water resources requires development of water-saving irrigation strategies in order to improve irrigationwater use efficiency (WUE_I).

Many studies have demonstrated that irrigation has significant effects on strawberry growth, berry yield and quality (Serrano et al., 1992; Krüger et al., 1999; Yuan et al., 2004). It has often been observed that berry yield and individual berry size correlates positively with the amount of irrigation water (Serrano et al., 1992; Yuan et al., 2004). Conventional deficit irrigation (DI), with an irrigation amount lower than the full plant water requirement, has been shown difficult to manage in strawberries as significant reduction in berry yield may occur at low soil water potentials (Serrano et al., 1992). During the last decade a novel irrigation strategy, partial root- zone drying (PRD), has been developed (Kang and Zhang, 2004). The PRD approach is to use irrigation to alternately wet and dry two spatially distinct parts of the plant root system. PRD irrigation has been tested for field crops and fruit trees (Kang and Zhang, 2004; Fernández et al., 2006; Shahnazari et al., 2007). Most recently, it has also been tested in vegetables (Kirda et al., 2004; Zegbe et al., 2006). In many cases, PRD irrigation has shown a great potential to increase WUE_I and to maintain yield (Davies and Hartung, 2004). However, until now PRD has not been studied in strawberry under field conditions. It is suggested that plants under PRD performs better than under DI when the same amount of water was applied (Kirda et al., 2004; Davies and Hartung, 2004). These authors proposed that PRD could stimulate root growth and maintain a constant ABA signaling to regulate shoot physiology; whereas plants under DI, some of the roots in dry soils for long period may die and signaling may diminish and shoot water deficits may occur. Accordingly, it is plausible to suggest that PRD maybe promising for strawberries. Therefore, the objective of this study was to test whether PRD could maintain berry yieldand improve WUE_I as compared to full-irrigation (FI) and DI.

2. Materials and methods

2.1. Experimental site and crop establishment

The experiment was carried out in a field lysimeter at Højbakkegaard, 20 km west of Copenhagen. The lysimeter (as described by Kristensen and Aslyng, 1971), comprises 18 plots, each with 2 m 2 m surface area and 1 m deep positioned in two rows separated by a 2 m wide covered drainage tunnel. Theplots were protected from rain by an automatic mobile glass roof. The soil in the plots was a loamy sand with 6.5% clay and 8% silt in the top soil (0–35 cm) having a volumetric soil water content (u) of 20% at field capacity (FC) and a u of 5% at permanent wilting point. Details of physical properties were described elsewhere (Jensen et al., 1998).

On 15 May 2005, strawberry (*Fragaria ananassa* Duch. cv. Honeoye) seedlings were planted 25 cm apart in rows. There were two rows per plot with a distance of 0.8 m between rows resulting in 16 plants per plot. After planting, sufficient water was applied until the plants were well established. Prior to planting, fertilizers were applied at rates of 68.5 kg N ha^{-1}, 14.0 kg P ha^{-1} and 73.5 kg K ha^{-1} according to the conven- tional cultivation practice for strawberry in the local area and soil nutrients status.

2.2. Irrigation treatment

The field trial was a complete randomized design with three drip irrigation treatments: full irrigation (FI), partial root-zone drying (PRD) and deficit irrigation (DI) and six replicates. The FI treatment was fully irrigated every second day and u was kept close to FC. The DI and PRD treatments received 60% of the irrigation water volume of FI at each irrigation event during the treatment periods. In DI both sides of each plant were irrigated; while in PRD only one side of the plant was irrigated and the irrigation was shifted over from the wetted to the drying side of the plant's root system every 5–11 days when u of the drying side dropped to 8–11%. Two sets of TDR (time domain reflectometer, TRASE, Soil Moisture Equip- ment Corp., USA) probes (33 cm in length) were installed in each plot at each side of one plant in the middle of the rows to monitor u. In the FI treatment, irrigation amount at day *i* (I_i, *l*) was calculated by the equation:

I_i ¼ ðFC — u_iÞ× 30

where u_i is the volumetric soil water content (%) measured by TDR at day *i* before irrigation in the FI plots, FC is the volumetric soil water content (%) at field capacity, viz., 20%; and 30 (*l*) is the soil volume of the root zone for one plant based on the assumption that the roots explore a soil cylinder of 33 cm in depth and 34 cm in diameter (Schuurman and Goedewaagen, 1971). Emitters in the drip lines were placed in the middle between two plants with 25, 25 and 50 cm apart in the FI, DI and the PRD treatments, respectively.

