Effects of Fertilizer Nitrogen and Irrigation on Root Growth, and Water Uptake with Special Reference to Postrainy Season Sorghum

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Abstract

Effects of fertilizer nitrogen (*N*) *and irrigation on root development are discussed by collating the observations in published reports with those in our study using field-grown sorghum* [*Sorghum biocolor* (*L.*) *Moench*] *on a deep Vertisol in semi-arid tropical India. In our study, the total root biomass was affected by fertilizer-N and irrigation and by their interaction. It is the top soil layers that contribute largely to increased root biomass due to fertilizer-N and irrigation. These observations agree with those in other reports. The total root length was not significantly affected by fertilizer-N, but was consistently higher under dry conditions than under irrigated conditions. Spatial distribution of root length did not fit a simple mathematical model such as linear, exponential or logistic curve, except at very young growth stages under irrigated conditions. Except the top 16-cm layer, the depth at which root length density zvas maximum shifted to deeper layers as sorghum grew. This may indicate that some roots die after water extraction and that new roots grow at the soil layers where water zvas available. This specific feature would contribute to the complexity of modeling of root development. Rooting depth was not affected by fertilizer-N, but it was consistently greater under dry conditions than under irrigated conditions. The root depth had a linear relationship with time under dry and irrigated conditions up to the physiological maturity stage. Water uptake by sorghum was determined as the difference between measured evapotranspiration and estimated soil evaporation. In non-irrigated treatment, the differences in water uptake among N treatments were not significant. In the irrigated treatment, the rates of 30 to 150 kg N ha* (*30 N and 150 N, respectively*) *resulted in significantly higher water uptake than no fertilizer-N. The fertilizer-N effect in our study zvas not as clear-cut as that in other reports.*

Introduction

The spatial and temporal development of roots in coordination with the development of the shoot largely determine soil water extraction and nutrient uptake. The size and pattern of

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root development are particularly important for crops growing in soil that supplies only limited quantities of water and nutrient in time and space.

In semi-arid tropical India, postrainy season sorghum is grown on Vertisols where the fertilizer applied near the soil surface is absorbed by sorghum only to a limited extent. In such an environment, it is necessary to study the effect of fertilizer on root growth in combination with the effect of soil water. In postrainy season, 1988, at the ICRISAT Asia Center (IAC), we initiated an experiment with sorghum in which root growth and extension were monitored under dry and irrigated conditions and with different N levels. Here, we discuss fertilizer-N and irrigation effects on root development by collating our observations with other published observations.

Root biomass

In our study, during the postrainy season with sorghum [*Sorghum bicolor* (L.) Moench] hybrid "SPH280", total root biomass increased almost linearly up to the dough stage, i.e., 93 days after emergence (DAE), and then nearly leveled off or declined both under dry and irrigated conditions (Fig. 1). A significant fertilizer-N effect on total root biomass was found throughout the growth duration. However, the extent of this effect was not always proportional to N-dose rate.

Overall, the pooled total root biomass across all N rates showed a trend of being always higher (except 31 DAE) under irrigated conditions than under dry conditions (Fig. 1). Interactive effects of fertilizer-N and irrigation were observed only at 93 DAE, when combined effects of both were higher than their additive effects.

Irrespective of irrigation treatment, a large part of the root biomass was found in the top layer of soil (0 to 0.1 m) (Table 1). It ranged from 32% to 41% of total root biomass across-N levels and irrigation treatments. Within the dry treatment, there was no significant difference in root biomass of the top layer between N-levels. Within the irrigated treatment, the rates of 60 to 150 kg N ha^{-1} produced significantly greater root biomass at the top layer than the zero N and 30 kg N ha^{-1} rates (0 N and 30 N, respectively). At a 1.80 m-depth (1.725 m to 1.875 m), there was a significant fertilizer-N effect. The two adjacent layers, 1.65 and 1.95 cm, had a similar trend. However, the root biomass at these layers comprises only a small portion of the total root biomass.

The ratio of root to total biomass was greater during early growth stages than during later growth stages irrespective of fertilizer-N levels or irrigation treatments (Table 2). At 31 DAE, this ratio under dry conditions was the highest, at about 30% of total biomass, and it was the highest at the zero N rate. Highly significant fertilizer-N effects were observed at 31, 45, and 59 DAE, and the 0 N rate produced the highest ratio irrespective of irrigation treatment. The root-total biomass ratio rapidly declined up to 59 DAE (booting stage), and then it leveled off until harvest. At 93 DAE (physiological maturity) and at harvest, the root-total biomass ratio did not differ among different N-levels or between irrigation treatments.

