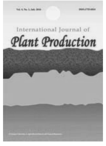

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Interaction of different irrigation strategies and soil textures on the nitrogen uptake of field grown potatoes

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Abstract

Nitrogen (N) uptake (kg ha^{-1}) of field-grown potatoes was measured in 4.32 m^2 lysimeters that were filled with coarse sand, loamy sand, and sandy loam and subjected to full (FI), deficit (DI), and partial root-zone drying (PRD) irrigation strategies. PRD and DI as water-saving irrigation treatments received 65% of FI after tuber bulking and lasted for six weeks until final harvest. Results showed that the irrigation treatments were not significantly different in terms of N uptake in the tubers, shoot, and whole crop. However, there was a statistical difference between the soil textures where plants in the loamy sand had the highest amount of N uptake. The interaction between irrigation treatments and soil textures was significant, and implied that under non-limiting water conditions, loamy sand is the suitable soil for potato production because plants can take up sufficient amounts of N and it could potentially lead to higher yield. However, under limited water conditions and applying water-saving irrigation strategies, sandy loam and coarse sand are better growth media because N is more available for the potatoes. The simple yield prediction model was developed that could explains *ca.* 96% of the variations of fresh tuber yield based on the plant evapotranspiration (ET) and N uptake in the tuber or whole crop.

Keywords: Potato; Nitrogen uptake; Partial root-zone drying irrigation; Deficit irrigation; Full irrigation; Soil texture.

Introduction

Potato production ranks fourth in the world after rice, wheat, and maize with the production of 321 million tones from 19.6 million hectares (FAOSTAT, 2007). Potato production is expected to continue to increase, providing an important source of food, nutrition and income (Bowen, 2003). Due to its sparse and shallow root system, potato is sensitive to drought stress and tuber yield might be reduced considerably in response to soil moisture deficits. Therefore, efficient and sustainable irrigation is needed to secure high yield and quality of tuber production but critical to reaching this goal in many regions will be access to an adequate water supply.

Worldwide shortage of fresh water resources has focused attention towards developing innovative water-saving irrigation strategies in order to reduce the excessive pressure on the fresh water resources. Partial root-zone drying irrigation (PRD) and deficit irrigation (DI) are water-saving irrigation techniques that are being investigated in many regions around the world. DI is an irrigation strategy that the root zone is irrigated applying an amount of water less than full irrigation (FI) and, therefore, may impose minor water stress that has minimal effects on the yield (English et al., 1990). However, PRD is the newest innovation in DI that only half of the root zone in fully or partly irrigated in each irrigation event, leaving another part to dry to a certain soil water content before rewetting by shifting irrigation to the dry side (Ahmadi et al., 2010a; Ahmadi et al., 2010b).

Cumulative studies show that PRD could increase product quality and allows considerable water savings compared to FI and DI (Sepaskhah and Ahmadi, 2010). PRD has been successfully tested on potatoes (Liu et al., 2006a; Liu et al., 2006b; Shahnazari et al., 2007; Saeed et al., 2008; Ahmadi et al., 2010a; Ahmadi et al., 2010b). Nimah et al. (2000), Liu et al. (2006a), Shahnazari et al. (2007) and Ahmadi et al. (2010b) showed that PRD and DI produced similar potato yield as FI, increased water productivity by 20-60% and reduced around 30% of applied irrigation water. However, Liu et al. (2006b) found that PRD could not improve the yield and water use efficiency compared to DI in potatoes.

Soil physical properties and soil water and nutrient content affect root growth; yet there is a lack of information and comparisons on how different soil qualities affect tuber yield and nitrogen (N) uptake in potato production (Parker et al., 1989; Bowen, 2003). Although in the last decade many studies have been carried out to investigate the effects of PRD and DI on plant growth and yield (Dodd, 2009; Sepaskhah and Ahmadi, 2010), yet little is known about how the irrigation strategies affects the plant nutrient status. Recently few studies have been carried out that reported discrepant results. Li et al. (2007), Shahnazari et al. (2008), Sepaskhah and Hosseini (2008), and Wang et al. (2009, 2010) reported that PRD enhances nitrogen accumulation in maize, potato, wheat, and tomato, but Topcu et al. (2007) and Hu et al. (2009) reported that PRD did not improve N uptake in tomatoes and maize. They could not explain these discrepancies. However, root N uptake is dependent on soil quality and soil water dynamics around root surfaces in a way which still has to be elucidated (Bahrun et al., 2002; MacKerron, 2008). Therefore, field comparison of N uptake at different soils is needed to clarify the optimal growth conditions for potatoes in combination with different irrigation strategies. This is in line with the sustainable agricultural strategies that should focus on using the available nutrient resources more efficiently to obtain higher agricultural productivity (Azam Shah et al., 2009).

