Soil microbial response, water and nitrogen use by tomato under different irrigation regimes

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\section*{1. Introduction}

Many vegetable crops including tomato (\textit{Lycopersicon esculentum} L.) require irrigation in order to achieve high yield and good fruit quality. However, irrigation water resources have become limited as a consequence of increased incidence of drought in many countries. Therefore, improvement in crop irrigation water productivity (IWP) in agriculture is of strategic importance. Both alternative partial root-zone drying (PRD) and deficit irrigation (DI) are water-saving irrigation strategies (Kirda et al., 2004; Leib et al., 2006; Shahnazari et al., 2007). The DI method irrigates the entire root zone with less water than the potential evapotranspiration, while the mild water stress develops has minimal effects on the yield (English and Raja, 1996). The PRD approach is a further development of DI. It involves irrigating only part of the root zone permitting the other part to dry to a predetermined level before the next irrigation. In this way, PRD allows the induction of the ABA-based root-to-shoot chemical signaling system to regulate growth and water use and thereby increase IWP (Liu et al., 2006).

The effects of PRD and DI on plant physiological (e.g. ABA signaling, leaf gas exchange, IWP), morphological (e.g. leaf, root and fruit growth, biomass partitioning) traits and fruit quality (e.g. color, sugar, soluble solids) of tomato plants have been extensively investigated (see Dodd, 2007 and literature cited therein). Direct comparisons between the two irrigation methods on crop performance have also been reported (Dodd, 2007; Tahi et al., 2007; Topcu et al., 2007). It is suggested that PRD is superior to DI in terms of maximizing ABA signaling, maintaining crop water status, fruit yield and photosynthetic efficiency (Dodd, 2007). In addition to the differential effects of PRD and DI on plant performance, the two irrigation strategies may cause significant differences in soil water distribution in the root profile and, thus may affect soil bio-physicochemical processes differently (Shahnazari et al., 2008; Wang et al., 2008). These processes influence soil microbial community (indicated by the microbial biomass C/N ratio) as well as soil carbon and nitrogen dynamics, and consequently nutrient availability (Kirda et al., 2005; Wang et al., 2009). However, until now these aspects have not been systematically studied. The objectives...
of this study were, therefore, to investigate the effects of three irrigation strategies, namely full irrigation (FI), PRD and DI, in combination with localized fertilization on water and nitrogen use, plant growth and soil microbial C/N ratios in pot-grown tomatoes and to determine if the changes in the soil properties could account for the difference in crop performance under different irrigation regimes.

2. Materials and methods

2.1. Soil

The soil was from Jyndevad, Denmark. It is coarse sand and is classified as a Humic Psammentic Dystrudept in USDA soil system, 1999. The soil contained 1.6% organic C and 0.1% total N. It had a pH of 5.9 and a cation exchange capacity (CEC) of 13.3 cmol kg\(^{-1}\). It contained 2.6% clay (<2 \(\mu\)m), 1.4% silt (2–20 \(\mu\)m), 11.4% fine sand (20–200 \(\mu\)m) and 84.2% coarse sand (200–2000 \(\mu\)m). The soil volumetric water content (\(\theta_v\)) at 100% water holding capacity (WHC) and 4.0% at the permanent wilting point. The soil was sieved <5 mm and carefully mixed by hand before use.

