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Variation in Root Water and Nitrogen Uptake and their Interactive Effects on Growth and Yield of Spring Wheat and Barley Genotypes

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Abstract: The study was conducted to investigate the effects of water and nitrogen on growth and to identify root traits that improve crop water and nitrogen uptake of wheat and barley genotypes at the Faculty of Agriculture Research Station, University of Jordan, Amman, during 2007. Two barley genotypes (*Hordeum vulgare* L., Vars Rum and ACSAD 176) and two wheat genotypes (*Triticum turgidum* L. var. durum, vars. Hourani and Om Qaise were subjected to two water treatments (rain-fed and rain-fed plus supplementary irrigation) and three nitrogen levels of 0, 50 and 100 kg N ha^{-1}. Barley produced higher above ground dry matter and Green Area Index (GAI) and leaf area ratio than wheat at anthesis stage. Root Length Density (RLD) was affected by genotype and nitrogen at depths from 0-80 cm. The effect of irrigation on root characteristics was only at depths below 20 cm where rainfed treatments produced higher RLD and root weight as compared to irrigation treatments. Results also showed an exponential decrease in RLD of various genotypes with soil depth. Barley vars had higher root weight and RLD than wheat vars especially at soil depths of 0-40 cm. Positive relationship between RLD and water and nitrogen used by wheat and barley plants was observed. Root water capture rate was higher for barley under irrigation by 4.5 folds as compared to rain-fed. On the other hand, stronger association between RLD and nitrogen uptake were observed for wheat genotypes under both rainfed and under irrigation as compared to barley.

Key words: Growth, nitrogen uptake, water uptake, root length density, wheat, barley

INTRODUCTION

Water availability is the most limiting factor for rainfed agriculture in the semi-arid areas of Jordan. Wheat and barley are two major field crops determining the fate of many farmers in the driest agricultural land areas in Jordan. These crops are subjected primarily to drought, which is a problem of major importance, as most of Jordanian arable land is characterized by strong water deficits and often suffer from strong drought episodes. Its economical and social impact is extraordinary. Increasing yield throughout management improvements in either capture or use efficiency of water and/or N is potentially enormous. In addition to water stress, nitrogen (N) is the second yield-limiting factor in these areas. Nitrogen deficiency accentuates the depressive effect of drought (Passioura, 2002). Management of N nutrition is very difficult because its effect on plant growth, development and physiology is related to unpredictable soil moisture under rain-fed conditions (Basso *et al*., 2010).

Increasing the capture and/or the use efficiency of water and nutrients determine crop productivity (Albrizio *et al*., 2010; Manal and Aly, 2008). For wheat and barley crops grown in Mediterranean environments, the interactions between fertilizer N applications yield and water use and root growth are crucial. Characteristics of plant species' root systems reflect environmental conditions typical of a species' native environment and that these characteristics vary with developmental stage and growth conditions (Nicotra *et al*., 2002). The ability of a plant to grow its root system and its capability to extract water and nutrients in different soil environments have profound effects on the above-ground growth as well as on the water and nutrient balance in the soil. Blum *et al*. (1983) found that the stability of yield across variable soil moisture regimes is associated with greater production of root mass, whereas Siddique *et al*. (1990) found that improvement of yield of modern cultivars is associated with reduced root dry matter. The horizontal spread of roots is usually 30-60 cm and roots grow to a depth of up to 200 cm (Gregory *et al*., 1978; Barraclough and Weir, 1988). However, about 70% of total root length is found within the top 30 cm of soil (Nagesh, 2006). Maintenance of root growth during water deficits is an obvious benefit to maintain an adequate plant water supply and it is under genetic control (O'Toole and Bland, 1987;

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Sponchiado *et al*., 1989). An important feature of the root system response to soil drying is the ability of some roots to continue elongation at low water content that are low enough to inhibit shoot growth completely (Sharp *et al*., 2004). Improvement in rooting aspects can be brought by increasing the rooting depth and root distribution with depth which are associated with an increase in the duration of the vegetative period (Brown *et al*., 1987; Wahbi and Gregory, 1995; Siddique *et al*., 1990; Miralles and Salfer, 1997). Developmental variation among genotypes has a large influence on genetic variation of rooting traits.

