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Partial root-zone drying increases WUE, N and antioxidant content in field potatoes

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ABSTRACT

Partial root-zone drying (PRD) is a new water-saving irrigation strategy which requires that the roots are simultaneously exposed to both dry and wet soil zones. This technique is now undergoing extensive trials with a range of agricultural crops. These results show significant benefit in increasing water-use efficiency. The field potato (*Solanum tuberosum* L. cv Liseta) experiments were conducted during 2007 and 2008. Subsurface drip irrigation was used. In 2007 season PRD plants received 70% of full irrigation (FI). To further enhance water saving during the last 3 weeks of the irrigation period, PRD using 70% of FI was replaced with PRD using 50% of FI in 2008. By five harvests during the season N content, fresh and dry matter (DM) of leaves, stems and tubers were followed. At final harvest the effects of PRD and FI irrigation on total and marketable yield and yield quality were investigated. Also, the irrigation water-use efficiency (IWUE) was calculated. As compared to FI, PRD treatment saved 33% (2007) and 42% (2008) of irrigation water while maintaining similar yield. This resulted in 38% and 61% increase in IWUE for the 2007 and 2008 seasons, respectively. In both years the PRD treatments resulted in the increase of N, starch content and antioxidant activity in potato tubers. The latter novel findings on the effect of PRD irrigation on tubers quality might be favorable for the health-promoting potato value.

1. Introduction

Many crops have high water requirements and supplemental irrigation is necessary for successful production. The predictions are that the demand for irrigation will increase considerably in years to come to alleviate the consequences of climate change and more frequent and severe droughts which are expected to become the main limiting factor in agricultural production in Southern Europe (FAO, 2002). However, in many areas as a consequence of global climate changes and environmental pollution, water use for agriculture is reduced (FAO, 2003). Therefore water resources saving and increasing agricultural productivity per unit of water ("more crop per drop") are becoming of a strategic importance for many countries (Morison et al., 2008).

In the last decades, one of the management options to overcome the agricultural drought is the use of partial root-zone drying (PRD). Partial root-zone drying is a deficit irrigation strategy designed to maintain half of the root system in a dry or drying state, while the other half is irrigated, in order to keep the leaves hydrated. The treatment is then reversed, allowing the previously well-watered side of the root system to dry down while fully irrigating the previously dry side. The principle behind PRD-irrigation is to alternately let one part of the root system be exposed to soil drying while another part is irrigated, in order to keep the leaves hydrated. This triggers hormonal signals from drying roots including abscisic acid (ABA) that partly close stomata and modify growth and hereby improve water-use efficiency. Successful application of PRD relies on the regular switching of the dry and irrigated sides that is required to sustain the supply of root borne chemical signals and to maintain turgor and water potential in the shoot (Dodd et al., 1996; Davies et al., 2000). Frequency of shifting depends on crops, growing stage and soil water balance.

The PRD method, by reducing irrigation water, has been demonstrated to be beneficial in terms of water-saving irrigation and improved water-use efficiency. In some cases almost a doubling was achieved with the small reduction or no effect on crops yield (Kang and Zhang, 2004; Morison et al., 2008). The PRD technique is now undergoing extensive trials under the drought conditions in many areas with a range of agricultural crops (grapevine, tomato, potato, cotton, peach, pear, soybean, olive). Costa et al. (2007) and Morison et al. (2008) reviewed the agricultural benefit of PRD showing that PRD has the potential to reduce field–crop and fruit–tree water use and maintain yields when compared with usual irrigation methods. However, there is also an opposite opinion on the

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advantages of PRD use in comparison to regulated deficit irrigation techniques (RDI). Very recently, Sadras (2009) concluded, on the basis of meta-analyses of already published PRD results, that substantial improvement in water-use efficiency in PRD irrigated plants can be achieved by closely monitored deficit irrigation, without the complexity and additional cost of partial root-zone drying.

In the presented work PRD-irrigation strategy was used for irrigation of potato. Potato (*Solanum tuberosum* L.) is the world's most produced and consumed vegetable with the annual production over 300 millions tons (FAO/ESS, 2005). The shallow and sparse root system of the potato plant makes it vulnerable to water deficits (Opena and Porter, 1999). For many potato cultivars even short periods of drought stress can cause significant reductions in tuber yield and quality. Therefore irrigation is required for production of high potato yield (Onder et al., 2005). Imposed water stress during early development (flowering and fruit set) might cause the essential yield reduction (Yuan et al., 2003). PRD-irrigation method has already been trialed with potato. Results of Lynch et al. (1995) showed that RDI irrigation is difficult to apply to potato because even short period of stress during tuber set phase might have a significant reducing effect on yield. Liu et al. (2006a,b) and Shahnazari et al. (2007) demonstrated a significant water for irrigation saving and increase in water-use efficiency, increase of the marketable yield and nitrogen use efficiency in PRD treated compared to fully irrigated potato.

PRD research has been focused mainly on potato yield and water-use efficiency with comparatively less research to characterize the effects of these techniques on tuber quality. One of the very important potato yield characteristic is tuber antioxidant activity. Recently, Andre et al. (2009) demonstrated that antioxidant activity is very important health-promoting value of potato tubers. Potato tubers are significant dietary source of important natural antioxidant compounds including polyphenols, flavonoids, carotenoids, ascorbate, glutathione, and tocopherols (Brown, 2005). These antioxidant compounds, which can neutralize free radicals, may be of central importance in the prevention of cancer and cardio- and cerebrovascular diseases (Liu, 2004).