Meyers (1980) observed that the above-ground biomass varied with fertilizer levels, whereas the root biomass varied very little with fertilizer levels. Brown et al. (1987)

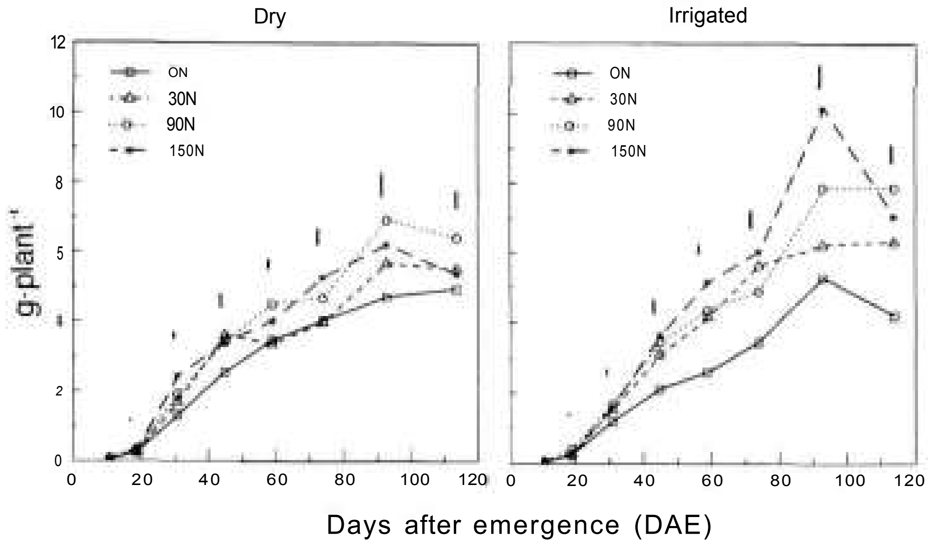

Fig. 1. Effects of irrigation and fertilizer-N on total root biomass. The bars are standard errors of means to compare fertilizer-N effects within an irrigation level at a particular growth stage.

Table 1. Root biomass as a function of soil depth at the time of maximum total root biomass, 93 DAE.

	N-level						
	0N		150N		SE[2]		
Depth(m)	Dry	Irrigated	Dry	Irrigated	Irrigated[3]	Nitrogen[4]	Irrigated[5]* Nitrogen[5]
		$g\ m^{-2}$					
0.05	26.9 (34)	31.9(36)	41.3 (40)	69.7(41)	0.43	4.43 **	7.05
0.16	6.0 (8)	10.5 (12)	8.5 (8)	16.1 (10)	0.70 *	0.98!	1.44
0.30	5.6 (7)	8.2 (9)	6.3 (6)	7.8 (5)	0.40 !	0.80	1.11
0.45	4.4 (6)	4.4 (5)	5.3 (5)	6.6 (4)	0.37	0.39!	0.63
0.60	5.2 (7)	3.9 (4)	3.6 (3)	8.6 (5)	0.77	0.88	1.38
0.75	5.6 (7)	4.8 (5)	4.0 (4)	8.4 (5)	0.37 *	1.54	2.01
0.90	3.3 (4)	4.4 (5)	2.5 (2)	77 (5)	0.58	0.91	1.31
1.05	3.4 (4)	3.9 (4)	4.1 (4)	8.1 (5)	0.29	0.63	0.87
1.20	3.5 (4)	5.0 (6)	6.1 (6)	9.1 (5)	0.19!	0.79	1.04
1.35	3.1 (4)	4.3 (5)	4.6 (4)	8.6 (5)	0.34	0.98	1.31
1.50	4.0 (5)	4.3 (5)	4.2 (4)	8.9 (5)	0.40	0.92!	1.25
1.65	3.7 (5)	1.9 (2)	5.1 (5)	4.5 (3)	0.26	0.73 !	0.98
1.80	1.8 (2)	0.7 (1)	4.4 (4)	3.6 (2)	0.38!	0.73*	1.01
1.95	1.7 (2)	0.2 (0)	3.3 (3)	1.7 (1)	0.70	0.51 !	0.96
Total	78.1(100)	88.6(100)	103.3(100)	169.3(100)	6.31 !	7.96 ***	12.08 !