2.3. *Measurement of leaf water potential (C_l) and stomatal conductance (g_s)*

Midday leaf water potential (C_l) and stomatal conductance (g_s) were measured on 7, 10, 11, 13–16, 20, 23, and 30 June during the first three shifts of irrigation in the PRD treatment. C_l was measured with a pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) on the fully expanded upper canopy leaves (two leaves per plot) from 11:00 to 13:00 h. g_s was measured on 3 cm^2 of the fully expanded

upper canopy leaves (two leaves per plot) from 11:00 to 13:00 h at photosynthetic active radiation (PAR) >1000 mmol m^{-2} s^{-1} with a LI-6200 portable photosynthesis system (LiCor Inc., Lincoln, NE, USA).

2.4. *Plant leaf area (LA), fresh berries yield (FY), yield components and irrigation water use efficiency (WUE_I)*

At the end of experimental period, one plant from each plot was harvested and plant leaf area (LA) was measured by a leaf area meter (model 3050A; Li-Cor Lincoln, NE, USA). Berries were harvested when mature and there were eight harvests at 2– 3 day intervals. Strawberries have normally a few harvests and the highest berry size happens in the early harvests. At each harvest, berries fresh yield (FY), berries number and average

fresh weight per berry were determined. Fresh berries were oven-dried at 85 8C to a constant mass to determine berries

dry weight (DW). WUE_I was calculated for each treatment by dividing either total FY or DW of berries (g $plant^{-1}$) by irrigation water volume (*l*).

2.5. *Data analysis and statistics*

Data were subjected to analysis of variance (ANOVA) procedures (SAS Institute Inc., 1988). Appropriate standard errors of the means (S.E.) were calculated. Tukey's Studentised Range (HSD) Test was applied to separate LA, the total berries FY and DW, total amount of irrigation water (AIW) and WUE_I of the plants had experienced different irrigation regimes. The least significant difference (L.S.D.) was used to compare the dynamic changes of C_l and g_s, berries yield and yield components during the harvests of plants under different irrigation treatments.

Table 1

Plant leaf area (LA), total fresh berries yield (FY), berries dry weight (DW), amount of irrigation water (AIW) and irrigation water use efficiency (WUE_I) under full irrigation (FI), deficit irrigation (DI) and partial root-zone drying (PRD) in lysimeter-grown strawberries

Irrigation treatment	LA (cm^2 plant^{-1})	FY (g plant^{-1})	DW (g plant^{-1})	AIW (l plant^{-1})	WUE$_I$ (g FY l^{-1})	WUE$_I$ (g DW l^{-1})
FI	4628a	805.9a	69.6a	21.6a	37.3b	3.2b
PRD	3347b	617.6b	62.5b	12.9b	47.8a	4.8a
DI	3329b	618.1b	62.2b	12.9b	47.8a	4.8a

Means with same letter within columns are not significantly different using Tukey's Studentised Range (HSD) Test at $P < 0.05$ ($n = 6$).