To the best of our knowledge, there is no comprehensive study that has investigated the N uptake by potatoes or any other crop under different irrigation strategies and soil textures at field conditions. Since potatoes are widely grown under diverse agronomic conditions (soils, irrigation amounts, and weather conditions) the objective of this study was to investigate the interaction effect of water-saving irrigation strategies and soil textures on N uptake of potatoes grown under humid and temperate climate conditions.

Material and Methods

Site and soil description

A semi-field study was conducted from April to August 2007 at Research Centre Foulum ($56^{o}30'$ N, $9^{o}35'$ E), Faculty of Agricultural Sciences, Aarhus University, Denmark. Experiments were carried out in 36 drainable concrete lysimeters, placed in three rows. Each row had 12 lysimeters with a length of 1.6 m, width of 2.7 m and a depth of 1.4 m. The lysimeters were equipped with an automatic mobile roof, which protected the experiments from rainfall. All three sets of 12 lysimeters were filled in 1990 with one of the soils collected from Rønhave (sandy loam), Foulum (loamy sand), and Jyndevad (coarse sand) areas, hence each soil was represented by 12 lysimeters. Before transferring the soils to the lysimeters, the soils had been cultivated for many years and, therefore, are representative of soils from those sites. Table 1 shows the physical properties of the repacked soils in the lysimeters. The climatic condition during the experiment is presented in Ahmadi et al. (2010b).

Table 1. Physical properties of the repacked soils used in the experiment measured from flat soil.

Soil	Texture	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Organic matter (%)	Bulk density (g cm^{-3})	Field capacity at pF=2 (vol. %)	Wilting point at pF=4.2 (vol. %)
Jyndevad	Sand	0-30	5.8	2.1	90.2	1.9	1.41	14.0	3.8
	Sand	30-70	5.9	0.5	92.9	0.7	1.46	11.2[*]	5.2
Foulum	Loamy sand	0-30	11.5	11	75.2	2.3	1.4	25.3	6.7
	Loamy sand	30-70	14.9	10.1	74.5	0.5	1.62	23.9	9.2
Rønhave	Sandy loam	0-30	17.6	12.9	67.2	2.3	1.44	28.0	12.5
	Sandy loam	30-70	21.6	13.4	64.5	0.5	1.53	26.3	13.8

[*] pF=1.7 (Madsen, 1976).

Plant cultivation, irrigation treatments and scheduling

Pre-sprouted potato tubers (*Solanum tuberosum* L. cv. Folva) were planted on 17 April when the soil temperature was around 8 ^{o}C at soil depth of 10 cm. The seed tubers were placed in four rows 30 cm apart and with an inter-row distance of 75 cm. The soil was ridged to 25 cm above the tubers and the distance from top of the ridge to the bottom of the furrow was around 34 cm. Fertilizer was applied partly as a basic dressing of chloride-free NPK-fertilizer with micronutrients before planting (40 kg N ha^{-1}, 9 kg P ha^{-1}, 43 kg K ha^{-1}) and partly as fertigation with $Ca(NO_3)_2$ and NH_4NO_3. One-hundred kg N ha^{-1} was applied as mineral N via fertigation in a number of doses during plant establishment. Mineral N was applied over a short period of two weeks in order not to interfere with the irrigation treatments. Dosing was accomplished with a Dosatron DI-16 injecting 1% of a stock solution into the irrigation flow. The stock solution was prepared from $Ca(NO_3)_2$ and NH_4NO_3.

Tuber initiation and tuber bulking are the two growth phases that have been recognized as differing in sensitivity to drought stress. In this study tuber initiation (P1) was from plant emergence (13 May) to around 10 June and tuber bulking (P2) was from 10 June until harvest (30 July). Drought stresses were imposed during P2 period and started on 13 June.