The aim of the presented experiments was to compare "static" PRD management approach with "dynamic" system when amounts of irrigation water in PRD were changed according to the plant growth phases by increasing water saving during later robust stages. This could be important because potato sensitivity to water stress varies during the growing season. None of the earlier PRD works assessed how deficit irrigation strategies would affect antioxidant activity in yield components of different agricultural crops. Thus, the aim of presented experiments was also to assess the effects of PRD technique on tuber antioxidative activity that might be important for understanding and possible promotion of these irrigation technologies for production of food with greater human health benefits.

2. Materials and methods

2.1. Experimental site

The experiments were carried out during the growing seasons of 2007 and 2008 in a vegetable commercial farm ("Salate Centre"), located 10 km north of Serbian capital, Belgrade. The soil of the field was silty-clay and it was developed on alluvial deposit. It was classified as mollic gleysol eutric according to IUSS working group soil classification (IUSS, 2006). The topsoil (0–0.4 m) contained 3.8% coarse sand, 22.8% fine sand, 42.5% silt, 29.1% clay and 1.93% of organic matter. The subsoil (0.4–0.8 m) contained 6.2% coarse sand, 28.5% fine sand, 39.4% silt, 25.4% clay and 0.47% organic matter. The bulk density of 1.53 g cm^{-3} was similar for both soil depths. Field capacity of 20–40 cm soil depth was 0.369 m^3 m^{-3} (volumetric soil water content). During the last decade, the land was used for production of lettuce, tomato and cabbage.

Table 1
Phenological codes of potato filed experiments in 2007 and 2008 seasons according to BBHC scale (Hack et al., 2001).

Codes	Description	2007 (mm dd)	2008 (mm dd)
00	Planting	April 4th	April 9th
09	85% emergence	April 29th	May 2nd
40	Initial tuberisation	May 25th	June 1st
42	80% tubers >20 mm	June 10th	June 21st
51	First flower opens	June 12th	June 17th
91	Leaves start yellowing	August 13th	August 9th
97	Full maturity	September 4th	September 5th
	Final harvest	September 6th	September 10th

2.2. Plant growth

Potato (*S. tuberosum* L.) cultivar Liseta was used for investigation. The field was organized as split plot design with six plots (three per treatment). Each plot had eight rows with 6 m width and 11.70 m length and 39 plants per row. The seed tubers were planted in the beginning of April at the depth of 10 cm, with distance between plants in a row of 30 cm and distance between rows of 75 cm. Seed tubers were ridged with 15 cm soil and ridges were formed about 30 days after planting. The final height of the ridge was app. 30 cm. During the vegetation season plants were treated against weeds and fungal disease. Fertilization included an initial application of nutrients (N, P, K and micronutrients) and then two additional fertilization treatments were made in 2007 and 2008 seasons. Fertilizers were applied through irrigation system and corresponding to 270 kg N, 70 kg P, 242 kg K and 23 kg ha^{-1} year^{-1} Mg (2007 season) and 243 kg N, 121 kg P, 371 kg K and 31 kg ha^{-1} year^{-1} Mg (2008 season). The calculations of fertilizing requirements were based on the analysis of soil nutrients. The growth stage (Table 1) of the potatoes during investigated seasons was followed according to the BBCH scale (Hack et al., 2001)

2.3. Experimental design and irrigation treatment

The irrigation method used was a drip-subsurface method. Water for irrigation was supplied from the canal which is located 100 m away from the experimental field. The irrigation strategies included full irrigation (FI) and partial root drying (PRD). The subsurface irrigation system was supplied by Netafim (A.C.S. Ltd. Netafim, Israel). For the FI treatment, one drip line was placed 10 cm below the top of the ridge although in PRD treatment two drip lines were operated separately and were placed in parallel. The distance between emitters in FI treatments was 30 cm and these were placed exactly in the middle between two plants. Their discharge rate was 1.0 L/h. In PRD treatments the drip line consisted of two bundled lines each with 60 cm distance between emitters but displaced to give 30 cm distance.

The FI treatment was applied to maintain the soil water content just below field capacity during the whole growing season. PRD treatments started in similar period in 2007 on 22nd June and in 2008 season on 25th June when 80% of tubers >20 mm diameter were formed. In the FI treatment the amount of water for irrigation was calculated on the base of volumetric soil water content data according to Shahnazari et al. (2007). The amount of water used for PRD irrigation differed in both irrigation seasons. During the 2007 season the PRD treated plants received 70% of FI plots at each irrigation event in which half of the root zone was irrigated while the other half was dried out (70% PRD treatment). In 2008 seasons the 70% PRD treatment was applied in the period between June and July, however in the last 3 weeks of the irrigation period, 70% PRD was replaced by 50% PRD (PRD plants received 50% of FI treatment). The PRD irrigation was shifted between the two sides of the plants each time when the FI treatment had received about 35 mm of irrigation. In both investigated seasons the shifting time interval varied between 3 and 7 days depending on evaporative demand and soil water content. Irrigation was done at least twice per week and ended 2nd August 2007 and 13th August 2008 season.