3. Results and discussion

At the end of the treatment period, FI plants had used 21.6 l water while PRD and DI plants had used 12.9 l water, which was 40% lower than that of FI (Table 1). u after each irrigation event of different irrigation treatments is shown in Fig. 1. All plots had a u of 20% at the beginning of the treatments; afterwards u of FI was always kept close to 20%; while u of DI decreased steadily until 20 June and fluctuated between 11 and 13% thereafter. In PRD, u of the L-side was kept at 20% while u of the R-side decreased sharply during the first 10 days after onset of treatment. After the first shift of irrigation, the PRD wetting side never returned to FC until the end of experiment. During the same period, u of the PRD drying side was significantly lower than that of the wetting side before next shift of irrigation. The PRD technique was developed based on the hypothesis that roots in the dry soil column sense soil drying and generate ABA-based chemical signals to reduce leaf expansion and g_s; simultaneously the wetted soil column can provide sufficient water to the plants and maintain a high water status of the shoot. Therefore, an ideal situation under PRD has been assumed that with irrigating 50% water of FI, u of the wet side should be maintained close to FC, while u of the dry side decreases fast to a predetermined level before shifting (Davies and Hartung, 2004). In the present study this was, however, achieved only during the first PRD cycle where the wet side had a similar u to that of FI. After the first shift of irrigation, it seems that the ideal situation of PRD could not achieve and the plants

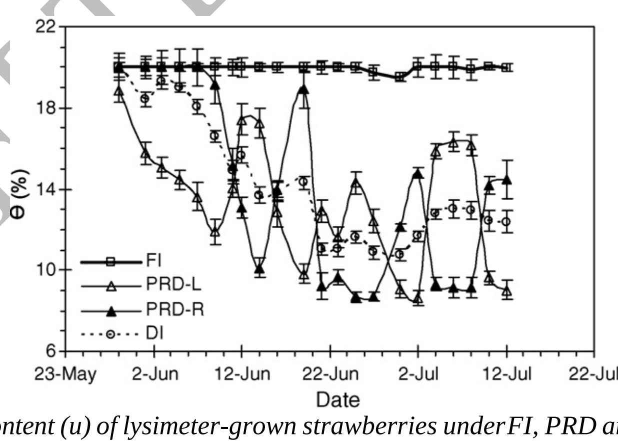

Fig. 1. Volumetric soil water content (u) of lysimeter-grown strawberries under FI, PRD and DI treatments. For the PRD treatment the alternating soil drying of the plant root-zone is indicated as PRD-L (left-side) and PRD-R (right-side), respectively. Vertical bars indicate S.E. (n = 6).

extract much more water from the wet side and less water from the dry side leading to a steady declining of u in the wet side. It is clear that with irrigating 60% water of FI in PRD was not enough to return u of the wet side to FC. Similar findings had been reported in crops under similar irrigation treatments (Kirda et al., 2004; Liu et al., 2006). Therefore, it is suggested that in future studies, instead of using a fixed ratio of water use to the FI plants, a dynamic irrigation volume should be adopted based on the u of the PRD wet side so that it could return to FC after each irrigation event.

g_s of FI plants was only slightly higher than those of PRD and DI plants on a few occasions late in the PRD treatment period (Fig. 2a). This result contrasts with the common observation that g_s would be reduced in plants under PRD irrigation (Davies and Hartung, 2004; Liu et al., in press), indicating that root-sourced chemical signals might not have played any role in inducing stomatal closure in PRD treated strawberries. Although g_s was similar for the three irrigation treatments, during the same period C_l was significantly lower in