Crop roots and shoots interaction for N and water uptake and their interactions are rare especially under field conditions because of the limitations associated with root sampling, preparation and analysis. Roots are the agents of both water and nutrient uptake and their activities are crucial. Understanding the relationship between root traits and water and nitrogen uptake is required for effective management. Field experiments were conducted to quantify the variation in responses of root and shoot growth, root-shoot partitioning and nitrogen and water use among wheat and barley genotypes. Therefore, the objectives of the present research were: to study the interactive effects of water and nitrogen on shoot and root traits of two wheat and barley varieties; to identify the crop trait(s) that improve crop water and nitrogen uptake and to evaluate the impact of rooting traits on above-ground growth and grain productivity.

MATERIALS AND METHODS

Experimental site: Field experiment was conducted at University of Jordan, Faculty of Agriculture Research Station at Jubeiha (32.02° N, 35.87° E, 980 m altitude) during 2006/2007 growing seasons. The soil of experimental site is clay loam (Typic Xerocherpt) (Ministry of Agriculture, Jordan, 1995). The location has a Mediterranean climate of mild rainy winters and hot dry summers. Average seasonal precipitation is 490 mm for this location with a mean yearly maximum temperatures of 21.1 and 11.4°C minimum temperatures.

Environmental parameters including Max. T°C, Min. T°C and precipitation were recorded from weather station on nearby the experimental field during the two growing seasons. Soil samples was also taken before planting at 20 cm increment for 100 cm depth and soil texture, total mineral nitrogen, extractable P, pH, soil moisture content and water storage capacity was determined (Table 1).

Table 1: Some physical and chemical properties of the experimental site

Soil factors	Value
Soil particle size: Sand (%)	20
Silt (%)	38
Clay (%)	42
Textural class:	Clay loam
Organic matter	1.9
Mineral N content: NH_4^+ N (ppm)	6.7
NO_3^- N (ppm)	12.7
$pH_{1:1 \text{ soil: water}}$	7.5
Extractable phosphorus (ppm)	17.1
Extractable potassium (ppm)	428
Bulk density	1.02
Field Capacity (FC)	0.35
Permanent Wilting Point (PWP)	0.19
Available Water (AW)	0.16

Plant materials and treatments: Two Jordanian spring wheat varieties (Hourani and OmQais) and two spring barley varieties (Rum and Acsad) were tested under two water regimes (rainfed and rainfed plus supplemental irrigation) and three nitrogen levels (soil residual N, intermediate 50 kg N ha^{-1} and optimum 100 kg N ha^{-1}) in four replicates. The treatment combinations were arranged in a split-split plot experimental design where water regimes, genotypes and nitrogen comprise the main, subplots and sub-subplots respectively. Sub-sub plot size was 17.5 m^2 (7×2.5 m, with 10 rows 0.25 m apart). Seeds of both genotypes were sown at the rate of 250 plants per square meter. Nitrogen fertilizers in the form of urea was applied in two doses for the intermediate and optimum levels; 50% at emergence time and 50% at early stem elongation stage (GS31). Phosphorous fertilizers (20 kg P ha^{-1}) was added as triple super-phosphate (46% P_2O_5) on all plots at sowing time. Supplemental irrigation water was to maintain soil moisture deficit to <50% Available Water (AW) up to GS83 and <75% AW thereafter up to full canopy senescence.

Measurements: Developmental stages of the two varieties under different treatments were recorded according to Zadoks scale (GS). Plots were harvested at Anthesis (GS61) and at maturity. Above-ground dry matter was separated into stems, leaf lamina, spikes and grains. At GS 61, area of different plant components (leaves, stems and spikes) was measured using leaf area meter (LI-COR. LI 3000) to estimate green area index (GAI), Leaf Area Ratio (LAR) and leaf mass ratio (LMR). Different plant parts were oven dried at 70°C for 48 h before being weighted. At maturity harvest, grain yield and its main components (no. of spikes per m^2 and grain yield, straw yield) were determined. Nitrogen content of various plant parts (leaves, stems, spikes, straw, grain and roots) was measured by micro-Kjeldahl procedure. Nitrogen uptake by various plant parts (leaves, stems, spikes/grains, roots) was estimated according to the equation:

$$\text{N uptake (g m}^{-2}\text{)} = \%\text{N} \times \text{Component dry weight (g m}^{-2}\text{)}$$

At GS 61, 4 soil cores from between and within the crop rows was taken by soil corers (7.0 cm diameter) and separated into five horizons (0-20, 20-40, 40-60, 60-80 and 80-100 cm). The roots were extracted from the soil by washing samples using a root washer (Delta-T Devices Ltd., Cambridge, UK) and stored for root analysis. Roots samples were scanned to estimate the root length and root length density using a root scanner (Regent STD 1600+ using a WinRhizo Pro 2005$_b$ software program) and then weighed after drying at 70°C for 48 h for dry matter determination and nitrogen analysis.