2.2. Experimental design

The experiment was carried out in a climate-controlled glasshouse at the experimental station of The University of Copenhagen, Taastrup, Denmark. The cultivation conditions were 20 ± 2 °C and 14 ± 2 °C for the day and night air temperature, 60% relative humidity. The light intensity (photosynthetic active radiation, PAR) was 500–600 μmol m\(^{-2}\) s\(^{-1}\) at the top of the plants. It was supplied by sunlight plus metal-halide lamps with a 15 h day-length. Seeds of tomato were sown in 200 ml pots filled with peat (GB-Pindstrup Substrates No. 1, pH 6.0) in December, 2007. When the fourth leaf appeared, the plants were transplanted into pots (17 cm diameter and 50 cm deep with volume of 12,363 cm\(^3\)). Each pot was vertically divided into two equal compartments with a plastic board. Thus, water and nutrient lateral exchanges were prevented between the two compartments. On the top of the board, the middle part (5 cm width \(\times\) 7 cm height) was cut off and the tomato seedling was planted. The plant roots were evenly divided (as nearly as possible) into the two soil compartments. The pots were filled with 16 kg soil to 47.5 cm depth, at a soil bulk density of 1.45 g dry weight cm\(^{-3}\). After transplanting, the soil was conditioned for 3 weeks at about full water holding capacity (WHC). Probes (35 cm in length) were installed in the middle of each soil compartment of every pot, to monitor the soil water content in the compartments using a time domain reflectometer (TDR) of TRASE, Soil Moisture Equipment Corp., USA.

2.3. Irrigation and fertilization treatments

When the first flower truss appeared (11th February, 2008), the plants were randomly divided into three irrigation regimes, and irrigated till end of the experiment everyday: (1) Full irrigation (FI), in which water was applied daily at 9:00 am to both soil compartments and the soil water content of both compartments constantly maintained at 100% WHC (i.e. 18 vol.%), (2) Partial root-zone drying (PRD), one soil compartment was irrigated to 18% and the another allowed to dry until soil water content of 7–8% was reached, at which the dryer compartment was irrigated and the former wet one stopping irrigation. (3) Deficit irrigation (DI), the same volume of water used in PRD treatment was evenly split and applied to the two soil compartments. The daily irrigation amounts for FI, PRD, and DI were determined based on the fixed WHC (18 vol.%) and the soil water content measured by TDR. Each irrigation treatment had 12 replicates, giving 36 plants in total.

For nutrient application, 5 ml of nutrient solution was sprayed into top soil of each pot from February 12 to February 19, then irrigation with tap water. In PRD, the nutrients were only applied to one side, while in FI and DI, the nutrients were applied evenly to both sides. In total 40 ml nutrient solution, containing 0.2 g N, was applied to each of the plant during the experiment.

2.4. Sampling and measurement

During the experimental period, the plants were harvested four times, i.e. at the onset of the irrigation treatment (February 11), after 3rd (February 22), 5th (March 3) and 7th (March 11) drying-wetting cycles of the PRD treatment. At each time, the leaves, stems, and fruits were collected and then the dry weights determined following oven-drying at 70 °C for 48 h to constant weight. Total C and N were determined by automated combustion according to the Dumas method (Hansen, 1989). Crop IW\(P\) was calculated by dividing the increment of total plant biomass by the total irrigation volume during the treatment period.

Soil samples were taken from both soil compartments at 0–20 cm at the 1st harvest, and at 0–10, 10–20, and 20–30 cm at the other three. Soil total C and N concentrations were determined using the Dumas method (Hansen, 1989). Soil mineral N (\(N_{\text{min}}\), the sum of NO\(_3\)–N and NH\(_4\)–N) was extracted by adding 100 ml 2 M KCl to 25 g dry weight equivalents of moist soil and shaking for 45 min. After settling for 30 min, the separated upper soil extract was filtered through Whatman No. 42 filter papers. Soil mineral N in the extracts was analyzed by a Technicon AutoAnalyzer II (Henriksen et al., 2007). Soil microbial carbon (MBC) and nitrogen (MBN) were measured by the fumigation extraction method (Brookes et al., 1985; Vance et al., 1987). The ratio of MBC to MBN, expressed as microbial C/N, implied the composition of soil microbial community. It is generally accepted that the higher the microbial C/N, the higher the ratio of fungal biomass in the whole soil microbial biomass.

