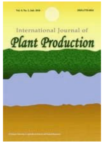

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Comparing canopy temperature and leaf water potential as irrigation scheduling criteria of potato in water-saving irrigation strategies

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Abstract

Irrigation scheduling is important in irrigation water management. In this study, full (FI), deficit (DI) and partial root drying (PRD) irrigation strategies were applied in Agria and Ramos potato cultivars. Canopy temperature (CT) and leaf water potential (LWP) were assessed as the potential tools for irrigation scheduling during the vegetative and productive growth stages. LWP varied between *ca.* -1.4 and -1.6 MPa and was not significantly different between FI, DI and PRD irrigation treatments. The LWP and CT values were not significant between the two potato cultivars during the measurements, but CT was frequently significant between the irrigation treatments such that the PRD treatments were significantly 5 and 2 ^{o}C warmer than FI and DI treatments, respectively. Higher CT in PRD caused significant yield penalty such that DI and FI produced almost two times higher fresh tuber yield. Analysis revealed that CT had significantly higher correlation (r=0.66) with water productivity (weight of fresh tuber yield divided by volume of applied irrigation water) than LWP, which its correlation was not significant (r=0.40). This showed that crop water productivity could be better controlled by CT. Moreover, it was realized that the seven-day irrigation interval was far longer than required and potatoes in all irrigation treatments were under water stress, especially in PRD, that might partially explain the 50% yield penalty of PRD compared to DI. The reason was that due to high atmospheric demand, soil water in the wet part of the root system would be completely depleted earlier by the time of next irrigation event. Conclusively, the CT is recommended as a more reliable crop water status and irrigation scheduling indicator than LWP in response to different water-saving irrigation managements.

Keywords: Deficit irrigation; Partial root drying irrigation; Canopy temperature; Leaf water potential; Potato cultivars.

Introduction

Potato (*Solanum tuberosum* L.) is one of the world's major stable food crops that its production ranked four after the major cereals rice, wheat and maize (Ahmadi et al., 2010b). Potatoes are generally vulnerable to water stress and require efficient irrigation to secure high yield of tuber production. The vulnerability of potatoes to water stress is attributed to their relatively shallow root growth (Ahmadi et al., 2011). Thus, continuous monitoring of soil and crop water status during the growing season is required to maintain the quality and quantity of potatoes under the competitive conditions of current water resources (Rud et al., 2014).

The increasing global shortage of water resources and high costs of irrigation have resulted in development of precise water-saving irrigation strategies that lead to minimize water use in crop production (Jones, 2004). Water-saving irrigation strategies reduce crop water consumptions and among these strategies are deficit irrigation (DI) and partial root drying irrigation (PRD) that have been developed for limited irrigation managements. The PRD is the subsequent improvement of DI that involves irrigating half of the root zone while leaving the other half to dry to a predetermined level before the next irrigation (Kang and Zhang, 2004). This wet and dry side alternation approach simultaneously sustains plant water situation at its maximum water potential and control vegetative growth via maintaining high leaf water potential and elevated transport of Abscisic acid (ABA) for decreasing water loss through transpiration for specific parts of the seasonal period of plant expansion (Kang and Zhang, 2004). Detailed reviews on the agronomic and physiological effects of DI and PRD for different crops are presented in Kang and Zhang (2004), Dodd (2009) and Sepaskhah and Ahmadi (2010).

A disadvantage of DI is that it needs to precisely keep the water status in a narrow range of water stress tolerance because both sides of crop roots are under-irrigated, but the potential advantage of PRD is that precise irrigation is less critical than it is for DI because crops are always fully irrigated in one side of the root system (Jones, 2004). Therefore, accurate irrigation scheduling is very important for achieving the benefits of these water-saving irrigation strategies. Former studies have shown that plants subject to DI and PRD show different physiological responses (e.g. Ahmadi et al., 2016; Ahmadi et al., 2011a; Sadras, 2009; Liu et al., 2006a). Liu et al. (2008) and Dodd et al. (2008b) declared that irrigation scheduling of PRD based on soil moisture may not result in accurate timing of irrigation and in this regard Dodd et al. (2008b) suggested that plant-based measurements should be employed. Likewise, Jones (2004) stated that soil water-based irrigation scheduling under water-saving irrigation strategies might be replaced by the plant-based methods that preferably consider the physiological responses to plant stress sensing. Among the plant-based indicators, leaf water potential (LWP) and canopy temperature (CT) have been often employed for monitoring water status of crops. Indeed, LWP indicates crop water status and CT is a physiological response of crops to water stress as thermal sensing (Jones, 2004). So far several studies on LWP (e.g. Williams et al., 2012; Tahi et al., 2007; Girona et al., 2006; Sepaskhah and Kashefipour, 1994) and CT (e.g. Baker et al., 2013; Bockhold et al., 2011; Edwards et al., 2011; Wang and Gartung, 2010) have been elaborated for irrigation scheduling in the DI strategy, but similar studies are very rare for PRD irrigation scheduling.