Data handling and statistical analysis: Data collected were subjected to Analysis of Variance (ANOVA) by Statistical Analysis System (SAS, Inst., 1998). Differences among treatment means were compared by using Duncan's Multiple Range Test (DMRT) at 5% probability level.

RESULTS

Weather and crop development: Total rainfall in the growing season was 512 mm for Jubeiha experiment (Fig. 1) which is about the long term seasonal average for this location and higher than last year precipitation. There was no effective rainfall before December 27th which delays emergence until 13-16 January. Barley emergence was 3 to 5 days faster than wheat. More than 43% of rain occurs between Dec., 27 and end of January which coincided with germination and early growth stages that has low water requirements.

Mean max- and min-T during this growing season were above 20 and below 8.0°C, respectively. Total amount of irrigation water supplied to irrigated treatments at Jubeiha ranged between 50 and 150 mm for both barley and wheat, respectively. Dates to flowering, physiological maturity and maturity harvest varied between genotypes and nitrogen treatments, barley flowered 2 weeks earlier than wheat. Both wheat and barley took the same length of grain filling period, 28 days from anthesis time.

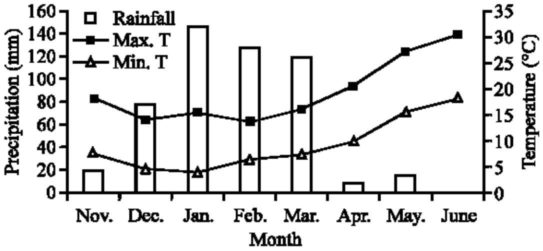

Fig. 1: Average monthly min- and max-temperature and monthly rainfall at Jubeiha during 2006/2007 growing season

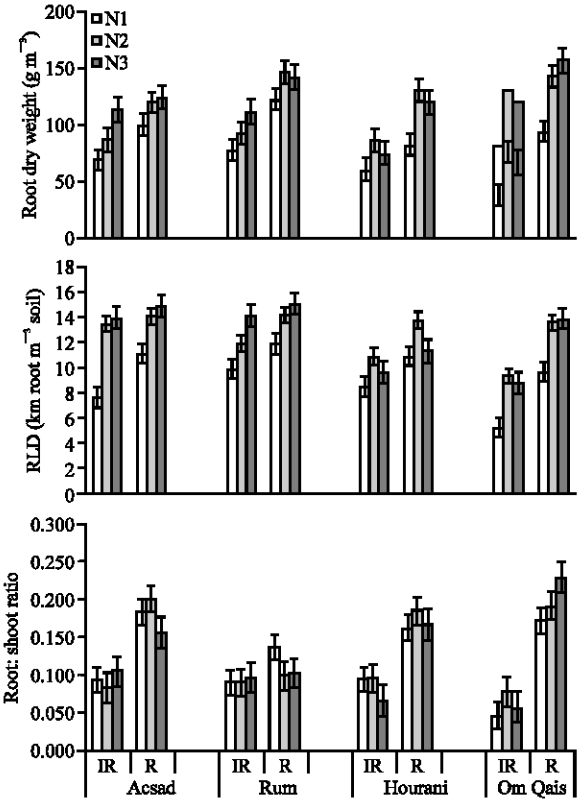

Fig. 2: Effect of irrigation (R vs. IR) and nitrogen on over all depths total Root Length Density (RLD), total root dry weight and root:shoot ratio of two barley (Rum, Acsad) and wheat (Hourani, Om Qais) vars. Bars stands for the standard error of the mean difference

Root Length Density (RLD) and root dry weight: Total root density (RLD) and total root dry weight per m^3 over all soil depths (0-100 cm) were significantly affected by irrigation and nitrogen treatments ($p<0.01$, Fig. 2). Supplemental irrigation resulted in lower root length than in rainfed and this varied among genotypes. The percentage reduction in RLD in response to irrigation ranged from 21-32% for barley vars and from 33-54% for wheat genotypes. Similar trend were observed in total root dry weight in response to irrigation. The effect of nitrogen on both RLD and root dry weight was positive and the highest percentage increase was in response to 50 kg N ha^{-1} treatment. Barley varieties had higher RLD and root dry weight as compared to wheat varieties ($p<0.05$).