Plants of all irrigation treatments received FI until they reached to P2. Irrigation treatments were designed in a completely randomized block design with three replications within each soil texture. However, the whole semi-field experiment was designed as a split-plot where soil texture and irrigation treatment were the main-plot and sub-plot, respectively, in four replications.

Irrigation of all treatments was scheduled three times per week. The FI treatment was irrigated according to the soil water depletion in the preceding two or three days. PRD and DI received 65% of FI in P2 that supports the idea of Marsal et al. (2008) of applying 50-70% of the water distributed to the fully irrigated plants. The dry and wet sides of PRD were switched weekly. Soil water content was monitored manually in all irrigation treatments three times per week before irrigation with Time Domain Reflectometry (TDR) using vertically installed probes down to the depths: 77 cm, 60 cm, and 43 cm measured, respectively, from top of the ridge, midway between the ridge and furrow, and from the base of the furrow. For each depth, three sets of TDR were installed at 15 cm to the right, 15 cm to the left, and close to the plant. More details of soil moisture content calculations are given in Shahnazari et al. (2007) and Ahmadi et al. (2010b). For the whole growing season irrigation depth in FI was determined to replenish 95% of plant available water in the root zone. This strategy was effective in reducing the drainage volume (Ahmadi et al., 2010b). Plant available water was calculated based on the difference between the soil moisture content at field capacity and wilting point (Table 1).

The irrigation amount was controlled by a programmable irrigation equipment that supplied the irrigation through a drip line system to any chosen plot. In the FI and DI treatments, one drip line was placed in the center of the ridge *ca.* 10 cm below the top of the ridge; the distance between emitters was 30 cm and each emitter (1 l h^{-1}) was then midway between two plants. In PRD treatment, two drip lines were placed in the centre of the ridge. The two drip lines were placed in parallel at the same depth and position as in FI, each with an emitter distance of 60 cm, but lines were offset 30 cm. Hence in PRD, each line was laid out to irrigate only one side of the root zone.

Measurement of yield, and N uptake

At the day of final harvest on 30 July (104 DAP or 78 DAE), six plants per lysimeter were harvested from the middle of each lysimeter for determining the tuber yield, biomass, and nitrogen content. Total fresh weight of the tubers and dry weight of sliced tubers (kg ha^{-1}) were determined after drying at 85 ^{o}C for 24 h. Stem and leaves were dried at 85 ^{o}C for 24 h. Nitrogen content (%) was measured for the tubers and shoot including stems and leaves and then was converted to N uptake (kg ha^{-1}) through multiplying by the dry weight of tubers and shoot. Total N content was analyzed by complete combustion of the sample in oxygen and measurement in thermal conductivity cell after removal of water, carbon oxides and sulfur oxides according to Dumas method (Hansen, 1989).

Data analysis and statistics

Data were subjected to analysis of variance using PROC GLM (SAS software 9.1, SAS institute Ltd., USA) based on the guidelines given by Gomez and Gomez (1986) and Littell et al. (2002). Duncan’s multiple range tests at P=0.05 probability level was applied to compare the means of measured parameters.

Results and Discussion

Effect of irrigation strategies

Table 2 shows the statistical analysis on the N uptake by tuber (TU), shoot (SH) and the whole crop (CR). The N uptake of the TU, SH, and CR under FI are not significantly different from PRD and DI. However, it seems that PRD plants tended to take up more N than DI so that PRD had 6, 13, and 8% more N uptake than DI in TU, SH, and CR, respectively. These results partly agree with the results of Shahnazari et al. (2008) who found that there was no statistical difference in the N content of the PRD and FI potato tubers through out the growing season. However, they found that at the end of the season (at harvest) the N content of the leaves was statistically higher in PRD than FI. Nevertheless, our results are inconsistent with the results of Wang et al. (2009) who found that PRD significantly increased the N uptake in different organs (tuber, stem, leaves) of potatoes.

Table 2. Summary of analysis of variance on the effect of experimental factors and their interaction on tuber FW (Mg ha^{-1}), tuber DW (Mg ha^{-1}), tuber N uptake (kg ha^{-1}), shoot N uptake (kg ha^{-1}), and total crop N uptake (kg ha^{-1}). Different letters in a column of each experimental factors show significant differences at 0.05 probability level.

