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Root Density and Water Use Efficiency of Wheat as Affected by Irrigation and Nutrient Management

K.G. MANDAL*, K.M. HATI, A.K. MISRA, P.K. GHOSH AND K.K. BANDYOPADHYAY
Division of Soil Physics, Indian Institute of Soil Science, Nabibagh, Berasia Road, Bhopal-462 038, Madhya Pradesh

ABSTRACT

A 3-year (1998-99 to 2000-01) field experiment was conducted on Vertisols at the Indian Institute of Soil Science, Bhopal to study the impact of integrated management of irrigation and nutrients on root growth and water use efficiency of wheat in a soybean-wheat cropping system. Results revealed that root length density (RLD) of wheat increased to 2.97 cm cm^{-3} in three post-sowing (PS) irrigations, 1.39 cm cm^{-3} in two PS-irrigations and only 0.55 cm cm^{-3} with no PS-irrigation; and 1.98 cm cm^{-3} with 100% NPK (100-21.5-24.9 kg ha^{-1}) + FYM *applied to preceding soybean @ 10 t ha-1, 1.82 cm* cm^{-3} *with* 100% NPK and 1.103 cm cm^{-3} in unfertilized control. RLD decreased with soil depth. Root mass density (RMD) showed a similar trend. Grain yield increased by 47.3 and 89.2% at two and three PS-irrigations, respectively over no PS-irrigation; and 100.4 and 151.4% by 100% NPK and 100% NPK+FYM, respectively, over control. Highest pooled grain yield (4088 kg ha^{-1}) was recorded in three PS-irrigations with 100% NPK+FYM and was significantly higher than three PS-irrigations with 100% NPK and two PS-irrigations with 100% NPK+FYM. Water use efficiency (WUE) decreased with higher levels of irrigation, 9.1 and 8.4 kg ha^{-1} mm^{-1} with two and three PS-irrigations, respectively, compared to no PS-irrigation (10.6 kg ha^{-1} mm^{-1}), whereas highest WUE of 11.7 kg ha^{-1} mm^{-1} was obtained in 100% NPK+FYM followed by 100% NPK (10.2 kg ha^{-1} mm^{-1}) and control (6.3 kg ha^{-1} mm^{-1}). The lower WUE associated with higher levels of irrigation, but 100% NPK+FYM positively influenced the WUE of wheat.

Key words : Irrigation, nutrient, root density, yield, water use efficiency, wheat.

Introduction

Wheat occupies nearly 50% of the total cultivable area during winter season in central India. Yield of this crop is low due to improper management of water and nutrients. Water and nutrients, and their positive interaction favourably influence the root growth, water use, yield and water use efficiency of wheat. Because a crop's root system absorbs water and nutrients as well as anchors the plant body, root system development could be a critical factor in determining sustainable agriculture. Previous research has demonstrated that the genotype determines root growth characteristics of wheat (Hurd, 1974). But water supply is one of the most significant factors determining the root system development. Singh and Das (1986) showed that root weight density (RWD), root length density (RLD) and root diameter (RD) increased with increasing irrigation levels and especially with increasing N-rates. Root length showed a significant positive correlation with soil water depletion and grain yield. Morita and Okuda (1994) found a longer axis of seminal roots of wheat in the wet treatment than in the dry treatment. Gajri and Prihar (1985) reported that the root weight density (μg root cm^{-3} soil) of field-grown wheat in upper layers increased due to irrigation in sandy loam soil.

The influence of NPK-fertilization on root growth has not been as definitive. Murakami *et al.* (1990) measured root length of wheat using an image analyzer, after separated roots into large and small fragments. they found that total root length density of wheat was highest in the NPK treatment, and was markedly reduced by the NK and no NPK treatments. Bosemark (1954) observed a negative correlation between root development in wheat seedlings and rate of N fertilization.

*Corresponding author: Tel.: 0755-2730970, Fax: 0755-2733310 e-mail : kgm@iiss.mp.nic.in

Campbell *et al.* (1977) found that rate of N fertilization had no effect on the root distribution on spring wheat, whereas Comfort *et al.* (1988) observed significantly higher root length in the top 30 cm by applying 67 kg N ha^{-1}, root length remained same or lower at 134 kg N ha^{-1}. Thus knowledge of root system development in relation to nutrient application is essential for selecting nutrient management options.