Root to shoot ratio was significantly affected by irrigation only ($p<0.01$, Fig. 2) and significant interactions were observed between irrigation x genotype and between irrigation x var ($p<0.05$). Irrigation treatments resulted in lower root to shoot ratio in both genotypes. However the percentage reduction was higher in wheat vars than in barley vars. The effect of nitrogen was not significant.

Analysis of variance of root length density by each soil depth (Fig. 3a-d, 4a-d) indicted that there was no effect of irrigation on root length density at 0-20 cm while at depths of 20-80 cm, irrigation has significant effects ($p<0.05$). The effect of nitrogen was also significant ($p<0.05$) at soil depths (0-20, 20-40, 60-80 cm). At deeper horizons no effect of irrigation and nitrogen treatments was observed. Rainfed treatments increased RLD through different soil horizons of all wheat and barley varieties and this was higher for barley genotypes. Nitrogen treatments also increased RLD of various genotypes with the exception of the deepest soil horizon (80-100 cm) where no effect of nitrogen was observed. The effect of nitrogen on root length density was higher under irrigation than under rainfed treatments. The effect of nitrogen and irrigation was almost consistent in all wheat and barley vars. RLD of barley vars were reduced with soil depth with the maximum values obtained at 0-20 and 20-40 cm and this effect trend was similar under both irrigation and rainfed treatments. Wheat RLD density

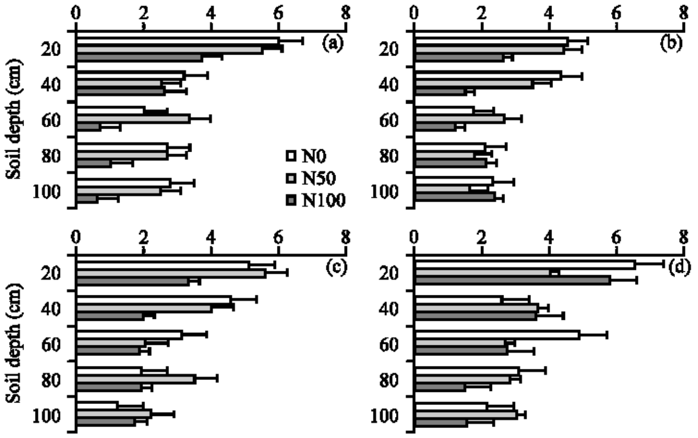

Fig. 3: Effect of nitrogen rates (N0, N50, N100) on RLD of barley varieties; irrigated Rum (a) and Acsad (b) and rainfed Rum (c) and Acsad (d) at different soil depths (0-20, 20-40, 40-60, 60-80, 80-100 cm). Bars stands for the standard error of the mean difference

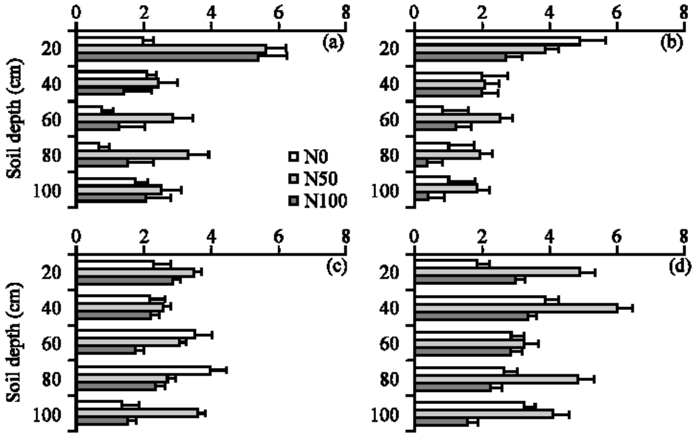

Fig. 4: Effect of nitrogen rates (N0, N50, N100) on RLD of wheat varieties; irrigated Hourani (a) and Om Qaise (b) and rainfed Hourani (c) and Om Qaise (d) at different soil depths (0-20, 20-40, 40-60, 60-80, 80-100 cm). Bars stands for the standard error of the mean difference

response to soil depth was similar to that of barley with some variability at the deepest horizons.