Factor	Tuber FW	Tuber DW	Tuber N	Shoot N	Crop N
Irrigation treatment					
FI	46.67^a	9.88^a	109.1^a	67.24^a	176.35^a
DI	41.90^a	8.84^a	99.67^a	57.43^a	157.59^a
PRD	42.96^a	9.38^a	105.26^a	65.05^a	170.32^a
p-value	0.14	0.26	0.32	0.68	0.41
Soil texture					
Coarse sand	42.34^b	9.19^a	97.32^b	47.53^b	146.85^b
Loamy sand	47.85^a	9.83^a	118.01^a	84.45^a	202.51^a
Sandy loam	41.34^b	9.08^a	98.64^b	57.74^b	156.41^b
p-value	0.03	0.44	0.005	0.02	0.002
Irrigation × Soil					
p-value	0.04	0.05	0.01	0.31	0.04

Other studies have also shown diverse responses of crops to N uptake under FI, PRD, and DI. For tomato, Topcu et al. (2007) reported PRD could not significantly outperform FI in improving the N uptake and the N content under PRD was 8% lower compared to FI. Similarly, the N content under DI was 8% lower than PRD but the difference was not significant, which their results also agree with our findings (Table 2). In a recent study, Wang et al. (2010) reported that FI and PRD tomato plants accumulated more N in the shoot compared with the DI plants, while N content of the leaves were higher in PRD and DI. They suggested that PRD allocated more N to the canopy and upper leaves than to the other parts of the plant. Furthermore, enhanced crop N uptake under PRD irrigation has been reported in maize (Kirda et al., 2005; Li et al., 2007) and wheat (Li et al., 2005), while Hu et al. (2009) observed that PRD does not improve plant N uptake in maize. The reasons for these discrepancies among the results of the former studies are not clear. However, the results might be affected by the amount of applied irrigation water in PRD and DI, physical size of the experiment (greenhouse or field), soil textures, crop cultivar, and environmental conditions that affect the crop growth. Therefore, it shows that generalization and scaling up the experimental results depends on how the specifications and setup of the experiments are close to real field conditions. One of the most important environmental factors is soil texture that primarily affects the root growth which is important for N uptake. It is noteworthy that many greenhouse studies are carried out in pots where the root growth is confined by the size of the experimental unit that ultimately affect the crop functionality. These artificial conditions generate a range of artifacts and influence the overall conclusions (Sadras, 2009).

Effect of soil textures

Table 2 shows that the potatoes grown in loamy sand have significantly higher N uptake than those grown in sandy loam and coarse sand; while N uptake in plants grown in sandy loam did not significantly differ from that of in coarse sand. Wang et al. (2009) suggested that at least two factors are involved in N uptake from the soil: 1) root surface uptake area and 2) N availability in the soil. Furthermore, Jensen et al. (1993) found that the soil-root contact area is an important factor in water and nutrient uptake especially in coarse textured soils. In this study we found that the irrigation treatments did not affect the N uptake that agrees with our former findings that root length density and root distribution of potatoes were not affected by the irrigation treatments (FI, PRD, and DI) (Ahmadi et al., 2008). However, it was found that loamy sand significantly produced more roots (about two folds) in the deep soil layers of loamy sand than the other soils (Ahmadi et al., 2008). Thus, the increased N uptake by the plants in loamy sand can mainly be attributed to an increased uptake area and soil volume searched by the roots. This finding clarifies that under sufficient or moderate water stress, plants may take up part of the required N by extending their root system in the soil profile to capture more soil volume and gain the nutrient needs.

The nature of PRD is frequent wetting and drying of the soil profile in the root zone, which may stimulate mineralization of soil organic N, thereby increase the mineral N available to the plants (Wang et al., 2009). Existing soil microbes play an important role in mineralizing the organic N in soil, and moisture condition is a major factor that controls survival and activity of the microorganisms in the soil (Magid et al., 1999). Due to its nature in wetting and drying, PRD irrigation maintain the best aeration and moisture condition in the soil and enhanced the activities of soil microorganisms as compared with the FI and DI treatments (Wang et al., 2008). Based on these findings, Wang et al. (2009) suggested that the microbial activity in the soil probably enhanced by the PRD irrigation, stimulating the mineralization rate and thus more mineral N became available for the plants. However, comparison between PRD and DI (Table 2) shows that PRD has taken up more N than DI (although not significant) and these results confirm that probably more N were available for the plants under PRD due to soil N mineralization. Nevertheless, more investigations on the effects of different irrigation strategies including PRD on soil microbial activity and soil organic N mineralization process are required (Wang et al., 2009).