The dynamic and static PRD and DI strategies were recently developed and tested on potatoes and the tuber yields and water-relations, water productivities and nitrogen content under these irrigation strategies were reported (Ahmadi et al., 2016; 2014). Indeed, the dynamic concept means that various fractions of the full irrigation (FI) requirement are applied in the water-saving irrigation treatments, either PRD or DI, during the growing season; however, the static concept means a fixed fraction of FI is used in the water-saving irrigation managements during the growing season. The dynamic PRD was a novel and newly developed irrigation strategy as compared to the dynamic DI (traditionally known as regulated DI), static DI (traditionally known as continuous DI) and static PRD (i.e. the conventional PRD) irrigation strategies. However, the physiological responses of crops to these irrigation managements under a specific condition are rather limited. Nevertheless, because of the complexities in practicing the dynamic and static PRD and DI strategies, accurate irrigation scheduling is required to achieve the highest yield productivity (Ahmadi et al., 2010b; Liu et al., 2008). Previous studies have proven that potato cultivars show contrasting responses to water deficits (Levy, 1986) that this may help in selection of suitable genotypes for growing in arid and semi-arid regions. In our earlier study (Ahmadi et al., 2014), it was found that Agria cultivar was more tolerant to water stress than the Ramos cultivar in terms of yield production and water productivity; and therefore the present study assesses if these two potato cultivars would show differences in terms of other crop physiological parameters that are commonly used for assessing the effect of water stress on crops. Hence, the objectives of this study were to (1) assess the potential in implementation of LWP and CT in irrigation scheduling under the dynamic and static PRD and DI irrigation, and (2) assessing if LWP and CT might be useful tools for irrigation scheduling of the two contrasting potato cultivars in the semi-arid environment of Iran.

Materials and Methods

Experimental site

The experiment was carried out in summer 2012 at the experimental fields of Faculty of Agriculture, Shiraz University, Iran, located 16 km north of Shiraz (29º, 36′ N, 52º, 32′ E, 1810 m.s.l.). The climate was warm with an annual average rainfall of about 386 mm. The mean air temperature during the growing period was 23.5 ºC. The weather data were collected at a nearby climate station situated approximately 20 m from the field. No rainfall occurred during the growing season. Table 1 presents the soil properties of the experimental site.

Table 1. Physical properties of the soil used in this study.

Depth (m)	Texture	Clay (%)	Silt (%)	Sand (%)	Bulk density (kg m^{-3})	FC (m^{3}m^{-3})	PWP (m^{3}m^{-3})
0-0.3	SiL	21.2	48.8	29.9	1290	0.32	0.17
0.3-0.6	CL	27.2	48.8	23.9	1460	0.35	0.198
0.6-0.9	SiCL	33.2	48.8	17.9	1540	0.35	0.212
0.9-1.2	SiCL	32.7	54.8	12.4	1570	0.36	0.224

SiL = Silt Loam, CL = Clay Loam, SiCL = Silty Clay Loam.

Experimental procedure

Potato seed tubers were planted on 19 April 2012, at 0.75 m inter-row and 0.25 m inter-plant distances. The field was divided into 30 plots of 5×4 m^2 (length×width). Experimental plots had four rows and were separated by a 1 m wide guard area. Seed tubers were ridged with 0.2 m soil in prepared furrows. The potato growth period was divided into three stages according to the BBCH scale (Hack et al., 2001) and the fertilizers were applied at the start of each stage. First fertilizer application was before the plantation at the rate of 100 kg ha^{-1} of Di-ammonium Phosphate (18-20-0 NPK). Later 300 kg ha^{-1} of Urea (46-0-0 NPK) was applied at the second one-third of growth period (82 DAP) that corresponded to BBCH code of 40-69. Finally, during the last one-third of growth period (BBCH code of 70-99) foliar application at the rate of 90 and 72 g l^{-1} of NPK (20-20-20) was applied at 108 and 115 DAP, respectively.

A factorial experiment as a randomized complete block design was designed with five irrigation strategies and two potato cultivars in three replications. The two potato cultivar treatments were Agria and Ramos. The irrigation interval was 7 days that is norm in the region. The amount of water for each irrigation event was determined based on multiplying the daily reference evapotranspiration (ET_o) and the recommended FAO's crop coefficient (K_c) (Allen et al., 1998). The five furrow-irrigated treatments started at the onset of tuber initiation on 35 DAP as 1) full irrigation (FI) receiving 100% of the potential crop evapotranspiration (ET_p=ET_o×K_c) that totally received 950 mm water in the growing season, 2) static deficit irrigation (SDI) receiving 75% of ET_p during the whole growth period that totally received 712 mm water; 3) dynamic deficit irrigation (DDI) receiving 90% of ET_p in the first one-third of growth period, 75% of ET_p in the second one-third of growth period, 50% of ET_p in the last one-third of growth period, which totally received 681 mm water; 4) static partial root drying irrigation (SPRD) receiving 75% of ET_p during the whole growth period that in total received 712 mm water; and 5) dynamic partial root drying irrigation (DPRD) receiving 90% of ET_p in the first one-third of growth period, 75% of ET_p in the second one-third of growth period, 50% of ET_p in the last one-third of growth period that totally received 681 mm water. The furrows of FI, DI and PRD were irrigated as suggested by Sepaskhah and Hosseini (2008) and Kang et al. (2000). For crop establishment, each plot was irrigated 30 mm in the first two irrigations at 8 and 22 DAP, respectively. Former studies have shown that the PRD treatments should be started after tuber initiation for potato tuber yield maintenance that occurred about 5-6 weeks after planting (Yactayo et al., 2013; Ahmadi et al., 2010b; Shahnazari et al., 2008).