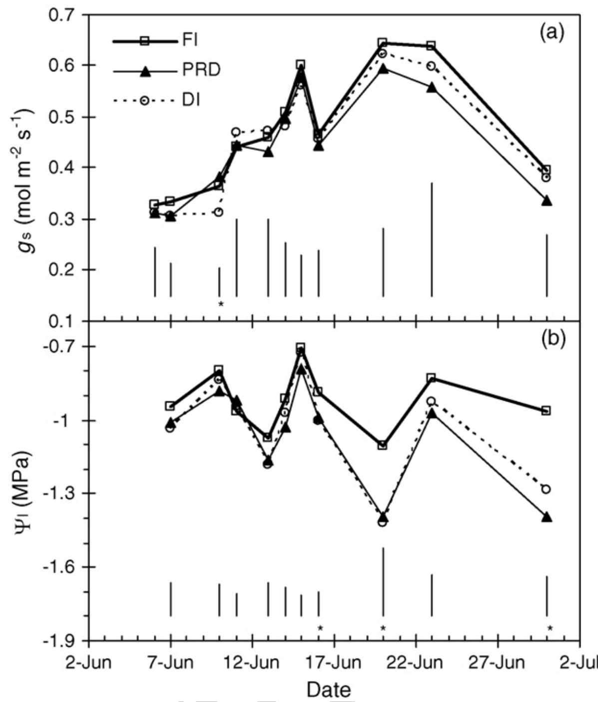

Fig. 2. Stomatal conductance (g_s) (a) and midday leaf water potential (C_l) (b) of strawberries under FI, PRD and DI treatments. Vertical bars indicate least significant difference (L.S.D.s) and asterisks denote significant difference among the three treatments at P < 0.05 (n = 6).

PRD and DI plants than that of FI on several days (Fig. 2b), indicating the plants had experienced shoot water deficits. In addition, PRD showed no advantage over DI in maintaining shoot water status in strawberries. Failure to maintain a high C_l has recently been reported by Zegbe et al. (2006) in PRD-treated processing tomatoes. This disagrees with earlier propositions that PRD would be able to maintain shoot water status better than DI (Davies and Hartung, 2004). It has been suggested that keeping a high u of the wet side in PRD may be essential to maintain a high C_l of the plants (Zegbe et al., 2003, 2006). In addition, putative genotypic differences in the mechanisms of stomatal control over plant water use and shoot water status in response to soil water deficits may help to explain the discrepancies regarding C_l maintenance under PRD in different studies. In grapevines (Stoll et al., 2000), potatoes (Liu et al., in press) and other crops with promising response to PRD irrigation, it is often observed that g_s is finely tuned to respond quickly to decrease of soil water availability via root-derived chemical signals, and therefore decreasing leaf transpiration which maintains u of the PRD wet side as well as C_l within a relatively narrow range; whereas in strawberry in the present study, soil water deficits under PRD and DI did not cause stomatal closure even under conditions of falling C_l, indicating that leaf turgor pressure might be maintained by other means such as osmotic adjustment (Zhang and Archbold, 1993). Under this strategy, short term responses to root-derived chemical signals regulating g_s may not be necessary (Loveys et al., 2004).

Leaf area (LA) at the end of the experiment was similar for PRD and DI plants, and which was significantly lower than thatof FI plants (Table 1). Both the total number of berries and the cumulative

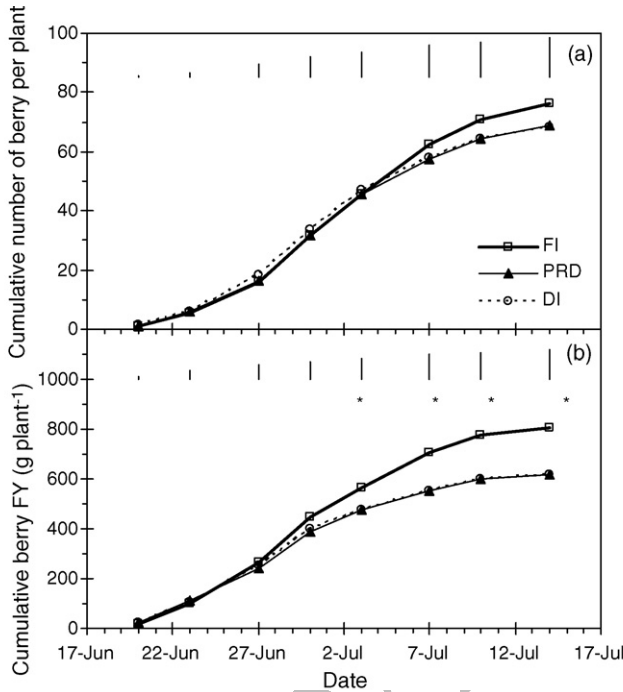

Fig. 3. Cumulative number of berries per plant (a) and cumulative berries freshyield (FY) per plant (b) of strawberries as affected by FI, PRD and DItreatments. Vertical bars indicate L.S.D.s and asterisks denote significantdifference among the three treatments at $P < 0.05$ (n = 6).