Interaction of irrigation strategies and soil textures

The interaction effect between irrigation strategies and soil textures on the potato N uptake is significant (Table 2), and Figure 1 illustrates the graphical presentation of the interactions. To the best of our knowledge, there are no previous studies that investigate the effects of soil textures on N uptake under PRD and DI compared with FI. Since there were no significant differences between the irrigation treatments (Table 2), the letters in Figure 1 show the results of analysis between the soils within each irrigation treatment. The interaction effect of irrigation strategies and soil textures is obvious as the effect of soil type on N uptake of TU was significant at FI. This clearly implies a great potential in manipulating soil and water resources in order to utilize the available resources efficiently. The interactions (Figure 1) show that under non-limiting water resources conditions loamy sand is the most suitable soil because N uptake from this soil is high and results in more economic yield of tubers. However, sandy loam and coarse sand are more favorable soils for applying water-saving irrigation treatments when the irrigation water resource is limiting in terms of plant N uptake and yield production (Figures 1 and 2). Bearing in mind that the soils in this study had relatively light textures, therefore, it is worth further studies on other heavy soil textures such as loam and clayey soils to reveal the responses of those soil textures to N uptake under different irrigation regimes.

The amount of fresh tuber yield (Figure 2) is associated well to the total N uptake of the CR or TU in different irrigation treatments, such that the potatoes grown in loamy sand have generally higher N uptake. As it is seen in Figure 2, fresh and/or dry tuber yield in PRD tends to be higher than DI (Ahmadi et al., 20101b). As already indicated, this could possibly be explained by higher N uptake in PRD from soil mineralization during the later part of the growing period and the “stay-green” effect (Ahmadi et al., 2010b), which is also confirmed by earlier studies showing higher N uptake under PRD than DI (Shahnazari et al., 2008; Wang et al., 2009; Wang et al., 2010).

Higher total tuber fresh or dry yields in PRD and DI than FI in sandy loam (Figure 2) strongly accords with the higher N uptake in PRD and DI than fully irrigated potatoes (Figure 1). This strongly supports the idea of the productive impact of nitrogen availability for gaining higher crop production (Shahnazari et al., 2008; Wang et al., 2010). Ferreira and Carr (2002) and Shahnazari et al. (2007) reported that higher N content is associated with denser crop canopy that intercepts more light and ultimately produce higher yield. However, some recent studies (Darwish et al., 2006; Ferreira and Goncalves, 2007) found that high N application in conditions of water stress reduced the yield, which could be due to the negative combined effects of low soil matric and osmotic potentials, and, it is worth to investigate the combined effect of different levels of applied N and PRD on potato yields. Recent studies, however, have shown that PRD increases the productivity of applied N compared to DI in potato (Wang et al., 2009) and tomato (Wang et al., 2010).