Measurement of soil water content was done with a time domain reflectometer (TDR, TRASE, Soil Moisture Equipment Corp., USA). TDR probes (20 cm length) were installed vertically on the top of the ridge (17 cm above the soil level), at the soil surface and 17 cm below the soil level. Soil water content was calculated as average of measurements from three investigated TDR positions.

2.4. *Measurements of plant growth, N and yield parameters*

Plant growth stages were recorded every 2 weeks (2007 season) and 10 days (2008 season) from planting to harvest according to BBCH's growth stage key for potatoes (Hack et al., 2001). During the PRD treatment period in 2007, five harvests were undertaken (H1–H5). At each harvest growth parameters (fresh and dry matter of leaves, stems and tubers), yield and yield quality were estimated in eight plants per plot. Because of longer irrigation period, during 2008 season, the number of harvest was increased to six (H1–H6). Measured parameters were the same as in 2007 except that measurements of N content were included. At each harvest fresh weight and tuber numbers of selected plants were determined. After drying at 85 °C, total dry mass of leaves, stems and tubers was measured. Harvest index (HI) was calculated as tuber DW × (tuber DW + top DW)$^{-1}$ according to Shahnazari et al. (2007). Plant nitrogen content in different plant organs (leaves, stems and tubers) was estimated by Kjeldahl method (Jones, 1990).

Final crop harvest was done on 8th September 2007 and on 10th September 2008. Fifteen plants per plot were taken for analysis. From each plant all tubers were collected for measuring fresh and dry weight. Tubers from each plant were graded into various size classes and weighed. Among the tubers, the tuber size categories of 40–60 mm diameter were considered as marketable tubers.

Irrigation water-use efficiency (IWUE) was calculated as the ratio between final harvest tuber fresh matter data and the amounts of irrigation water given to the plants during treatments period.

2.5. *Tuber quality*

Potato tuber quality was assessed by measuring titrable acidity (TA), concentrations of starch and reducing sugars (RS) and antioxidant activity. Samples for tuber quality analyses were taken at a final harvest. Tubers were taken randomly from three individual plants in each plot. Tubers were rinsed, hand-peeled, weighted and diced. Then they were homogenized, extracted with distilled water (1:1 w/v), filtered and finally centrifuged. To measure the titrable acidity resulting supernatant was taken and titrated with sodium hydroxide. Titrable acidity (TA) was calculated as malic acid by using the conversion factor of 0.067 (Board, 1988). For measuring reducing sugars test samples were prepared and homogenized as indicated earlier and the slurry was filtered. Reducing sugars (RS) were measured in filtrate by Luff-Schoorl's method (ISI method 28-1e, 2002).

To measure starch content samples were homogenized in cold distilled water then filtered under vacuum and washed with cold distilled water. Starch in the sample was measured after acid hydrolyzing of the sample by determining RS using Luff-Schoorl's method and estimated as invert sugars as follows: (Nourian et al., 2003)

$$\%\,\text{starch} = \%\,\text{RS found} \times 0.9$$

Antioxidant activity of tubers ethanolic extract was evaluated according to Miller's method against ABTS$^{\bullet+}$ radical cation and expressed as Trolox equivalent antioxidant capacity (TEAC) (Miller et al., 1996). Briefly, ABTS$^{\bullet+}$ radical cation was prepared by oxidizing ABTS with manganese dioxide. The absorbance was measured at 734 nm after 2 min of the reaction. A water-soluble vitamin analog – Trolox was used as an antioxidant standard. The dose-response curve for Trolox (0–100 μmol) was used to determine the TEAC values of all investigated extracts. Results were expressed as TEAC in μmol of Trolox per 100 g of sample fresh weight. To assess the antioxidant status of potato tubers were peeled, samples were taken from the middle section in slices and homogenized in a high speed blender. Extraction was performed using an ethanol/water (80/20) extraction solution (1:10, w/v) under agitation for 15 min. Homogenate was centrifuged (10,000 rpm for 10 min) the supernatant transferred to vials and stored (−20 °C) until assayed. Three extracts were collected for each sample and analyzed in duplicate for their antioxidant capacity.

2.6. *Data analysis*

Data were analyzed by two-way ANOVA/MANOVA procedure (STATISTICA'99, StatSoft, Inc.).

3. Results

3.1. *Climate conditions and irrigation*

The climate in experimental farm (Salate Centre) is continental, with hot, dry summers and mildly cold, rainy winters. During the 2007 and 2008 years the winters and springs were very warm and summers extremely hot (Fig. 1). During the period of potato vegetation, rainfall was higher in 2007 (237 mm) than in 2008 season (187 mm). Similar differences between 2007 and 2008 season were for evapotranspiration data (Etp). Average temperature did not differ much between investigated seasons. Although irrigation started in similar period in both seasons it ended differently. High precipitation in the beginning of August in 2007 was enough to replenish soil water storage in the plant root zone and, therefore, in 2007 irrigation ended 11 days earlier (2nd August) than in 2008 (13th August). The number of irrigations in 2008 (12) was higher comparing to 2007 (10).