Water use efficiency (WUE) represents a given level of grain yield or biomass per unit of wate used by the crop. With increasing concern about the availability of water resources in both irrigated and rainfed agriculture, there is renewed interest in developing an understanding of how WUE can be improved and how farming systems can be modified to be more efficient inwater. In Syria, Zhang and Oweis (1999) estimated WUE of 2.5 kg ha^{-1} mm^{-1} of bread wheat in multiple cultivars underline source irrigation with N rates at 0-150 kg ha^{-1} and P rates at 40-50 kg ha^{-1}. WUE ranged from 6.6-9.1 kg ha^{-1} mm^{-1} of spring wheat with application of N and P-fertilizers at Sidney (Tanaka, 1990). Kang *et al.* (2002) found WUE ranging from 7.3 to 9.3 kg ha^{-1} mm^{-1} that are not the highest values because seasonal evapotranspiration was the highest while yield was not. Crop responses to NPK-fertilization depend on the level of water availability (Pala *et al.*, 1996). Application of fertilizers not only increases plnat shoot and root growth (Brown *et al.*, 1987), but also increases ET through a larger root system and greater extraction of stored water (Cooper *et al.*, 1987). On average, the application of 5, 10 and 15 g N m^{-2} significantly increased WUE for grain yield of wheat from less than 6.0 kg ha^{-1} mm^{-1} to between 8.0 and 9.9 kg ha^{-1} mm^{-1} in the November and December sowings at Syria (Oweis *et al.*, 2000). WUE for supplemental irrigation ranged from 2.5 to 23.4 kg ha^{-1} mm^{-1}, depending on the level. WUE increased when the applied water increased, but dropped sharply at full irrigation.

Studies on root development, growth and water use provide a basis for efficient management of water and nutrients to boost yield of this crop, especially under limited irrigation water availability. Therefore, the present investigation attempts to study the effects of irrigation and nutrient management and their interaction on root growth, yield and water use efficiency of wheat in a soybnean-wheat cropping system in Vertisols of central India.

Materials and Methods

Field experiments were conducted for three consecutive years (1998-99 to 2000-01) at the Indian Institute of Soil Science, Bhopal, Madhya Pradesh (23° 18' N, 77° 24' E, 485 m above msl). Soil was heavy clay, Vertisol (*Typic Haplustert*), low in organic C (0.40%), available N (245 kg ha^{-1}) and available P (5.0 kg ha^{-1}) but high in available K (460 kg ha^{-1}). The pH was 7.8, CEC 46 $cmol^{(+)}$ kg^{-1} soil, water holding capacity 62.5%, moisture retention 40.6% at 0.33 bar and 25.8% at 15 bar.

The experiment was conducted in a split-plot design with three replication. Three levels of post-sowing (PS) irrigation treatments, viz. control i.e. without PS-irrigation (I_0), two PS-irrigations (I_1) and three PS-irrigations (I_2) were laid out in main-plots and three nutrient management treatments, *viz.*, F_0 (control i.e. without fertilizer or manure), F_1 (100% NPK- 100-21.5-24.9 kg ha^{-1}) and F_1 (100% NPK + farmyard manure @ 10 t ha^{-1}) were allotted to sub-plots. In I_1, irrigations were applied at crown root initiation (CRI) stage and flowering stage of the crop and in I_2, irrigations were applied at CRI, maximum tillering and flowering stage of the crop. Each irrigation was applied with measured amount of water (6 cm). The individual plot size was 6 m x 4 m. Farmyard manure (FYM) was applied once for the crop sequence to preceding soybean. Once pre-sowing irrigation was applied to all the plots uniformly irrespective of treatments for proper germination and establishment of the crop and subsequent irrigations were given as per treatments. Wheat seeds (cv. Sujata) were sown with the use of tractor drawn seed drill on mid November each year with 2.5 cm row spacing.

Root studies were performed using the Delta-T scanner and image analysis software. Root samples were collected from the crop rows with a core sampler at the grain filling stage. Samples were washed by the root-washing unit and were analysed. Soil moisture was measured through neutron moisture meter and thermo-gravimetric method and water use calculated by water balance equation. The crop was harvested during the first week of April every year. Grain yield was estimated from the net plot harvest. Water use efficiency (WUE) was calculated as grain yield divided by seasonal water use (i.e. evapotranspiration). Analysis of variance technique, as outlined by Gomez and Gomez (1984), was employed to compare the treatment effects, and Duncan's multiple range tests (DMRT) were performed to compare treatments. Critical difference (CD) was calculated for the main effects as well as interaction effects, when the analysis of variance F-test was significant at 0.05 probability level.