Root water capture rate: The relationship between total RLD (km m^{-3}) and water used by the crop (mm at harvest) for irrigated and rain-fed wheat and barley plants is shown in Fig. 5a-d. To calculate root water capture rate, a simple linear model fitted through the origin was applied to data. Root water capture rate was higher for barley under irrigation and rain-fed conditions as compared to wheat. Irrigation in barley increased root capture rate by almost 4.5 folds as compared to rainfed only while no such differences was observed in wheat. Higher RLD were associated with higher water uptake especially in barley genotypes.

Root nitrogen uptake rate: The relationship between total RLD (km m^{-3}; at GS 61) and shoots N uptake (g m^{-2} at harvest) for irrigated and rain-fed wheat and barley plants is shown in Fig. 6a-d. To calculate root N capture rate, a simple linear model fitted through the origin was applied to data. Under rain-fed conditions, both species had higher RNUR as compared to that under irrigation conditions. Stronger association between RLD and shoot nitrogen uptake were observed for wheat genotypes under both rainfed and rainfed plus supplemental irrigation (R^2= 0.89, 0.91) as compared to barley (R^2= 0.35, 0.29)

Crop growth: Above ground dry matter were significantly varied (p<0.01) between genotypes, varieties and nitrogen treatment at flowering stage (GS 61, Fig. 7). No effect of irrigation was observed at this stage since supplementary irrigation water was not added until early flowering stage in barley and at boating stage in wheat. The positive effect of nitrogen was more in barley than in wheat

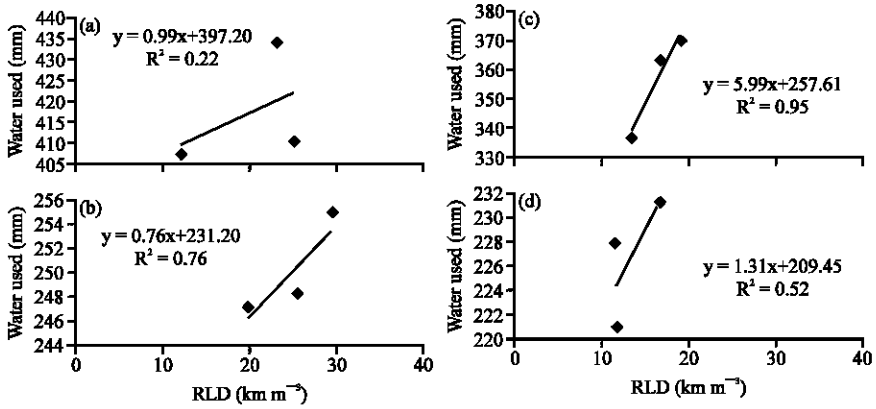

Fig. 5: Regression of RLD (km m^{-3}) against water used by the crop (mm) for (a) irrigated wheat (b) rain-fed wheat (c) irrigated barley and (d) rain-fed barley

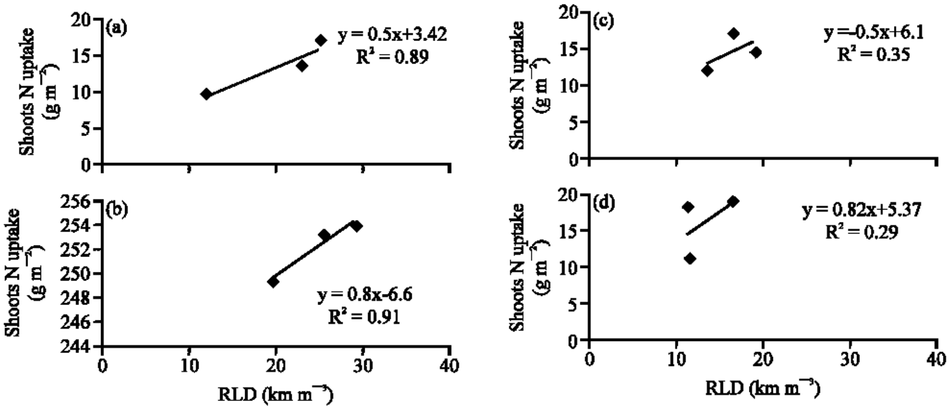

Fig. 6: Regression of RLD (km m^{-3}) against shoots N uptake (g m^{-2}) for (a) irrigated wheat (b) rain-fed wheat (c) irrigated barley and (d) rain-fed barley