Furthermore, irrigation scheduling also differed among investigated seasons. In 2007 season PRD treated potato plants were irrigated as 70% of FI and this "static" approach (unchanged amount of water for irrigation comparing to FI) was in 2008 seasons replaced by "dynamic" approach (the amount of water depending on crop growth stage). The change from 70% to 50% PRD was done when plants were in the middle of tuber bulking phase.

3.2. *Plant growth and N content*

The dynamics of potato plants growth was assessed as dry matter (DM) accumulation in different plant organs. Fig. 2 presents the results of 2007 season measurements of leaf, stem and tuber DM. In general, there were no statistically significant differences between FI and PRD irrigated plants in DM production and tendency of DM translocation from leaves to tubers was similar.

Differences in DM translocation were found between harvest periods. Data for harvesting periods H3 (16th July) and H4 (2nd August) showed that in H4 leaf DM of FI and PRD plants was significantly lower (by 39% and 23% for FI and PRD, respectively). The highest increase in tuber DM was found in the period between H4 and final harvest in both FI (by 55%) and PRD plants (by 66%). At final harvest (6th September) tuber DM of FI crops was 205 g plant^{-1} and

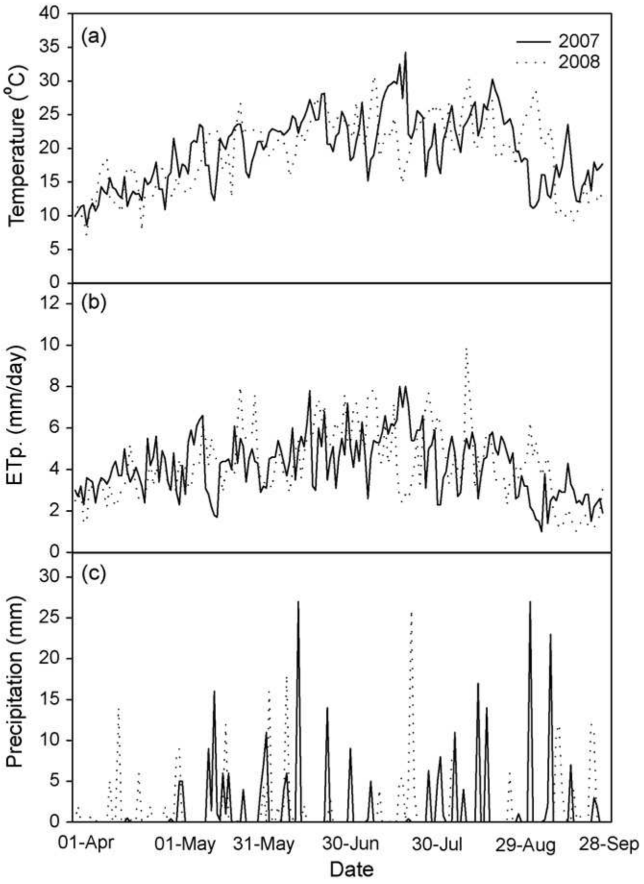

Fig. 1. Daily means of temperature (a), evapotranspiration (ETp) (b) and precipitation (c) during the irrigation treatments in 2007 and 2008 seasons.

was not statistically different from the tuber DM of PRD irrigated crops (192 g plant^{-1}).

Comparison of data for different harvesting periods in 2008 season showed that between H4 (28th July) and H5 (7th August) a significant increase in DM translocation from leaves to tubers occurred (Fig. 3). This period coincided with the change of PRD irrigation from 70% to 50% of FI. Here DM in tubers of PRD irrigated plants significantly increased ($P < 0.01$) in H5 by *ca.* 35% comparing to H4, although in FI plants this increase was only 12%. At final harvest (10th September) the tuber DM was slightly but not significantly higher in PRD (207 g plant^{-1}) than in FI (197 g plant^{-1}).

Comparison of data for both investigated seasons indicated slower translocation of DM from leaves to tubers during almost all harvesting periods in 2007 season comparing to 2008. However, at final harvest significant differences between tuber DM of investigated plants were not found. In both seasons harvest index data (Fig. 2 and 3) did not show significant differences between the applied irrigation strategies.

During 2008 season N content in the leaves, stems and tubers of PRD and FI irrigated plants was measured (Fig. 4). These results, similarly to the results obtained during 2007 season (Jovanovic et al., 2008), showed that the N concentration in leaves and stems was progressively reduced during the growing season until final harvest when the lowest values were found in all irrigation treatments. Similarly to DM results (Fig. 3), N data for different plant's organs also indicated that translocation of N (from leaves to tubers) tended to increase after H4 period. At final harvest N content was by *ca.* 19% significantly higher ($P < 0.05$) in PRD than in FI plants.