Results and Discussion

Root density

Root length density (RLD) of wheat increased to 2.97 cm cm^{-3} in three post-sowing (PS) irrigations (I_2), 1.39 cm cm^{-3} in two PS-irrigation (I_1) and only 0.55 cm cm^{-3} with no PS-irrigation (I_0). Crop receiving nutrients also registered higher root density (Fig. 1). RLD was 1.98 cm cm^{-3} with 100% NPK (100-21.5-24.9 kg ha^{-1}) + FYM applied to preceding soybean @ 10t ha^{-1} (F_2), 1.82 cm cm^{-3} with 100% NPK (F_1) and 1.10 cm cm^{-3} in unfertilized control (F_0). Thus, it revealed that RLD of wheat increased with increasing PS-irrigation levels and with application of 100% NPK and 100% NPK+FYM. The higher rooting densities seem to be associated with higher soil moisture storage in the profile and particularlyin the surface layers. Our data conformed to the findings of Gajri and Prihar (1985). They reported that the root weight density (μg root cm^{-3} soil) of field grown wheat increased in upper layers due to irrigation in sandy loam soil. The rapid drying of the surface layers containing most of the roots early n the growing cycle caused water stress in the crop, which could also have reduced root development in I_0 (no PS-irrigation). Irrigation at critical growth stages in I_1 and I_2 eliminated water stress and decreased mechanical soil impedance, thus removing the constraints for root growth and extension beyond plough layer. Moreover, optimum supply of water to crop in the critical growth stages in combination with NPK or NPK

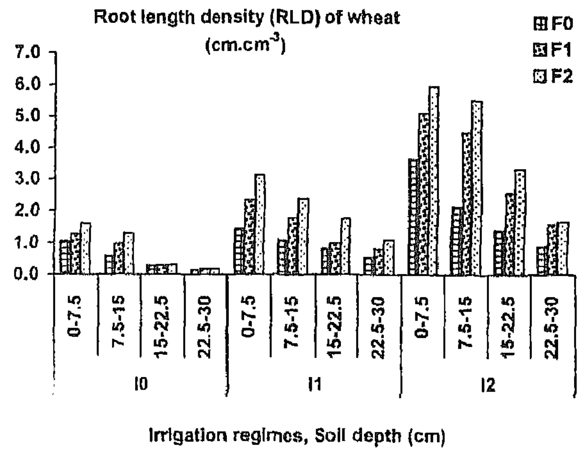

Fig. 1. Effect of irrigation and nutrient management on root length density (RLD) of wheat (I_0, without post-sowing (PS) irrigation; I_1, two PS-irrigations; I_2, three PS-irrigations; F_0, control i.e. without fertilizer or manure; F_1, 100% NPK (100-21.5 - 24.9 kg ha^{-1}; F_2, 100 % NPK + farmyard manure @ 10 t ha^{-1})

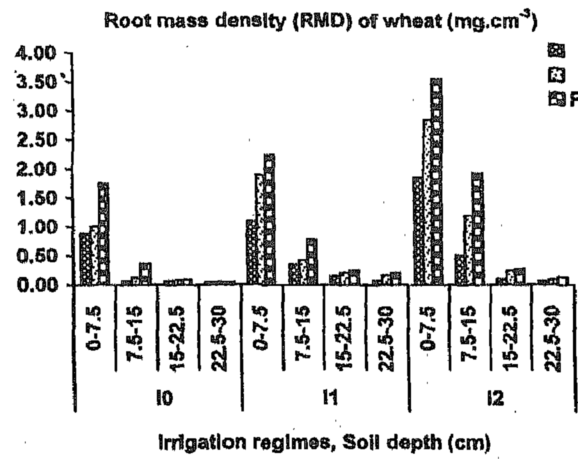

Fig. 2. Effect of irrigation and nutrient management on root mass density (RMD) of wheat (I_0, without post-sowing (PS) irrigation; I_1, two PS-irrigations; I_2, three PS-irrigations; F_0, control i.e. without fertilizer or manure; F_1, 100% NPK (100-21.5 - 24.9 kg ha^{-1}; F_2, 100 % NPK + farmyard manure @ 10 t ha^{-1})

+ FYM induced the crop to distribute roots into greater volume of soil. Greater RLD, in the plough layer (0-15 cm depth), was recorded in 100% NPK (2.65 cm cm^{-3}) under three PS-irrigation treatment. The effect of PS-irrigation and nutrient management on root mass density (RMD, mg cm^{-3}) of wheat (Fig. 2) was similar to RLD. Singh and Das (1986) also reported higher root length density, root weight density and root diameter with increasing irrigation levels especially with increasing N rates. The trends of our data of RLD with respect to main effect of nutrient management treatments are also in agreement with the findings of Murakami *et al.* (1990). They measured root length of wheat using an image analyser and found that total RLD of wheat was highest in the NPK treatment, and was markedly reduced by the NK, and no NPK treatments.