berries FY per plant were reduced by PRD and DI treatments relative to FI (Fig. 3), even though the decrease in berries number per plant was not significant (Fig. 3a). Cumulative berries FY was similar between treatments until 30 June (the fourth harvest); thereafter it was same for PRD and DI and was significantly lower than in FI (Fig. 3b). Both berries water content and individual berry fresh weight were significantly reduced by PRD and DI treatments (Fig. 4). Itis apparent that decreased berries FY in PRD and DI was due mainly to a reduced individual berries weight and not to changes in berries number in the two treatments (Figs. 3 and 4).Moreover, compared with DI, PRD did not result in any yield benefit, contrasting to the common view that plants would perform better under PRD than under DI given the same amount of irrigation water (Davies and Hartung, 2004).

Although berries FY and DW were decreased by PRD and DI treatments (Fig. 3b and Table 1), WUE_I during the experimental period of PRD and DI was similar and was 28 and 50% in berries FY and berries DW base, respectively, greater than that of FI plants (Table 1). This result is in accordance with normal observations that drought stress to a certain extent mayincrease plant water use efficiency (e.g. Liu and Stützel, 2004). One of the reasons for this might have been that due to the non- linear relationship between photosynthetic rate and g_s, partial stomatal closure (although not significant in this case) inducedby PRD and DI treatments may improve water use efficiency atleaf level (Liu et al., 2005). In addition, modification in leaf growth, e.g. an increased specific leaf area (data not shown) under PRD and DI might also have contributed to improved WUE_I as suggested by Liu and Stützel (2004).

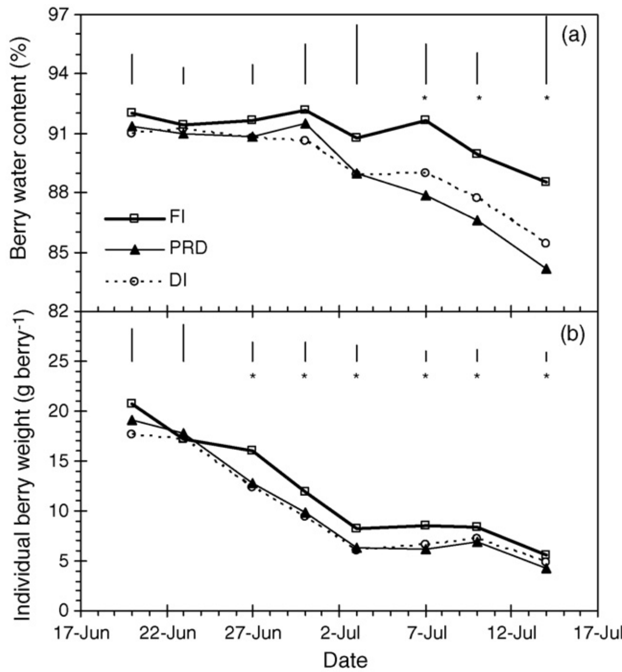

Fig. 4. Berries water content (a) and individual berries fresh weight (b) of strawberries under FI, PRD and DI treatments. Vertical bars indicate L.S.D.s and asterisks denote significant difference among the three treatments at $P < 0.05$ ($n = 6$).

4. Conclusion

It is concluded that, given the same amount of irrigation water, PRD had no advantage compared to DI in maintaining plant water status and berries yield. Even though WUEI was significantly increased by PRD and DI, both irrigation treatments led to significant reductions in berries yield. Therefore, under the conditions of the present study, PRD and DI are not recommended for strawberry production. However, further research is warranted using much more irrigation water (e.g. >70% of FI) to optimize the irrigation strategies. If successful, this will lead to appreciable saving of water in strawberry production considering the large area it enjoys worldwide.

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