Measurements and data analysis

After potatoes started flowering on 70 DAP (BBCH Code 69) that coincided with full soil coverage, LWP and CT were measured every two-weeks till leaves senescence. Midday LWP was measured with the Scholander pressure chamber (1000 Pressure Chamber Instrument, PMS Instrument Company, U.S.A.) on a fully expanded leaf from top of the plant during 13:00 and 15:00 p.m. in all replications. Since 83 DAP, measurements were done four times during the growing season. The measurements were made just before the irrigation event when water stress was potentially maximal.

Infrared thermometer (Infratrace 800, Kane International Ltd, UK) was used to measure the canopy temperature (CT) of potatoes. The infrared thermometer was calibrated by adjusting its sensitivity coefficient to correctly read the temperature of the potato leaves that had fully covered the water surface in a large pot. Having reached the temperature equilibrium between water and leaves, the temperature of the floated leaves was measured by infrared thermometer and the sensitivity coefficient was adjusted to accurately measure the water temperature that was measured by a regular thermometer.

The CT was measured from 13.00 to 15.00 p.m. in all replications aiming the canopy cover with an angle of 45 degrees. Since 69 DAP, measurements were done five times during the growing season. For accurate measurements, six readings were made in each plot. The measurements were done just before the irrigation event when water stress was potentially maximal.

On 12 and 13 September 2012 (146 and 147 DAP), the potato crops were harvested from a 1 × 1 m^2 area from the center of each plot for determining and measuring the total tuber fresh weight. Water productivity (WP) in every irrigation treatment was calculated as dividing the total tuber fresh weight (kg) by the total applied irrigation water (m^3) after starting the irrigation treatments at 35 DAP.

Data were analyzed for analysis of variance (ANOVA) using the GLM procedure (SAS Software, version 9) and the means were compared at p=0.05 probability level.

Correlations were made between the LWP and CT with the water productivity. In addition, the dimensionless crop water status ratio of $\frac{LWP_r}{CT_r}$ was calculated and its correlation with the relative tuber yield, Y_r, was determined. The subscript r denotes the relative value, which implies the ratio of the measured parameter in any of the four water-saving irrigation treatments and the corresponding value in the FI treatment.

Results and Discussion

Irrigation effects on leaf water potential

In total, the LWP was measured in four days spanning the times between flowering and senescence (Table 2). It is seen that there were no increasing or decreasing trends in the LWP values between the measured dates and overall, the LWP values varied between *ca.* -1.4 and -1.6 MPa in all irrigation treatments. They were not significantly different between the irrigation treatments and potato cultivars (Table 2). The LWP values measured in this study matched to the LWP values of the five potato cultivars as low as -2.4 MPa in Tourneux et al. (2003) but were much lower than the potato LWP values as low as -0.6 MPa in any of the FI, DI, or PRD (Ahmadi et al., 2010a). Ahmadi et al. (2010a) have also indicated that the diurnal variations of LWP values in potatoes were essentially similar in the PRD and FI treatments. Shahnazari et al. (2007) investigated the LWP under PRD and DI and showed that the LWP was similar in all irrigation treatments at nine days after onset of treatments (DOT), whereas it was considerably lower in PRD than FI and DI at 21 DOT. The considerable conflicting LWP values in several studies indicates that potatoes would exhibit a wide range of LWP values depending on the potato cultivars, water stress level and climatic conditions.

Table 2. Average leaf water potential (MPa) in the different irrigation treatments at the different days after planting (DAP). Different letters in a column of each experimental factors show significant differences at 0.05 probability level.

Factor	83 DAP	97 DAP	111 DAP	125 DAP
Irrigation treatment				
FI	$-1.50^{a}\pm0.14^{*}$	$-1.58^{a}\pm0.13$	$-1.47^{a}\pm0.08$	$-1.38^{a}\pm0.15$
SDI	$-1.4^{a}\pm0.11$	$-1.55^{a}\pm0.14$	$-1.56^{a}\pm0.14$	$-1.38^{a}\pm0.27$
DDI	$-1.45^{a}\pm0.05$	$-1.58^{a}\pm0.19$	$-1.48^{a}\pm0.13$	$-1.58^{a}\pm0.16$
SPRD	$-1.48^{a}\pm0.11$	$-1.57^{a}\pm0.12$	$-1.55^{a}\pm0.16$	$-1.58^{a}\pm0.18$
DPRD	$-1.42^{a}\pm0.12$	$-1.58^{a}\pm0.13$	$-1.63^{a}\pm0.14$	$-1.58^{a}\pm0.24$
p-value	0.52	0.99	0.26	0.14
Cultivar				
Agria	$-1.49^{b}\pm0.11$	$-1.61^{a}\pm0.14$	$-1.55^{a}\pm0.15$	$-1.48^{a}\pm0.21$
Ramos	$-1.41^{a}\pm0.09$	$-1.54^{a}\pm0.12$	$-1.53^{a}\pm0.13$	$-1.53^{a}\pm0.23$
p-value	0.03	0.23	0.74	0.51
Irrigation × Cultivar				
p-value	0.53	0.56	0.51	0.16

* Represents the standard deviations (±SD) of the means for each treatment.