Irrespective of irrigation and nutrient management treatments, nearly 73-79% of the total RLD was recorded in the plough layer (0-15). All the root density parameters (root length density, RLD; root mass density, RMD; root volume density, RVD) decreased with soil depth, but the RMD and RVD decreased more sharply than the RLD irrespective of irrigation and nutrient management treatments. This indicates that at deeper layers especially beyond 15 cm depth, concentration of finer adventitious/seminal roots increased which contributed more to length than mass and volume increase (Mishra *et al.*, 1999). Thus, optimum supply of irrigation water in conjunction with NPK+FYM favourably influenced the crop to enhance root proliferation and distribution that in turn helped the crop to uptake soil moisture and nutrients from greater volume of soil.

Grain yield and water use efficiency

The grain yield and water use efficiency (WUE) of wheat varied significantly due to irrigation and nutrient management treatments. Considering the main effect of PS-irrigation, the pooled grain yields (averaged over three years) significantly increased to 3047 kg ha^{-1} in I_2, 2372 kg ha^{-1} in I_1 and 1610 kg ha^{-1} in I_0 (Table 1). Similarly, grain yields were significantly different due to nutrient management treatments, 1274 kg ha^{-1} in F_0, 2553 kg ha^{-1} in F_1 and 3203 kg ha^{-1} in F_2. The findings are in agreement with the results of other researchers. Singh *et al.* (1987) recorded highest yield of wheat in I_3 (three irrigation) in a normal rainfall year and in I_4 (four irrigation) in a low rainfall year. In terms of percent increase it was found that grain yield increased by 47.3 and 89.2% at two and three PS-irrigations, respectively over no PS-irrigation. At ICARDA, Syria, applying two or three irrigations (80-200 mm) to wheat increased crop grain yield by 36 to 450% (Oweis *et al.*, 1998). Similarly, percent increases in grain yield due to nutrient management were 100.4 and 151.4% in 100% NPK and 100% NPK+FYM, respectively, over control. It indicates the positive effect of balanced nutrition of NPK and residual FYM (applied soybean) to the succeeding wheat crop on the soil quality and physiological functions of wheat. Hussain and Al-Jaloud (1995) recorded a range of grain yield of wheat from 770 to 5010 kg ha^{-1} in different N treatments (control, 25%, 50%, 75% & 100% N), the grain yield increased significantly with increase in N application relative to the control treatment.

Table 1. Effect of irrigation and nutrient management on grain yield and water use efficiency of wheat (pooled over 3 years)

Treatments	Grain yield (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})
I_0	1610 c	10.6 a
I_1	2372 b	9.1 b
I_2	3047 a	8.4 c
CD (P=0.05)	379	0.6
F_0	1274 c	6.3 c
F_1	2553 b	10.2 b
F_2	3203 a	11.7 a
CD (P=0.05)	349	1.2

I_0, without post-sowing (PS) irrigation; I_1, two PS-irrigations; I_2, three PS-irrigations F_0, control i.e. without fertilizer or manure; F_1, 100% NPK (100-21.5-24.9 kg ha^{-1}; F_2, 100% NPK + farmyard manure @ 10 to ha^{-1}; Mean values followed by different letter within columns differ significantly and indicate ranks accoding to Duncan's multiple range tests (P=0.05).

The interaction effects between PS-irrigation levels and nutrient management treatments were significant. The highest pooled grain yield of 4088 kg ha^{-1} was recorded under I_2F_2 treatment, which was significantly higher than I_2F_1 (3377 kg ha^{-1}) and I_1F_2 (3288 kg ha^{-1}) treatments (Table 2). Again, I_2F_1 and I_1F_2 treatments were statistically at par. Thus, in the event of scarcity of irrigation water one PS-irrigation can be compensated if FYM @ 10 t ha^{-1} is applied to previous soybean crop during

Table 2. Interaction effect of irrigation and nutrient management on grain yield and water use efficiency of wheat (pooled over 3 years)

Treatments	Grain yield (kg ha^{-1} mm^{-1})			Water use efficiency (kg ha^{-1} mm^{-1})		
	F_0	F_1	F_2	F_0	F_1	F_2
I_0	957 f	1640 e	2233 cd	7.4 c	10.8 b	13.5 a
I_1	1188 ef	2641 c	3288 b	6.0 cd	10.3 b	11.1 b
I_2	1676 de	3377 b	4088 a	5.5 d	9.4 b	10.4 b
CD (P=0.05)		566			1.7	