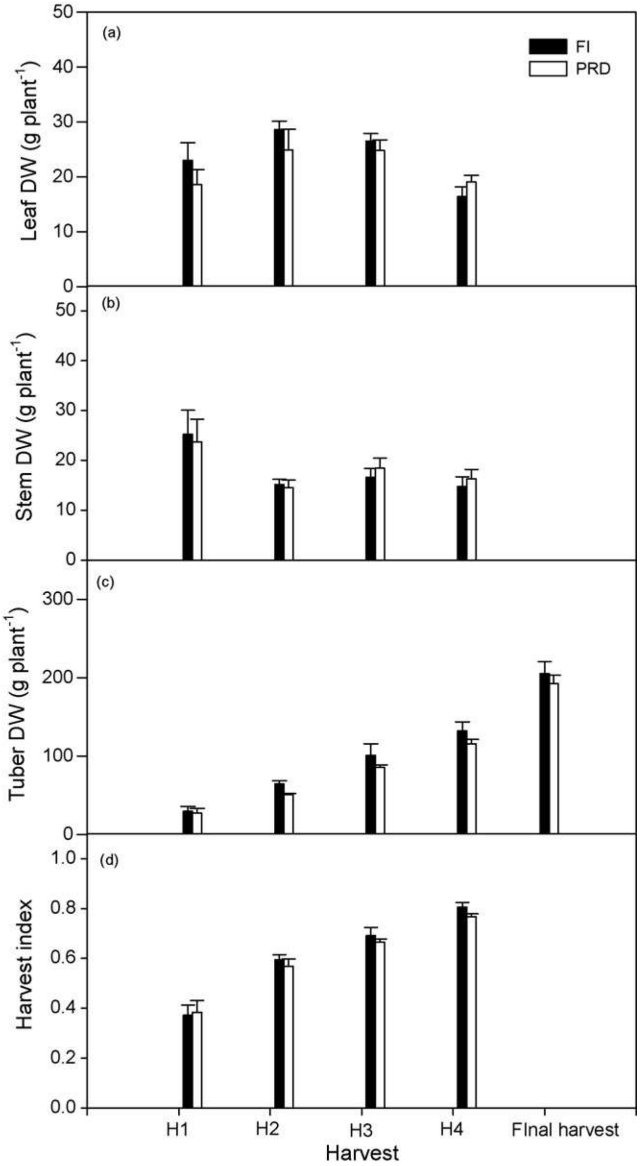

Fig. 2. Leaf (a), stem (b) and tuber (c) dry matter (g plant^{-1}) and harvest index (d) of potato plants under PRD and FI irrigation measured after different harvesting periods (H1, H2, H3, H4 and final harvest) in 2007 experimental season. Bars are means ± S.E.

3.3. Yield and irrigation water-use efficiency (IWUE)

Table 2 shows final yield, marketable yield, amount of irrigation water and irrigation water-use efficiency in both investigated seasons.

Table 2
Total and marketable yield, amount of applied irrigation water (AIW) during treatments and irrigation water-use efficiency (IWUE) of potato under full irrigation (FI) and partial root-zone drying (PRD) in 2007 and 2008 seasons.

Water treatment	Yield (t ha^{-1})	Marketable yield (t ha^{-1})	AIW (mm)	IWUE (kg ha^{-1} mm^{-1})
FI$_{-2007}$	45.31 AB	43.10	188	241.00 A
PRD$_{-2007}$	41.78 A	40.00	125	334.27 B
FI$_{-2008}$	53.19 C	42.52	225	236.40 A
PRD$_{-2008}$	50.46 BC	41.28	130	380.14 C

Different letters show significant differences at 95% level for comparisons between irrigation treatments and investigated seasons.