Anyway, the LWP values measured were extremely low, even for the FI treatment and this could be recognized by comparing the LWP values with other studies on potato under full irrigation (Ahmadi et al., 2010a, Shahnazari et al., 2007; Tourneux et al., 2003). Potato plants at LWP as low as *ca*. -1.5 MPa were probably close or even below their wilting point. This is a situation where irrigation timing and scheduling was clearly wrong. It suggests that in the study area the seven days interval between irrigation events is far longer than required even for fully irrigated potatoes. Although soil water content was not measured during the growing season, based on the physical properties of the soil it could be concluded that soil water content within the very active top 30-40 cm root zone (Ahmadi et al., 2011; Opena and Porter, 1999) has decreased fast few days after irrigation events because of high atmospheric demand, VPD (Figures 1B and 1C) such that the decrease in sap flow from the root system has been limited and LWP decreased to the relatively constant LWP of *ca.* -1.5 MPa in all irrigation strategies (Dodd et al., 2008a; Liu et al., 2005). Therefore, it can be suggested that the absence of differences in LWP might indicate that potato close stomata to maintain stable leaf water potentials. There are strong evidences in potatoes (Ahmadi et al., 2009; Liu et al., 2005; 2006a) that the root-source Abscisic acid (ABA) signal interacts with LWP to justify the stomatal conductance to reduce transpiration loss via maintaining a relatively constant LWP under contrasting water stress levels (Tardieu and Simonneau, 1998; Tardieu et al., 1993).

Potatoes are generally sensitive to water stress and LWP drops rapidly by water stress (Ahmadi et al., 2009). Gregory and Simmonds (1992) stated that potatoes have limited ability to maintain a large difference between soil water potential and LWP values in contrast to other field crops such as maize, wheat, lucerne and sugar beet and therefore LWP values in water stressed potatoes rarely falls below -1.0 to -1.5 MPa, even if soil moisture deficit and VPD would be large. These arguments show that potatoes generally avoid falling LWP below *ca.* -1.5 MPa via limiting transpiration by stomatal closure. There are several evidences that gas exchange of potatoes is strongly related to LWP (Ahmadi et al., 2009; Liu et al., 2006a, b). Previous studies on potatoes have showed that LWP values lower than nearly -0.4 and -0.6 MPa would reduce the assimilation rate by limiting gas exchange (Ahmadi et al., 2010a; Gregory and Simmonds, 1992; Shimsi et al., 1983; Levy, 1983). In this regard, Tourneux et al. (2003) and Stark (1987) reported that the LWP thresholds for reducing gas exchange of potatoes were -1.0 and -0.8 MPa, respectively. In addition, high VPD would influence LWP variations by closing or narrowing stomata (Ahmadi et al., 2009; Aphalo and Jarvis, 1991). So, low LWP values between -1.38 MPa and -1.63 MPa (Table 2) that occurred simultaneously with the high VPD values between *ca*. 2.5 and 3.5 kPa during the high vegetative and productive growth stages (Figure 1) could be the reasons behind non-significant differences between the tuber yields in FI and DIs (Ahmadi et al., 2014). This suggests that tuber production in the fully irrigated potatoes might have been suppressed due to decreased transpiration and assimilation rates, which imply the fully irrigated potatoes might have been also experiencing water stress levels.

It is noteworthy that the LWP measurements; however, could not support the physiological concept behind the PRD irrigation such that under equal amount of applied water, the PRD strategy generally favors higher LWP than DI because of the increased stream flow through the irrigated root system that maintains favorable plant water status (Sepaskhah and Ahmadi, 2010; Ahmadi et al., 2010b; Liu et al., 2006a;

Kang et al., 2003). In fact, responses of plants to different water-saving irrigations are pretty complex such that not only are influenced by the irrigation strategy but also by other environmental factors like growth conditions, cultivars and the level of applied water stress (Beis and Patakas, 2015). Nevertheless, low LWP values in all irrigation treatment showed that all the potato crops were experiencing water stress caused by substantial decrease in soil water content/potential a few days after irrigation event. Apparently, this showed the need for more frequent LWP measurements after irrigation events during the high vegetative and productive growth stages to elucidate the optimum irrigation scheduling. Most likely a fixed irrigation interval might not be the appropriate idea in the water-saving irrigation treatments of potatoes in this region.

It is worth mentioning that both DI and PRD irrigation strategies equally received 712 mm irrigation water during the whole growing season, but the fresh tuber yield production in PRD was remarkably suppressed by nearly 50% relative to DI, 16 Mg ha^{-1} *vs.* 33 Mg ha^{-1}, respectively (Ahmadi et al., 2014). This pinpoints the importance of proper irrigation scheduling and shifting between dry and wet sides in PRD strategies to maintain tuber yield production (Liu et al., 2008; Dodd et al., 2008a). It clearly shows that due to the different irrigation practices and imposed wet/dry cycling, the potato water uptake pattern in the PRD is very different compared to the DI under equal amount of water and therefore determination of irrigation depth based on the FAO methodology (Allen et al., 1998) might not be the recommended approach for irrigation scheduling of the PRD.