varieties. At physiological maturity, above ground dry matter was significantly affected by irrigation ($p<0.01$, Fig. 8). There were a significant interaction between irrigation genotype and varieties. The effect of irrigation varied among genotypes and varieties (22-27%). Nitrogen fertilizers were also increased dry matter and this increase was higher under irrigation (27 to 45%) than under rainfed (19 to 37%). Similar observations for the effect of genotype, variety and nitrogen treatment for green area index, leaf mass ratio and leaf area ratio measurements at GS61 stage (Fig. 3). Green area of plants affects the ability of the crop canopy to intercept solar radiation and biomass accumulation and partitioning. A significant effect of genotypes and nitrogen treatments on green area index at anthesis (GS61) was obtained ($p<0.01$). Barley shows higher GAI and Leaf Area Ratio (LAR) as compared to wheat especially under high nitrogen levels. There were also varietals differences were Acsad had the highest GAI, LMR and LAR as compared to Rum barley.

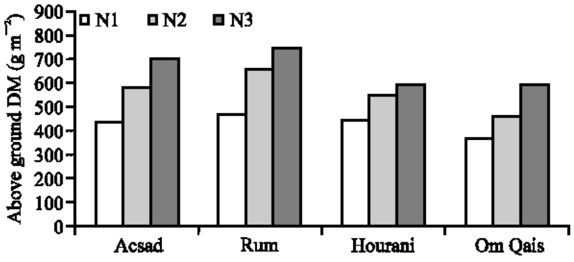

Fig. 7: Effect of nitrogen on above-ground dry matter of 2 barley (Acsad and Rum) and wheat vars (Hourani and Om Qais) at GS61. Bars stands for the standard error of the mean difference

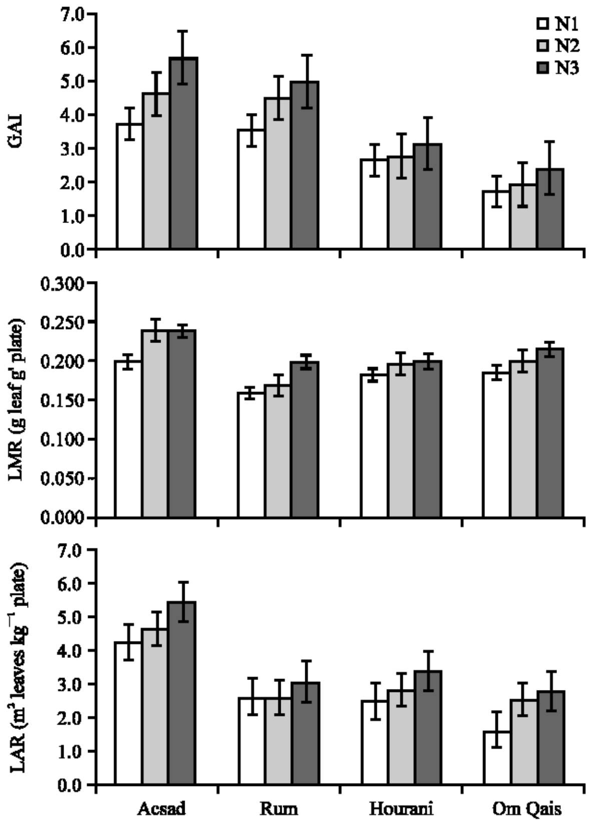

Fig. 8: Effect of nitrogen on Green Area Index (GAI), Leaf Mass Ratio (LMR) and Leaf Area Ratio (LAR) of 2 barley (Acsad and Rum) and wheat vars (Hourani and Om Qais) at GS61. Bars stands for the standard error of the mean difference

Yield and yield components: At harvest, biomass; grain and straw yield was higher for barley vars than for wheat vars ($p<0.01$, Fig. 9). Overall irrigation increased grain yield by 30% ($P< 0.001$) and 50 kg N ha^{-1} increased grain yield by 34% in barley and 24% in wheat compared to control ($p<0.05$). 100 kg N ha^{-1} did increase biomass by 10% in barley and by 20% in wheat as compared to 50. There was an interaction between irrigation x genotype x var ($p<0.01$) and between irrigation x genotype x nitrogen ($p<0.05$). These effects were associated with differences in number of grains per square meter and with number of spikes (ears) per square meter as well as number of grains per spike (data not shown).