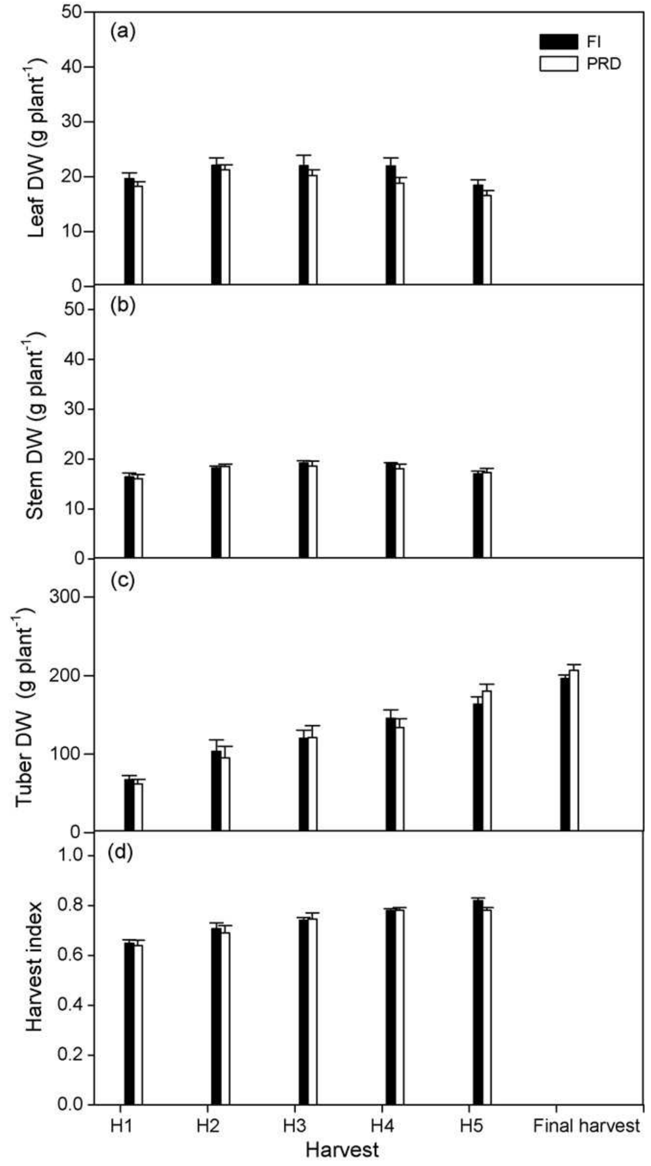

Fig. 3. Leaf (a), stem (b) and tuber (c) dry matter (g plant^{-1}) and harvest index (d) of potato plants under PRD and FI irrigation measured after different harvest periods (H1, H2, H3, H4, H5 and final harvest) in 2008 experimental season. Bars are means ± S.E.

Yield and marketable yield in 2007 was slightly (but not significantly) lower in PRD than in FI treatments and similar was also in 2008 season (Table 2). Comparison between investigated seasons showed that in both treatments in 2008 season yield was significantly higher comparing to 2007 season. This yield increase in 2008 season was *ca.* 8 t ha^{-1}. However, irrigation strategies did not have any large impact on marketable yield. Marketable yield (FW of tubers with diameter between 40 and 60 mm) was not significantly different between FI and PRD irrigated plants or investigated seasons.

In both seasons significant saving of water was achieved with PRD irrigation. The water saving was higher in 2008 comparing to 2007. During 2007 season FI plants received 188 mm of water during the treatment and PRD plants 125 mm of water (Table 2). Therefore, during 2007 PRD plants received 63 mm less water than FI. In 2008 season the water saving by PRD treatment was higher (95 mm) because plants received 225 and 130 mm in FI and PRD treatments, respectively.

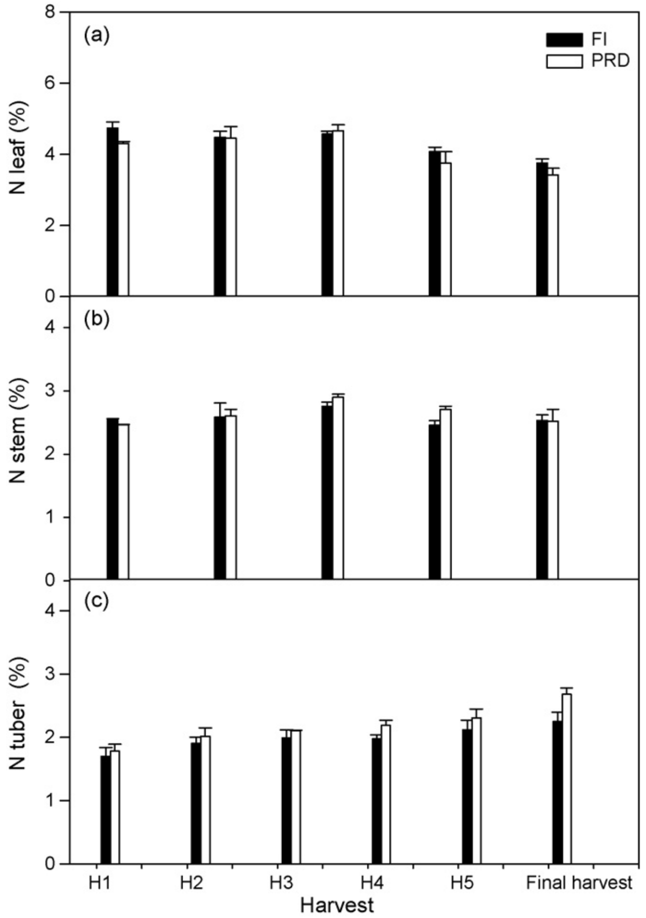

Fig. 4. Nitrogen content (in %) in the leaves (a), stems (b) and tuber (c) of potato plants under PRD and FI irrigation measured after different harvesting periods (H1, H2, H3, H4, H5 and final harvest) in 2008 experimental season. Bars are means ± S.E.

In both seasons IWUE was significantly higher in PRD comparing to FI irrigation. 2007 season data showed that IWUE in PRD plants (334 kg ha^{-1} mm^{-1}) was by 38% higher than in FI plants (241 kg ha^{-1} mm^{-1}). This effect was more expressed in 2008 (increase by 61%) IWUE being 380 and 236 kg ha^{-1} mm^{-1} for PRD and FI, respectively. Also, comparison between investigated seasons showed that new dynamic PRD approach in 2008 had a beneficial effect on IWUE. In 2008 season IWUE in PRD irrigated plants was significantly increased when compared to the 2007 season (by 14%).

3.4. Tuber quality

In both investigated years tuber yield quality data (reducing sugars, titrable acidity, starch content and antioxidant activity) were assessed (Table 3).

Table 3
Tuber quality data at final harvest of potato plants under full irrigation (FI) and partial rootzone drying (PRD) in 2007 and 2008 seasons.