1 The values in parentheses are percent of total root biomass.
2 Standard error or means calculated from all treatments in this study;!, *, ** and *** significant at P = 0.1, 0.05, 0.01 and 0.001 respectively.
3 For irrigation effect comparison.
4 For N-fertilizer effect comparison..
5 For interactive effects of irrigation and fertilizer-N comparison.

Table 2. Effect of irrigation and fertilizer-N on the ratio of root to total biomass.

N level (kg ha^{-1})	Days after emergence 11	19	31	45	59	74	93	114
Dry								
0	0.26	0.25	0.34	0.27	0.18	0.12	0.10	0.10
30	0.27	0.23	0.30	0.24	0.15	0.09	0.11	0.10
60	0.24	0.22	0.32	0.22	0.13	0.12	0.10	0.09
90	0.29	0.27	0.28	0.20	0.14	0.11	0.11	0.10
120	0.27	0.24	0.25	0.21	0.12	0.13	0.12	0.10
150	0.26	0.26	0.32	0.20	0.12	0.10	0.10	0.10
Mean	0.27	0.24	0.30	0.22	0.14	0.11	0.11	0.10
Irrigation								
0	0.26	0.27	0.35	0.32	0.20	0.13	0.10	0.10
30	0.27	0.20	0.27	0.23	0.12	0.11	0.08	0.10
60	0.24	0.24	0.24	0.20	0.14	0.08	0.11	0.09
90	0.29	0.25	0.24	0.19	0.12	0.10	0.10	0.09
120	0.27	0.22	0.22	0.15	0.10	0.10	0.10	0.09
150	0.26	0.22	0.21	0.17	0.13	0.09	0.10	0.09
Mean	0.27	0.23	0.26	0.21	0.13	0.10	0.10	0.09
SE(1)	±0.039	±0.021	±0.017**	±0.026**	±0.013**	±0.010	±0.010	±0.012
SE(2)		±0.007	±0.005**	±0.018	±0.010	±0.001	±0.005	±0.006

SE(1): To compare N level; SE(2): To compare irrigation.
**: Significant difference at the 0.01 level.

observed that at maturity, fertilizer-N had little effect on root-to-total plant weight ratios of barley, which indicates that root biomass production responded to fertilizer similarly to above-ground biomass production. On the contrary, a reduction in root biomass of grain sorghum was observed with measuring fertilizer-N when compared with that of an unfertilized control (Roder et al. 1989). In our study, a highly significant effect of fertilizer-N on the root biomass was observed. It is the shallow soil layers that largely contribute the effects on total root biomass production. The equal responsiveness of the root biomass and the above-ground biomass production to fertilizer-N was also supported by the ratio of root biomass to total biomass around the maturity stage of sorghum. Although our observation leads us to believe that root biomass production responded positively to fertilizer-N, it is possible that root growth characteristics differ with crop species, cultivars, soil conditions and climatic factors.

Compared with the information on the effect of fertilizer-N on root biomass production, less information is available on the effect of irrigation or soil water on root biomass production under field conditions. Kaigama et al. (1977) reported for field grown grain sorghum that a major difference between irrigated and nonirrigated treatments was the increased quantity of irrigated roots in the top 15 cm of soil. A greater proportion of total root dry matter accumulated at the deeper depths in nonirrigated than in the irrigated sorghum. However, the increased quantities at the deeper depths are far less than those at the shallower depths. Gairi and Prihar (1985) also reported that the root weight density *(fig* root cm^{-3} soil) of field grown wheat in upper layers increased due to irrigation in sandy loam soil. As our study demonstrated, it is the root biomass in the top 0.3 m of soil that greatly increased due to irrigation, and increased root biomass was not generally observed at the deeper depths, although there were some layers at which statistically significant but small increases in root biomass were observed. In terms of increased quantity, our observation is in agreement with those of Kaigama et al. (1977) and Gajri and Prihar (1985).