I_0, without post-sowing (PS) irrigation; I_1, two PS-irrigations; I_2, three PS-irrigations; F_0, control i.e. without fertilizer or manure; F_1, 100% NPK (100-21.5-24.9 kg ha^{-1}; F_2, 100% NPK + farmyard manure @ 10 t ha^{-1}; Mean values followed by the same letter within and across columns did not differ significantly and indicate ranks according to Duncan's multiple range tests (P=0.05).

kharif season. On an alluvial soil (*Udic Haplustalf*) of the Doon Valley, Singh *et al.* (1996) also found the highest grain yield of wheat (4474 kg ha^{-1}) with pre-sowing irrigation plus irrigation at CRI stage in conjunction with N rate of 150 kg ha^{-1}.

Water use efficiency (WUE) of wheat decreased with increase in PS-irrigation levels. Pooled WUE of 10.6 kg ha^{-1} mm^{-1}, 9.1 kg ha^{-1} mm^{-1} and 8.4 kg ha^{-1} mm^{-1} were recorded in I_0, I_1 and I_2, respectively (Table 1). In contrast to irrigation levels, nutrient management treatments *viz.*, F_1 and F_2 registered higher WUE of wheat, the values were 11.7 and 10.2 kg ha^{-1} mm^{-1}, respectively, compared to F_0 (6.3 kg jha^{-1} mm^{-1}). It was also noted that WUE increased at F_1 and F_2 for any particular level of PS-irrigation. Increase in ET decreased WUE. Our result corroborates the findings of previous researchers in other countries. They reported WUE for wheat of 4.0-8.8 kg ha^{-1} mm^{-1} (Howell *et al.*, 1995) and 8.2 kg ha^{-1} mm^{-1} (Musick *et al.*, 1994) in the US southern plains, 10.8-11.9 kg ha^{-1} mm^{-1} (Zhang and Oweis, 1999) in the Mediterranean region and 8.4-13.9 kg ha^{-1} mm^{-1} (Zhang *et al.*, 1999) in the north China plain. The relatively decrease in WUE in the higher levels of irrigation compared to no PS-irrigation seems to relatively greater water use through evapotranspiration than the corresponding increase in grain yield. Greater increase in grain yield in F_2 and F_1 over control and relatively lessl increase of the corresponding evapotranspiration have evidently resulted in significantly higher WUE in F_2 and F_1. Aggarwal *et al.* (1986) also reported higher WUE in unirrigated wheat compared to irrigated wheat in terms of g DM kg^{-1} water used. 100% NPK and 100% NPK+FYM resulted into better crop growth and registered higher grain yield under any particular level of irrigation, which led to higher WUE under these nutrient treatments compared to control. Hussain and Al-Jaloud (1995) also found significantly higher WUE with increase in N application. The irrigation x nutrient management interaction effect on WUE of wheat was significant (Table 2). Highest WUE of 13.5 kg ha^{-1} mm^{-1} were obtained with I_0F_2 and the lowest value at I_2F_0 (5.5 kg ha^{-1} mm^{-1}). Thus lower WUEs were associated with irrigation treatments, but nutrient management positively influenced the WUE of wheat.

Results revealed that root density of wheat is related to both the application of PS-irrigation water and integrated nutrient management (balanced inorganic nutrient sources like NPK-fertilizers and organic sources like farmyard manure) to the crop. This integrated water and nutrient management enhanced the grain yield. Thus there is a direct relationship between root growth and grain yield (Gajri and Prihar, 1985 and Gujri *et al.*, 1989). Increase in root growth also increased the capacity of the plants to extract water from greater volume of soil, thus increased water use.

Conclusion

Increasing levels of irrigation influenced the crop to proliferate roots in terms of root density and to extract moisture from greater volume of soil. Maximum density of roots was confined to the plough layer (0-15 cm depth). NPK+FYM helped the crop to extract moisture and nutrients from greater volume of soil. To achieve higher growth, root density and grain yield of wheat, one pre-sowing irrigation plus three post-sowing irrigations in conjunction with 100% NPK and 10 t ha^{-1} farmyard manure could be a viable option in a soybean-wheat cropping system in Vertisols of central India. As grain yields at three post-sowing irrigations with 100% NPK are similar to two post-sowing irrigations with 100% NPK + FYM, one pre-sowing irrigation plus two post-sowing irrigation in conjunction with 100% NPK and 10 t ha^{-1} farmyard manure could be a viable option in the event of limited irrigation water.

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