Water treatment	Reducing sugars (g kg^{-1} FW)	Titrable acidity (%)	Starch (% FW)	Antioxidant activity (μmol TE 100 g^{-1} FW)
FI$_{-2007}$	3.38 A	0.036 A	13.72 A	19.92 A
PRD$_{-2007}$	3.11 A	0.039 A	15.02 BC	22.63 B
FI$_{-2008}$	3.10 A	0.02 B	13.45 AB	19.13 A
PRD$_{-2008}$	2.66 B	0.02 B	15.76 C	22.81 B

Different letters show significant differences at 95% level for comparisons between irrigation treatments and investigated seasons.

The content of reducing sugars and titrable acidity did not show any significant differences between PRD and FI treatments or investigated seasons. In both seasons PRD tubers starch content was significantly higher than in FI tubers. The antioxidant activity in both years was also significantly higher in PRD irrigated plants (*ca.* 22 μmol TE 100 g^{-1} FW) than in FI plants (*ca.* 19 μmol TE 100 g^{-1} FW). However, comparison between different PRD approaches (static and dynamic) did not show any significant impact on investigated tuber quality parameters, particularly not on starch content nor antioxidant activity. These parameters were significantly different between FI and PRD plants in both years.

4. Discussion

Our climate data for both seasons showed tendency of decreased summer rainfall accompanied by rising temperature in 2008 compared to 2007 and this led to more intensive agricultural drought in 2008 than in 2007 season (Fig. 1). In Serbia, as in other south east European countries, it is not common practice to irrigate potato during the final phases of tuber ripening. This is usually from the middle of August to the beginning of September. The high precipitation in the beginning of August that was enough to replenish soil water storage in the plant root zone was the reason that in 2007 irrigation ended earlier (2nd August) than in 2008 (13th August). Because of the shorter period for irrigation plants in both FI and PRD treatments plants during 2007 season received less water than PRD and FI plants in 2008 (Table 2).

The amount of irrigation water required to avoid drought stress in potato as in other crops depend on rainfall and ET but also on plant's growth stage. According to Iqbal et al. (1999) water stress imposed during early development (flowering and fruit set) might cause the greatest yield reduction and therefore irrigation should be done during these phases. Results of Liu et al. (2005, 2006a,b) showed that PRD treatment is not feasible for potato during tuber initiation stages. Results of Shahnazari et al. (2008) demonstrated that PRD imposed just after tuber initiation until maturity was the only strategy able to maintain the yield. According to this suggestion in our both experimental years PRD management started from the end of tuber setting phase.

In 2008 season in our experiment additional reduction of water for PRD irrigation from 70% to 50% was done in the stage of tuber ripening. According to Iqbal et al. (1999) it is the growing stage of potato that is least sensitive to drought. Comparing to FI PRD approach in 2008 season allowed saving of 95 mm of irrigation water. This saving was higher than irrigation water saving in 2007 season (63 mm). It was also higher than PRD-irrigation water saving obtained by Shahnazari et al. (2008).

Although the re-wetting frequency under PRD depends on plant, climatic or soil conditions (Stoll et al., 2000), it is still uncertain when the irrigation should be shifted between sides for optimizing PRD. Drying parts of the soil profile during PRD induce generation of chemical signals in the roots. Liu et al. (2008) developed a novel model for prediction of when to shift side based on accumulation of xylem ABA in potatoes grown in pots. Their model simulation results indicated that irrigation should be shifted between the two sides when Ψ_{soil} of PRD dry side decreases to −80 kPa, and xylem ABA of PRD plants reaches a peak of *ca.* 150 nM. However, the xylem ABA value predicted by the model was significantly lower than the measured value and, therefore, further verification of a proposed model should be done especially with plants grown under field conditions.

In PRD experiments it is important to sustain yield. Reduced irrigation has a decreasing effect on potato yield (Fabeiro et al., 2001; Onder et al., 2005). Drought reduces the final number of tubers or average tuber dry weight (Deblonde and Ledent, 2001) as well as the quality of potato yield (Tekalign and Hammes, 2005). In our experiments leaf, stem and tuber DM were similar although PRD irrigated plants received much less water than FI plants (Figs. 2 and 3). We did not measure any parameters of plant's water regime, but the maintenance of biomass in PRD similar to FI and continued growth of tubers, according to Yuan et al. (2003), indicated that PRD plants have not been exposed to drought stress.

The efficiency of dry matter accumulation by tubers depends on the rate of photosynthesis, efficiency of assimilate translocation to tubers (bulking rate) and maturity period.

Results of Mingo et al. (2004) showed that PRD tomato plants achieved biomass equivalence with FI plants but in PRD plants translocation of dry matter from leaves and stems was increased comparing to FI plants. This resulted in the increase of root biomass by 19% over control plants. Similar translocation tendency was also found in potato (Liu et al., 2006b; Shahnazari et al., 2007). Our leaf, stem and tubers DM results indirectly confirmed positive effect of PRD on DM translocation especially during 2008 season when 70% of PRD was replaced by 50% PRD irrigation during the latest growth period (Fig. 3).