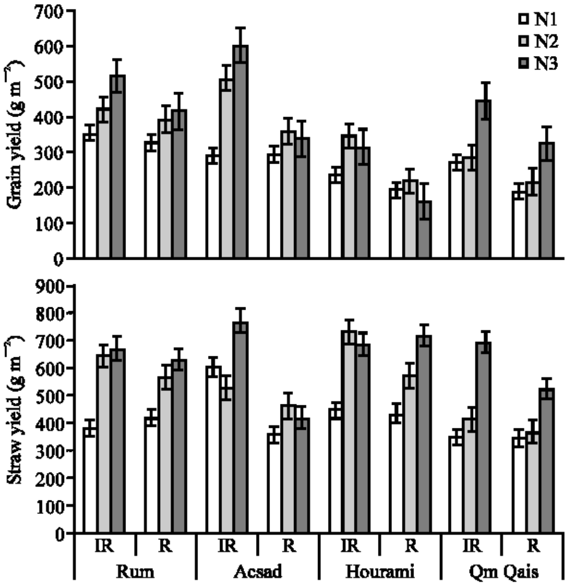

Fig. 9: Effect of irrigation (R vs IR) and nitrogen on grain and straw yield of 2 barley (Acsad and Rum) and wheat vars (Hourani and Om Qais) at maturity harvest

DISCUSSION

Over the past two centuries, alteration of dry matter partitioning of plants was the main target for plant breeders to improve grain yield (Hamblin *et al*., 1990; Passioura and Angus, 2010). Despite the success in improving management practices of the above ground crops, less attention was devoted to resource capture by underground parts. Foulkes *et al*. (1998) indicated that high yielding modern genotypes may be less efficient in capturing soil resources. Therefore, the present study focused on the role of root in capturing resources, primarily water and nitrogen and their impact on growth and yield on two important cereal crops.

Root characteristics: Root traits may have a significant role to play in resource capture and dry matter partitioning especially in water and nitrogen limited environments. Root traits that are usually linked to resource capture are root length and rooting depth (King *et al*., 2003). There is genetic variation in rooting characteristics which can be used in breeding programs under resource limited environments. Dardanelli *et al*. (1997) reported that in all the crops, maximum root depth was reached when the grain filling started. This agrees with Begg and Turner (1976) who stated that when the main sink of photoassimilates is grain, the growth of all other plant parts is reduced to its minimal expression. On the other hand, other studies found that roots continue to grow during grain-filling (Wright and Smith, 1983). Robertson *et al*. (1993) concluded that the inconsistency between these results may be due to the differing balances between new root growth and root loss, which depends upon the particular conditions experienced by the crop. Furthermore, this variation in root growth could be attributed to mechanical impedance of soil that can be managed through tillage operations that might interfere with root growth (Barzegar *et al*., 2004).

Ebrahim (2008) indicated changes in RLD at various sampling stages in response to irrigation and nitrogen treatments for wheat and barley under controlled environments. The total root length of wheat and barley increased rapidly between stem elongation and physiological maturity and then increased, remained almost static or decreased after physiological maturity depends upon the particular treatment. Total root length density of barley under both stressed and non-stressed conditions continue to increase after physiological maturity. Root length density was increased under rainfed conditions and showed that supplemental irrigation have not resulted in improving RLD in both wheat and barley (Fig. 4-6). This trend is not in agreement with the results of Zhang *et al*. (2004) who also found that more frequently irrigated wheat had more RLD than less-irrigated and non irrigated treatments. Application of nitrogen to soils causes an increase in root length throughout the root system (Robinson, 1986). The effect of nitrogen application appears to be in general agreement of that found in the present study (Fig. 2-4).

The root attributes of cereals vary significantly between species (Gregory, 1994; Marschener, 1998). In the present study, wheat maintained a lower RLD than barley significantly at 40-100 cm soil depth (Fig. 3, 4). It has long been known that nutrient rich soil patches lead to localized root proliferation (Gregory, 1994) and surface applications of nitrogen fertilizer tend to result in high root densities in the surface layers of the soil. In our study, plants fertilized with intermediate N50 and high N150 levels of nitrogen had higher values of RLD in the top 0-40 cm layer and seem to meet the above-mentioned criteria (Fig. 2-4).

The effect of N on total root mass was significant. Higher N concentration 50 and 100 kg ha^{-1} increased root dry matter production (Fig. 4). Results of the current experiment on root mass growth was opposite to those of Maranville (1994) who found that this growth was negatively affected by high N fertilizer.