2.5. Calculations, data analysis and statistics

Apparent N loss (%) was expressed as: percentage of the uncovered N (i.e. the difference between the decreased soil total N concentration soil during the experiment and the total N in the aboveground plant biomass). Nitrogen growth efficiency (%) was expressed as the percentage of the N in fruit in terms of the total N in the aboveground biomass; while the apparent fruit N use efficiency (%) was expressed as the percentage of the N uptake by fruits in terms of the total N applied to the pot (i.e. 200 mg pot\(^{-1}\)).

Harvest index (%) was calculated from the ratio:

\[
\text{Harvest index} = \frac{\text{Fruit fresh weight}}{(\text{leaves} + \text{stems}) \text{dry weight}} \times 100
\]  

The IWP for fruit production was expressed as:

\[
\text{IWP} = \frac{\text{Fruit fresh weight}}{\text{Irrigation water use}}
\]

According to the general terminology of water use, here the IWP means the efficiency in beneficial consumption of irrigated water to produce fresh tomato fruit. It only measures the integrated impact on fruit (economic) production of different irrigation methods.

All data were subjected to analysis of variance (ANOVA) procedures with SAS software. Appropriate standard errors of the means (S.E.) were calculated. Tukey’s studentized range test (HSD) was applied to separate measured parameters of the plants exposed to different irrigation regimes.
3. Results

3.1. Water use and plant biomass distribution

During the experimental period, FI received 26% and 23% more irrigation water than DI and PRD. The soil water content of FI was thus always much higher than that of DI and PRD, ranging from 13% to 17%, equaled to about 72–94% of WHC. In contrast, the soil in DI had lower water content, ranging from 39% to 61% of WHC. The soil water content in the two compartments of PRD treatment changed with the wetting and drying cycles. Although similar volume of water was used in DI and PRD, the soils of irrigated compartment in PRD had about 8% higher water content than those in DI (Fig. 1).

The FI treatment produced significantly higher dry biomasses of leaves, stems, and fresh weight of fruit and water use efficiency of aboveground dry biomass production than either DI or PRD (Table 1). However, the harvest index of FI was significantly lower than that of DI and PRD treatments, resulting in higher water use efficiency for fruit production in both DI and PRD treatments. Although both DI and PRD received similar volumes of irrigation water, DI had a higher harvest index and IWP for fruit production, but a lower IWP for aboveground biomass.

3.2. Plant nitrogen uptake

Table 2 shows that tomato plants in the different irrigation treatments had different N use patterns. Full irrigation (FI) induced high N uptake in the aboveground biomass, but less N in fruit. The apparent N loss reached about 69%, which resulted in both decreased N growth efficiency and apparent fruit N use efficiency. The PRD had similar effects on N utilization as FI, but lower N aboveground biomass and higher N growth efficiency.

3.3. Soil mineral nitrogen

There were no significant differences in N\textsubscript{min} contents within the 0–10 and 10–20 cm soil depths of the three treatments (Fig. 2).

![Fig. 1. Daily soil water content (vol.%) in upper 35 cm soil depth under FI (full irrigation), DI (deficit irrigation) (a) and PRD (partial root-zone drying) (b) irrigation treatments. PRD-N and PRD-S indicate the two sides in PRD pots. Arrow lines indicate the day when irrigation side changed in PRD treatment. Values are mean ± standard error (SE) (n = 4–12).](image)

![Fig. 2. Soil mineral N (N\textsubscript{min}, the sum of NO\textsubscript{3}^- -N and NH\textsubscript{4}^+ -N) content in the upper 30 cm soil layers at the end of experiment. The different letters indicate significant differences (P < 0.05) between treatments among the same layer. Error bars indicate SE (n = 4). For the definition of terms see Fig. 1.](image)
However, $N_{\text{min}}$ values at the 20–30 cm depth were significantly different between the three irrigation methods, in the order FI > DI > PRD.