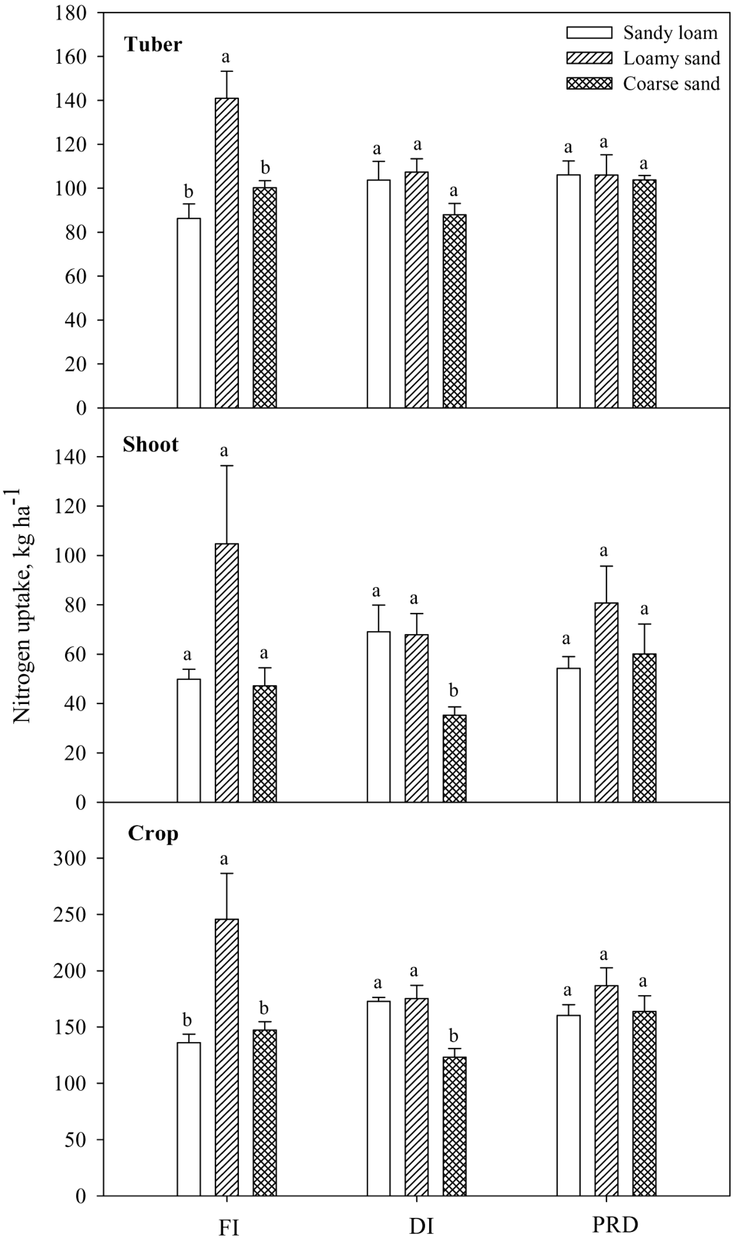

Figure 1. Nitrogen uptake in tubers, shoot, and crop of the potatoes in different irrigation treatments and soil textures at the harvest date. Different letters show significant differences between soils within each irrigation treatment at 0.05 probability level. Error bars represent + SE of the mean.

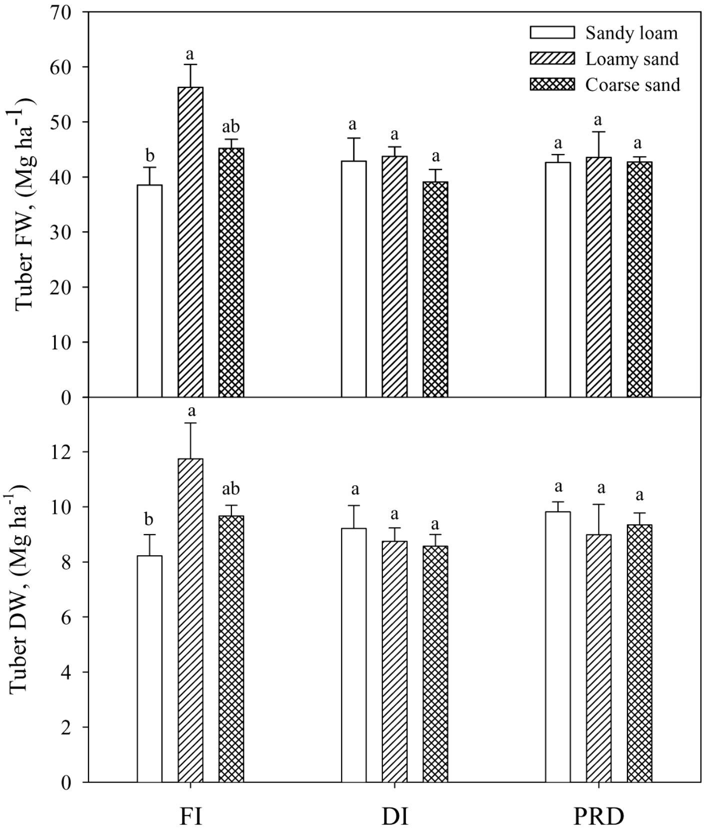

Figure 2. Tuber fresh yield and tuber dry yield in different irrigation treatments and soil textures at the harvest date. Different letters show significant differences between soils within each irrigation treatment at 0.05 probability level. Error bars represent + SE of the mean.