Root water uptake: The capacity to acquire belowground resources is associated with root length (Ryser, 1998). This trait is phenotypically plastic and their responses improve resource acquisition. Uptake of water takes place over most of the profiles. Even when roots extend deep into the soil, there is a preferential uptake of water from the surface layer (Gregory, 1994). The effect of root characteristics on soil water depletion was examined in the present study (Fig. 5). Our results showed that root water capture rate of barley plants was higher than wheat plants under rainfed and rainfed plus supplemental irrigation. Furthermore, nitrogen application resulted in increased soil moisture depletion. These differences may be associated with variation on RLD of such plants which is in a general agreement with the results of above-mentioned studies.

The high magnitude of increase in water capture per unit total root length for the low-root biomass species (barley; Fig. 5) with its high specific root length may be associated with the root systems of this species which consist of very fine roots (Eissenstat, 1992). This appears to allow water absorption more efficiently (Barber and Silberbuch, 1984).

Root nitrogen uptake rate: Figure 6 shows a strong relationship between root length density and shoots N uptake. The rate of N uptake per unit total root length increased with increasing RLD and the magnitude of increase was higher for plants that are grown under rain-fed conditions. This trend is also in agreement with the results of Cure *et al*. (1988) on soybean where increased N uptake was associated with larger root systems, as uptake per unit of root mass was lower than controls. Obviously, the soil water status plays a major role in the utilization of nutrients by plant roots since the water is the carrier of nutrients to the root surfaces and this can be greatly supported by our finding which residual soil mineral nitrogen increase with decreasing soil moisture content. This trend is in agreement with the results of (Danilova *et al*., 1991) who found that changes in soil water status directly impact root-nutrient relationships. Reductions in the rate of uptake of soil resources such as water and nitrogen lead to changes in assimilate allocation, which can increase the size of the root system (Hoad *et al*., 2001). However, an understanding of how root systems behave in different environments allows the risks of root limitation to be minimized.

Crop growth, yield and its components: Nitrogen fertilization and supplemental irrigation affected wheat and barley growth and yield. By harvest, barley grain yield was higher than that of wheat (Fig. 9). Such increase in grain yield may be attributed to high values of spikes m^{-2} and grains m^{-2} (data not shown). This trend is in agreement with the results of Bulman and Hunt (1988) who found that number of fertile spikes per unit area, grain spike^{-1} and individual grain weighs and harvest index are among the important yield components that contribute to grain yield of cereals. Passioura (1983) also argued that a large root system may not be necessary in plants and suggested that yield could be improved if plants partitioned more dry matter to the shoots rather than the root system. The relationship between the RLD of barley and the higher yield obtained in this study encourage such conclusion. The presence of efficient root system could be necessary for high productivity since superfluous allocation of resources to the root is avoided (Mwale *et al*., 2007). In many experiments, higher grain yields over species have been attributed largely to the progressive increase in harvest index (Syme, 1970; Donald and Hamblin 1976; Austin *et al*., 1980). Foulkes *et al*. (2002) found that grain yield is determined by the amount of water the crop extracts from the soil, the efficiency with which this water is converted into above-ground biomass and the fraction of this which is partitioned to grains. Albrizio *et al*. (2010) indicated that increased grain yield of wheat and barley in response to nitrogen fertilization is due primarily to the increase in grain number per unit area. Interaction of irrigation and N rate significantly affected grain and straw yield (Fig. 9). This trend is in agreement with the results of Das and Yaduraju (1999) who also reported that the interaction between irrigation and nitrogen treatment, affected all the nutrient treatments to produce significantly higher tillers of wheat under frequent irrigations as compared to under limited irrigation treatments. Similarly, Roy *et al*. (2004), reported that nitrogen uptake differed greatly among the varieties and nitrogen rates. The increase of total N uptake with N rate was almost linear for the modern varieties, whereas the traditional varieties showed a quadratic relationship between total N uptake and N level.

CONCLUSIONS

Crop root capture studies are rare especially under field conditions because of the limitations associated with root sampling, preparation and analysis. However, knowledge of shoot and root characteristics are very essential for optimizing cropping systems and resource capture. The results of the present study indicated a positive linear relationship between root length density and resource capture. Large root system of barley resulted in high resource capture and higher above ground biomass and grain yield as compared to wheat. The differences between genotypes of wheat and barley found in this study could be important factors for barley adaptation to rain-fed and stressed conditions. Therefore, selection for crops for high RLD might be utilized as selection criteria in breeding programs, especially under stressful environments.

ACKNOWLEDGMENTS

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