Even though the FAO methodology considers water stress, it does not take into account the root split in PRD that effects on crop water uptake and use. Jones (2004) did argue that PRD irrigation management needs appropriate and timely water application for vegetative crops. Accordingly, Sepaskhah and Ahmadi (2010) reported that PRD might not be a successful practice in arid and semi-arid areas where the atmospheric demand is high (Figure 1). They recommended that the irrigation planning should be more frequent in sensitive crops in arid and semi-arid environments, which means the 7-day irrigation interval in this study should have been shorter, which partly explains the poor results of PRD compared to DI, as soil water in the wet part of the root system would be completely depleted by the time of next irrigation event. This confirms the idea that irrigation frequency should be determined based on crops, growing stages, irrigation management and soil water balance (De la Hera et al., 2007; Kang and Zhang, 2004).

However, shorter irrigation intervals cause more soil evaporation that would decrease water productivity, but it could be justified by higher tuber production. Such tradeoffs need more investigations especially in PRD. In addition, when soil kept dry in hot conditions for a long time, the tuber sizes and yield might be negatively affected because of increased soil strengths and hardness, particularly in heavy soil textures such as silty clay loam in this study. These conditions are more pronounced in the PRD where all furrows are not irrigated in every irrigation event. Therefore, heavy soil and long-term soil drying in PRD will impose severe impact on tuber production. Nevertheless, more researches are required to investigate these conditions.

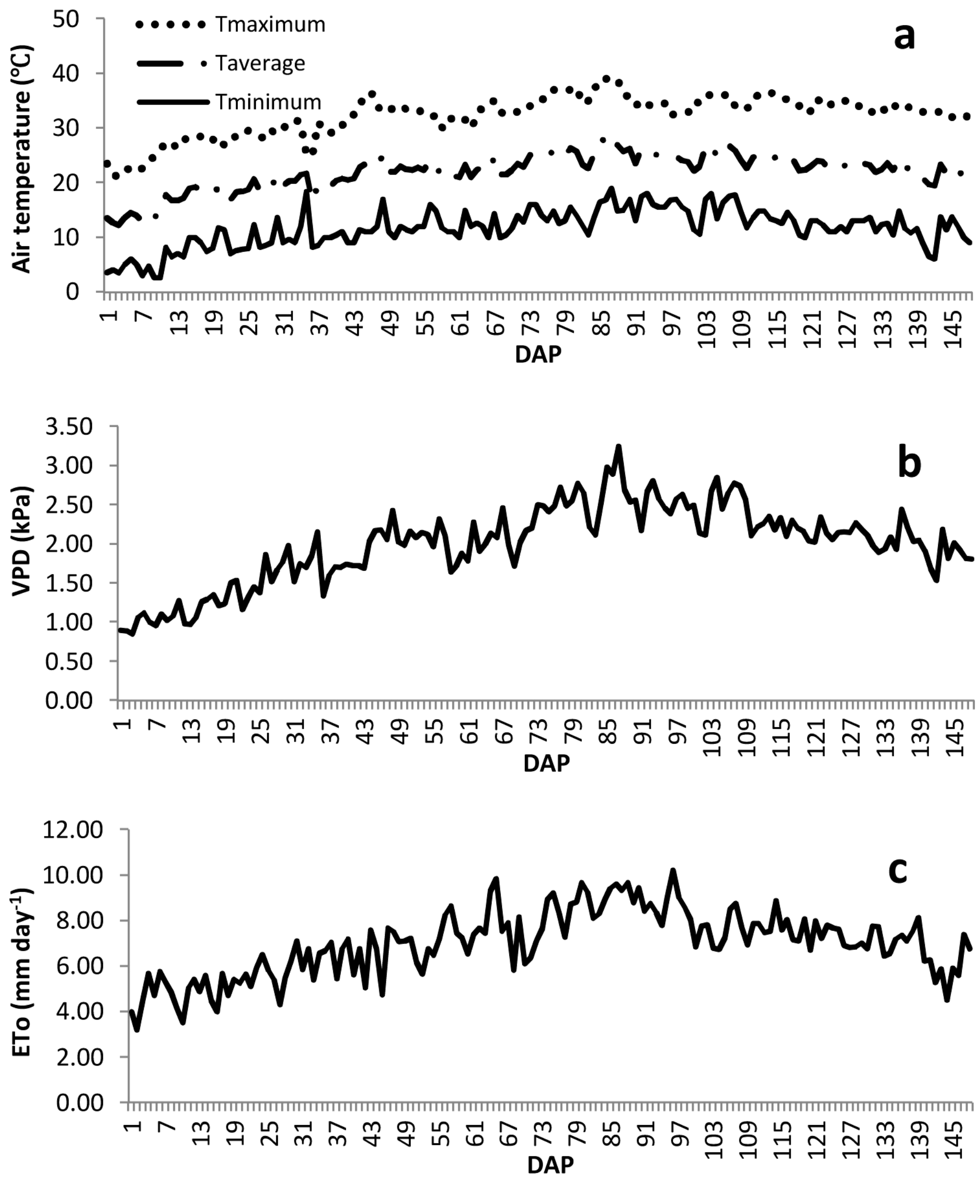

Figure 1. Daily variations of a) mean, minimum and maximum air temperature b) vapor pressure deficit and c) reference evapotranspiration.