Measurements of N content in leaves and stems, similarly to DM data, also indicated that enhanced translocation of N (from leaves to tubers) occurred during 2008 growing season (Fig. 4). At final harvest N content in tubers of PRD irrigated plants was *ca.* 19% higher in PRD than in FI irrigated plants. Similar results were also obtained for 2007 season (Jovanovic et al., 2008). These results indicated that PRD treatment could improve translocation of N from shoot to tubers at final harvest and also increase the N-use efficiency. Shahnazari et al. (2008) found lower residual N in PRD than in FI treatments confirming that PRD treatment may improve soil nitrogen availability during the late phases of potato growing season. N results, similarly to DM data, might suggest a more beneficial effect of "dynamic" PRD approach than "static" PRD on plant growth.

In our 2007 experimental season, the yields of 45.3 and 41.8 t ha^{-1} were obtained from potato plants in FI and PRD irrigation, respectively. During 2008 yield was higher in both treatments: FI (53.2) and PRD (50.5 t ha^{-1}). The yield of both experimental seasons in our experiments was 20% lower than in similar field experiments of Shahnazari et al. (2007). The average temperature is the main determinant factor for potato final tuber size and dry matter concentration at harvest. According to Haverkort and Verhagen (2008) optimum temperature threshold for potato growth coincides with day–night temperatures of 27–15 °C. At higher temperatures, daily potato growth is reduced due to increased respiration. Dry matter distribution mainly favors the foliage and tuber dry matter concentration becomes low. In the last few seasons in Serbia the number of days when temperature during summer exceeded 30 °C increased significantly. This could explain lower yield and dry matter production of potato comparing to the production in Denmark (Shahnazari et al., 2007).

Comparison of the effects of PRD and FI irrigation technologies did not show significant differences in both yield and marketable yield in investigated seasons (Table 2). As the result of yield maintenance in PRD irrigation and reduction of water applied for irrigation, a highly significant increase in IWUE comparing to FI was obtained in both seasons. Similar yield and IWUE responses to PRD treatment were found for several other crops (Costa et al., 2007). Liu et al. (2006a) for pot grown potato and Shahnazari et al. (2007) for field-grown potato showed that compared with FI, PRD treatment saved 30% of water and increased water-use efficiency by 59%. However, the results of the same group of authors (Liu et al., 2006b) showed that exposure of potato to PRD in early phase of growth (tuber initiation) did not have similar advantage comparing to full or deficit irrigation.

Comparison of our IWUE data also showed that differences in IWUE between PRD and FI were higher in 2008 season when "dynamic" PRD was applied than in 2007 year when "static" approach of PRD irrigation was used (by 14%).

The presented study was also done with the aim to evaluate the effect of dynamic PRD criteria on yield quality. Many studies in different species have also shown that comparing to FI the classical (fixed) PRD might increase quality of yields in many agricultural crops (Costa et al., 2007). Our quality assessment data (Table 3) did not show any significant differences in reducing sugars content and titrable acidity of PRD and FI irrigated crops. However, in both seasons a significant increase in antioxidant activity (by 3 μmol TE per 100 g FW) and in starch content (from *ca*. 13% to 15% FW) was found in PRD compared to FI tubers. In literature there are no data on the effect of PRD on antioxidant activity in yield components (fruits, tubers, seeds) of agricultural crops. Only available data on the effects of PRD irrigation are those of Aganchich et al. (2007) who showed the increase in activity of several antioxidant enzymes in PRD and RDI (regulated deficit irrigation) irrigated olives. According to these authors this increase can be an important protection mechanism of the olive plant against an oxidative stress that might occur under PRD and RDI treatments. Very recent studies of Andre et al. (2009) were done on the effects of drought on antioxidative compounds in tubers of several native Andean potato cultivars. These results demonstrated that the increase in oxidative stress, induced by drought, might be responsible for modification of antioxidative contents, which relied mainly on cultivars stress sensitivity. Their research highlighted the importance of polyphenols and carotenoids as antioxidative compounds. Our research did not include any of antioxidant compounds and because of a complex relationship between antioxidant activity and content of different antioxidant compounds it is difficult to explain the observed increase in PRD treated plants. However, the employed Trolox equivalence antioxidant capacity method for assaying antioxidant activity in fact measures the reducing capacity of antioxidants. In literature on antioxidants the findings of excellent correlation between total phenolic content measured by Folin–Ciocalteu assay and antioxidant activity (measured by assays based on electron transfer) can be seen because these assays are based on similar redox reactions (Huang et al., 2005). Thus, the obtained values for increased antioxidant activity may reflect higher content of total phenolic compounds in PRD treated potato. Furthermore, the increase of the antioxidant activity under PRD is very desirable characteristic that increases health-promoting value of potato tubers.

5. Conclusion

Experimental results for both seasons showed that PRD irrigated plants produced tubers similar in yield to FI plants but with improved quality in terms of higher N and starch content. Also, the increase in tubers antioxidant activity under PRD might be beneficial for the health-promoting potato value.

Although the obtained values for increased antioxidant capacity may reflect higher content of total phenolic compounds in PRD treated potato, further work should be performed to clearly identify the antioxidative compounds responsible for this increase.

Greater saving of irrigation water and increase in IWUE that was achieved when 70% PRD was replaced with 50% PRD during drought tolerant growth stages indicate that "dynamic" approach could be more promising strategy for saving water for potato irrigation than classical "static" approach. Further research of PRD dynamic approach should be done to a wider variety of field-grown crops and on a larger scale.

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