3.4. Soil microbial biomass N

Soil microbial biomass N changed with irrigation methods (Fig. 3). The FI treatment caused increased soil microbial biomass N, which reached a maximum at 20 days after the treatment. In contrast, both DI and PRD treatments generally resulted in decreased soil microbial biomass N. The soil microbial biomass C/N ratio increased and reached a maximum by the end of the experiment. The changing patterns in each compartments of PRD were generally similar although the soil microbial biomass N concentration and the microbial C/N ratio were occasionally different due to shifting irrigation.

4. Discussion

A large body of evidence has demonstrated that deficit irrigation strategies including DI and PRD can significantly improve crop water use efficiency for various crops (Wakrim et al., 2005; Wang et al., 2007; Saeed et al., 2008). In the present study, even though the water use efficiency for aboveground dry biomass production was lower in the DI and PRD compared to the FI treatment, both deficit irrigation treatments significantly increased water use efficiency for fruit production under the experimental condition (Table 1). Similarly, both DI and PRD treatments significantly improved the harvest index (Table 1), meaning fruit production efficiency of vegetative biomass. This was also true for N growth efficiency. Thus, more N was allocated into fruit and higher fruit production efficiency per unit of N uptake by the DI and PRD treatments (Table 2). These results indicate that moderate soil water deficits caused by the DI and PRD treatments stimulate resource allocation into fruit. Similar findings were also reported by Topcu et al. (2007) with tomato.

In the current study, the high apparent N loss in the FI treatment indicated that high soil water content results in greater N loss, presumably due to enhanced denitrification rate (Valé et al., 2007) as no leaching occurred during the experiment. In contrast, low soil water in the DI treatment causes less N loss. It was notable that PRD also caused higher N loss than the DI treatment, which might be related to the temporary high soil water content upon re-watering the dry soil compartment and thus stimulating the denitrification process (Valé et al., 2007).

Soil microbial biomass N is a soil N pool that is potentially available for plant uptake, especially under an alternating wet-dry environment (Wu and Brookes, 2005). Gordon et al. (2008) found that either drying or wetting caused a significant reduction in microbial biomass C and N, associated with increased microbial activity. In our experiment, the larger microbial biomass N in FI was a good indicator that more soil organic N was immobilized during tomato growth.

It is generally accepted that microbial C/N ratios can roughly indicate the proportion of bacterial to fungal biomass (Killham, 1994; Wichern and Hafeel, 2004), since bacteria have a lower ratio (6–8) than fungi (15) (Killham, 1994; Joergensen et al., 1995). The tested soil at pH 5.5 had a microbial C/N ratio of 9.6 which may indicate a fungal-dominated community. The soils receiving the DI and PRD treatments had higher microbial C/N ratios than that of FI, which may imply a more fungal dominant community in the dry soils. This is consistent with the concept that fungi are more important in dry and acid soil conditions (Joergensen et al., 1995; Paul and Clark, 1996). Under frequent drying and wetting conditions in the PRD treatment, the shift in soil microbial C/N ratio occurred even earlier. However, the effect of this change in the soil microbial community on soil N transformation, especially the interactions of the soil fungal community with plant growth are not known.
5. Conclusions

Under the controlled condition in greenhouse, the current study explored the effect of full irrigation, deficit irrigation, and partial root-zone drying on plant biomass, water use efficiency, and N use efficiency of tomato, and soil microbial C/N ratio. The results showed that full irrigation could produce significantly higher dry biomass of leaves and stems and the water use efficiency of aboveground dry biomass was higher than deficit irrigation or root-zone drying. On the other hand, with less water used in deficit irrigation and root-zone drying, water use efficiency for fruit and harvest index were improved compared with full irrigation. Meanwhile, nitrogen was used more efficiently to produce fruit in deficit irrigation. During the experiment, the proportion of fungal biomass was relatively higher in soils under deficit irrigation and root-zone drying. The primary result of the current study indicates that the linking between plant aboveground N uptake and the underground microbiologically mediated N transformation under different water-saving irrigation regimes was a potential area to be more explored.

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