Irrigation effects on canopy temperature

In general, irrigation strategies significantly affected the CT (Table 3). Clearly, CT outperformed LWP in elucidating the effect of irrigation strategies on crop physiology. However, the CT values were not significantly different between the potato cultivars during the growing season (Table 3). Interestingly, the PRD treatments (SPRD, DPRD) were significantly warmer than FI and had often significantly higher CT than DI treatments during the measuring period (Table 3). Neither dynamic nor static strategy did affect the CT in any of the water-saving irrigation strategies.

Table 3. Average canopy temperature (ºC) in the different irrigation treatments at the different days after planting (DAP). Different letters in a column of each experimental factors show significant differences at 0.05 probability level.

Factor	69 DAP	83 DAP	97 DAP	111 DAP	125 DAP
Irrigation treatment					
FI	29.27^{b}±2.01*	32.71^{b}±0.88	34.21^{c}±0.90	32.15^{b}±2.1	32.72^{c}±2.60
SDI	30.70^{ab}±2.45	34.69^{b}±2.14	36.57^{ab}±1.50	35.64^{a}±1.63	33.06^{c}±1.78
DDI	31.07^{ab}±1.91	34.54^{b}±2.04	35.93^{bc}±1.32	34.72^{a}±1.90	33.05^{bc}±0.80
SPRD	33.41^{a}±1.83	38.73^{a}±1.55	38.34^{a}±2.11	36.93^{a}±2.19	36.92^{ab}±2.50
DPRD	32.24^{a}±2.17	39.85^{a}±1.70	37.94^{a}±1.96	36.80^{a}±1.46	38.85^{a}±2.56
p-value	0.05	<0.001	0.002	0.004	0.001
Cultivar					
Agria	31.04^{a}±2.34	36.24^{a}±2.98	36.67^{a}±2.41	35.22^{a}±2.80	35.53^{a}±2.60
Ramos	31.63^{a}±2.52	35.97^{a}±3.49	36.53^{a}±1.89	35.31^{a}±2.67	35.11^{a}±3.54
p-value	0.48	0.65	0.81	0.91	0.61
Irrigation × Cultivar					
p-value	0.93	0.15	0.24	0.95	0.90

* Represents the standard deviations (±SD) of the means for each treatment.

The PRD treatments were nearly 5 °C and 2 °C warmer than the FI and DI treatments, respectively. In all irrigation events, the DI treatments were cooler than the PRD treatments. The FI treatments were 1-3 °C and 3-7 °C cooler than DI (DDI and SDI) and PRD (DPRD and SPRD) treatments, respectively. Lower fresh tuber yield in the PRD treatments (*ca.* 16 Mg ha^{-1}) clearly indicated that warmer potato plants produced much lower tuber yields than the cooler ones in DI treatments (*ca.* 33 Mg ha^{-1}) implying that DI produced almost two times more yield than the PRD treatments (Ahmadi et al., 2014). Indeed, cooler CT in the FI treatment than the water-saving irrigation treatments (PRD and DI) confirms the principle that transpiring leaves are generally cooler than the slowly transpiring leaves (Kramer and Boyer, 1995). The significant lower tuber yield in the PRD treatments compared to the DI and FI treatments could be well in agreement with the reduced transpiration rate based on the higher CT and its subsequent loss in assimilation rate. Under water-saving irrigation treatments, plants with cooler CT potentially transpire at higher rates and are capable of relatively high photosynthetic rates, growth and yields (Kramer and Boyer, 1995; Pinter Jr et al., 1990). However, the large yield gap between PRD and DI could not be solely related to the significant CT differences, and since this study focused only on two physiological variables (CT and LWP), a further objective could have been whether cultivar variations in yield responses can be explained in terms of other physiological parameters, suggesting that other crop physiological mechanisms such as root growth pattern and water uptake and physico-biochemical responses to water stress were more important in yield determination (Sepaskhah and Ahmadi, 2010).

In a recent review paper, Monneveux et al. (2013) stated that "*No information is available concerning variation of canopy temperature under drought conditions and its association with yield*". Apparently the findings in this study showed that the yield differences among the irrigation treatments were quite well associated with the CT variations rather than the LWP variations. The CT has been potentially recognized to reflect the whole crop water status with close association to crop yield (Kirkham, 2014; Prashar et al., 2013; Jackson et al., 1981), but LWP could affect locally leaf level intrinsic water use efficiency (Ahmadi et al., 2010a). Furthermore, CT varied considerably among the irrigation strategies showing the water stress effect and crop water status, but LWP in all irrigation treatments varied in a narrow range and was less variable to water stress levels (Table 2). It could be suggested that the existence of differences in CT together with the absence of differences LWP might indicate that potatoes closed stomata to maintain stable leaf water potential. However, it should be noted that the measurements were taken just before the irrigation event (the highest possible water stress) and there were no intermediate measurements between two irrigation events (the days between two irrigation events). This means that it is rather difficult to precisely assess the utility of both tools without knowing their dynamic responses as soil dries during the seven-day irrigation interval. Ideally, we would need to know when differences in CT (or LWP) start to be detectable and what extent of CT difference induces a yield penalty. Therefore, intermediate measurements during the drying cycle of each irrigation event is required to compare CT values between different irrigation approaches that can be used either for more robust irrigation scheduling or to understand potato responses to water deficits. Nevertheless, based on the measurements, we realized that CT could reflect the effect of water stress on potatoes clearly well but LWP could not recognize the trends and was less sensitive to water stress treatments than CT (Tables 2 and 3).