Further analysis showed that there is a significant polynomial relationship between the fresh tuber yield, and the mean N uptake in the tuber and/or the crop and the mean crop evapotranspiration (ET) of the potatoes under different irrigation treatments and soil textures. Detail of ET computations is given in Ahmadi et al. (2010b). Equations 1 and 2 show these relationships. Such simple models are very useful for predicting the yield under different water and nitrogen scenarios and could be successfully used in the dynamic crop growth models. The advantage of these models is that they have been obtained under different nitrogen uptakes and irrigation strategies including full and water-saving irrigations.

$$Y = -2.867 - 1.094N_{tuber} + 0.941ET + 0.006N_{tuber}^2 - 0.002ET^2 \quad (1)$$

R^2=0.96 *SE*=1.45 *p-value*=0.0047 *n*=9

$$Y = -51.396 - 0.569N_{crop} + 1.386ET + 0.002N_{crop}^2 - 0.004ET^2 \quad (2)$$

R^2=0.94 *SE*=1.80 *p-value*=0.012 *n*=9

Where Y is the fresh tuber yield (Mg ha^{-1}), ET is the actual crop evapotranspiration (mm), N_{crop} and N_{tuber} are the total N uptake (kg ha^{-1}) in the whole crop and tubers, respectively. These equations are obtained based on the mean values of the yield, and the corresponding mean values of the crop ET and N uptake of the tuber and crop. Figure 3 demonstrates that the regression plane fitted well to the measured tuber yields with R^2=0.96. It is noteworthy that the fitted model could be validated for the datasets of other experiments that have similar range of ET and N uptake.

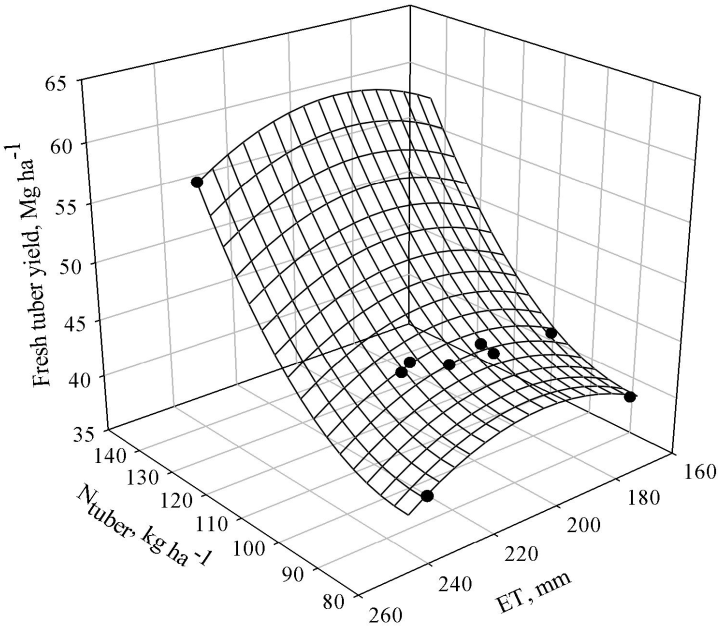

Figure 3. Fitted polynomial plane on the measured fresh yield potato yield as a function of crop evapotranspiration (ET) and nitrogen uptake in the tubers (N_{tuber}).

Conclusion

This study showed that irrigation treatments (FI, PRD, and DI) did not significantly affect the N uptake of the potato organs. The N uptake in the potato tubers, shoot, and the whole crop were statistically the same. However, a statistical difference between the soil textures was observed and the potatoes grown in the loamy sand had the highest amount of N uptake. In addition, there was a significant interaction between the irrigation treatments and soil textures on the N uptake of the tubers, which implied that under non-limiting water conditions loamy sand is a suitable soil for potato production because plants can take up sufficient amounts of N that could potentially lead to higher tuber yield. On the other hand, under limited water conditions and water-saving irrigation strategies, it seems that sandy loam and coarse sand are better soils because N is more available for the potato tubers, and therefore higher yield is potentially achievable. A combination of root growth and soil N mineralization, however, might be the main reason behind the significant interaction between the irrigation treatments and soil textures. The simple yield prediction model explains *ca.* 96% of the variations of fresh tuber yield based on the crop ET and N uptake in either the tuber or the whole crop. This model could be validated for other datasets holding similar experimental conditions.

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