Canopy temperature is measured above a relatively large area of crop canopy and averages the whole canopy instead of individual leaves, but LWP is generally measured on a single and fully expanded leaf on top of the canopy that might not fully represent the whole crop water status (Prashar et al., 2013). Vos and Groenwold (1988) showed the vertical gradient in LWP along the stem of potato where top leaves had lower LWP than middle and bottom leaves. In another study that focused on the yield of five chickpea cultivars under supplemental irrigation, Silva et al. (2014) reported that the Elixir cultivar presented the higher grain yield even though it registered the lower LWP. Therefore, it is concluded that LWP measurement on a leaf could not be potentially a good covariate for crop yield. In addition evidences demonstrated that crop yields of potato (Erdem et al., 2006; Dalla Costa et al., 1997), soybean (Irmak et al., 2002) and corn (Irmak et al., 2000) were efficiently modeled and correlated with the CT. So, it is apparent that CT is a reliable crop parameter to monitor plant water status and irrigation scheduling, which is also confirmed and suggested for potatoes by Rud et al. (2014) and Vos and Haverkort (2007). However, Stockle and Hiller (1994) reminded that the CT method shall not be solely regarded as the practical irrigation scheduling method for potatoes because it could not be applied with confidence until the potato leaves completely cover the ground, or when the potato begins senescence.

Generally, transpiration and water loss variations might be likely better recognized by CT than the LWP, which could be due to physiological and genetically backgrounds of the potato cultivars as highlighted in the studies of Tourneux et al. (2003) and González-Dugo et al. (2006) who stated that the CT variability among crops is an indicator of crop water stress severity and is very sensitive to variations in crop water stresses. Improved and significant correlation of water productivity with CT (r=0.66 and p=0.036) than the non-significant correlation with LWP (r=0.40 and p=0.25) showed that crop water use and productivity were considerably controlled by the CT (Figure 2), possibly through adjusting stomata conductance. However, Prashar et al. (2013) stated that among other morphological and physiological traits that determined potato yield, the CT played a significant role in determining yield, though there was possible interaction of CT with other physiological traits in potato. In this regard, Figure 3 illustrates the relation between $\frac{LWP_r}{CT_r}$ with relative tuber yield, Y_r. High correlation coefficient (r=0.96) reveals that the relative potato yield is well correlated with the ($\frac{LWP_r}{CT_r}$). The maximum Y_r would be attained when the $\frac{LWP_r}{CT_r}$ is 0.98 that could be achieved under DI treatments. Figure 3 implies that tuber yield would decrease at higher or lower $\frac{LWP_r}{CT_r}$ values of 0.98. However, this ratio might need to be verified for other conditions.

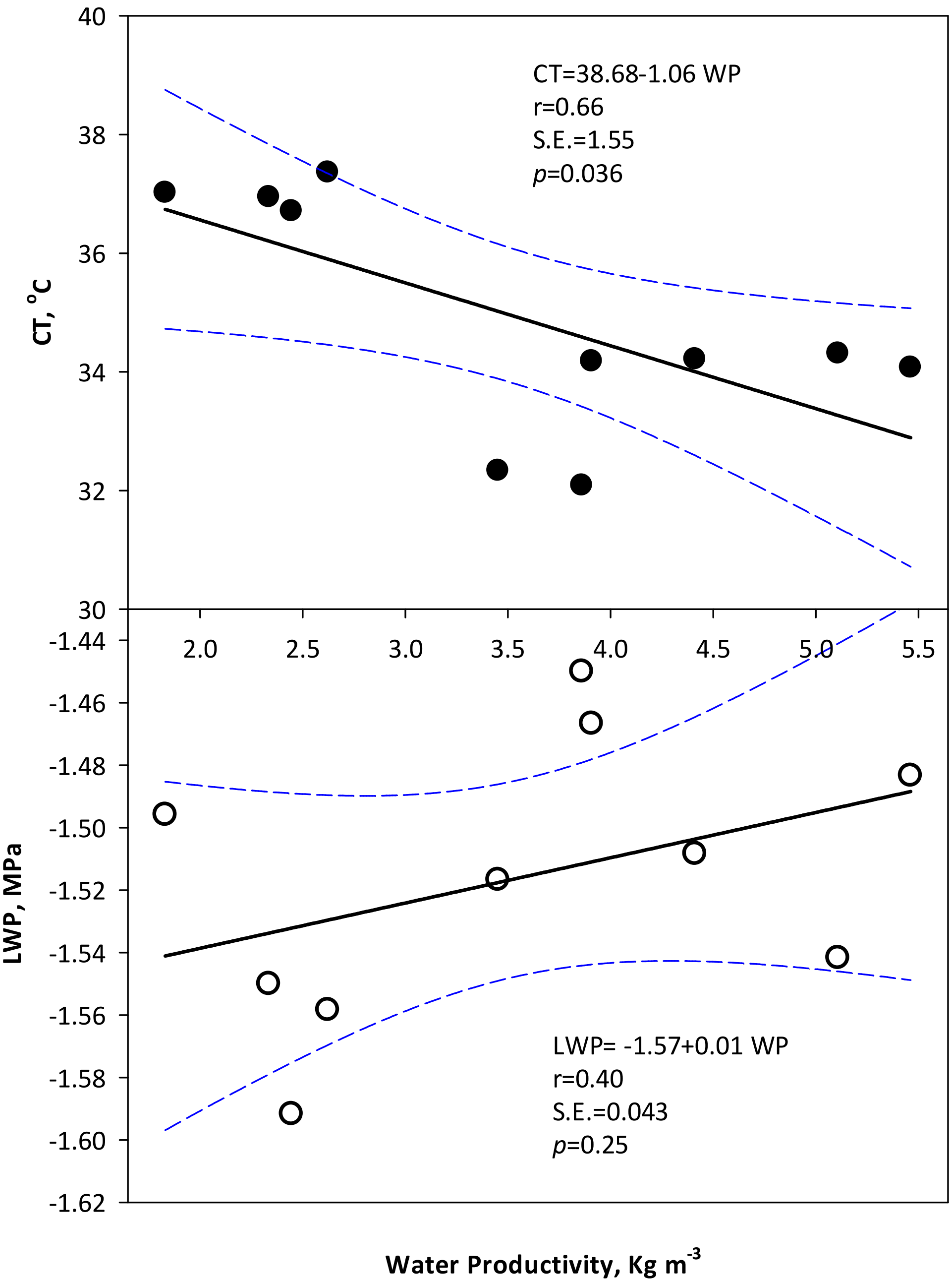

Figure 2. The linear correlation between the water productivity and CT (upper) and LWP (lower). The data points represent both Agria and Ramos cultivars as they were not significantly different (Ahmadi et al., 2014). The dashed lines are the 95% confidence intervals.

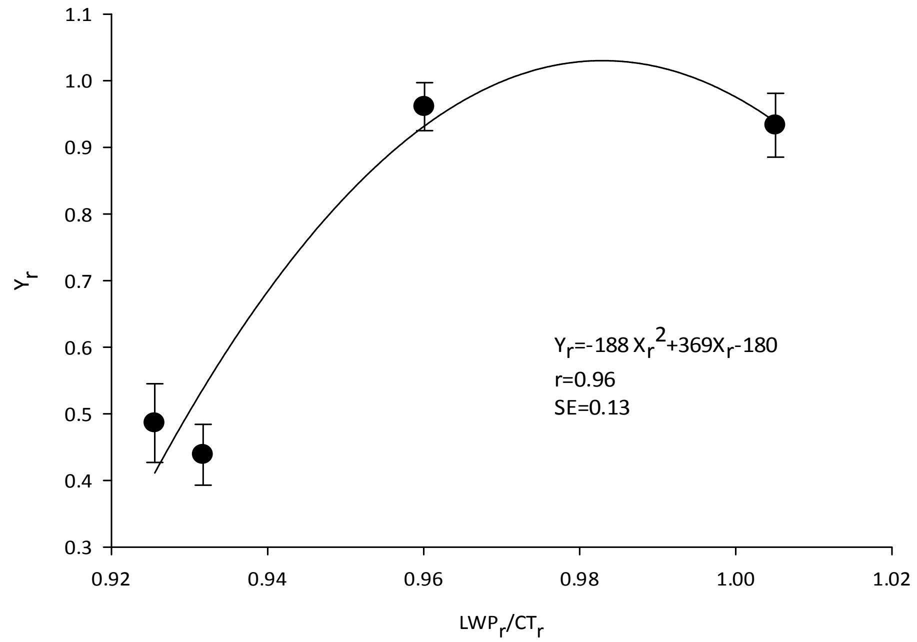

Figure 3. The correlation between the relative crop water status parameters and the relative tuber yield in different irrigation treatments pooled across the potato cultivars. Error bars are the ±SE (standard error).

Conclusions

This study revealed that LWP and CT have different responses to diverse water-saving irrigation strategies. It was observed that LWP could not detect the differences between irrigation strategies but CT could make it because measurements showed that the PRD strategies consistently had significantly higher temperature than FI and DI. On average, PRD strategies were nearly 5 and 2 °C warmer than FI and DI treatments, respectively, which might imply that transpiration rate was probably restricted in PRD strategies. However, the LWP and CT were not different between the two potato cultivars in response to the water saving irrigations. More analysis on LWP and CT indicated that seven-day irrigation interval was rather long in all irrigation treatments, especially in the PRD that led to 50% tuber yield loss compared to the DI. This is because soil water content in the wet part of the root system would be completely depleted by the time of next irrigation event.

CT was significantly correlated with water productivity much better than the LWP. Therefore, it could be concluded that tuber yield differences among the irrigation treatments could be associated well to CT variations rather than the LWP. Since CT was more responsive to water stress and irrigation water management strategies and was also an easy-to-measure parameter it is recommended to be applied for irrigation scheduling of potatoes under different irrigation managements.

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