Root length

It has been reported that fertilizer-N and irrigation affect root length of various crops. For example, application of N and P fertilizers increased the total root length of barley (Brown et al. 1987). Total root length was significantly increased by N-fertilizer (67 kg N ha^{-1}), but high rates of N-fertilizer (134 kg N ha^{-1}) decreased the total root length (Comfort et al. 1988). The total soybean root length was affected by drought stress and irrigation treatments and significantly increased by irrigation treatment (Hoogenboom et al. 1987). Gajri et al. (1989) also observed an increase in root length index (km root m^{-2} surface area in the rooted profile) of wheat, which is comparable to total root length.

In our study with field-grown sorghum, both under dry and irrigated conditions, total root length increased up to 93 DAE and then declined at harvest (Fig. 2). Only at 59 DAE and at harvest there were differences in total root length among N-levels. A significant irrigation effect on total root length across N-levels was observed only at 31 DAE and at harvest. Overall, the roots tended to increases their total length more under dry conditions than under irrigated conditions throughout the growth duration, while roots tended to have less biomass under dry conditions as mentioned earlier. No interactive effects of fertilizer-N and irrigation on total root length were found throughout the growth duration.

Although total root length was affected by N-fertilization and irrigation at some growth stages, it can be contemplated that effects of N-fertilization and irrigation at upper soil layers may be different from those at lower layers because fertilization and irrigation treatments are applied to the top layers of soil. The effect of irrigation on root length density in the soil profile was different between the layers above and below 0.45 m (Fig. 3). After 59 DAE, the root length densities in the top layers at the zero N rate were greater under irrigated conditions than under dry conditions. Such an irrigation effect was more obvious at the rates of 30, 60, and 90 kg N ha^{-1} (30 N, 60 N and 90 N, respectively) (data not shown), but less obvious for the rates of 120 and 150 kg N ha^{-1} (120 N and 150 N, respectively). Unlike root length densities in the top three layers, the ones at depths below 0.45 m were greater under dry conditions than under irrigated conditions, which depends on the depth and the growth stage. At 31 DAE, the root length density under dry conditions was significantly greater than under irrigated conditions only at upper to middle depths (0.30 to 0.60 m). As the plant grew older, such significant differences shifted to the middle depth, the depth of lower middle, and then to the lower depth. Root length density was not affected by fertilizer-N application as much as root biomass.

Comfort et al. (1988) found that root length was significantly increased in the top 0.3 m by applying 67 kg N ha^{-1} but remained the same or decreased at 134 kg N ha^{-1}

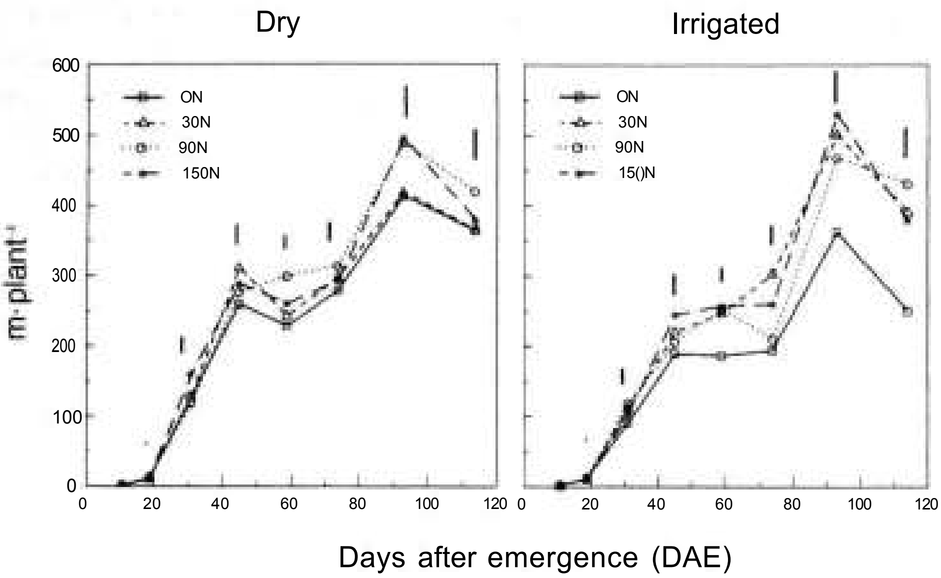

Fig. 2. Effects of irrigation and fertilizer-N on total root length. The bars are standard errors of means to compare fertilizer-N effects within an irrigation level at a particular growth stage-

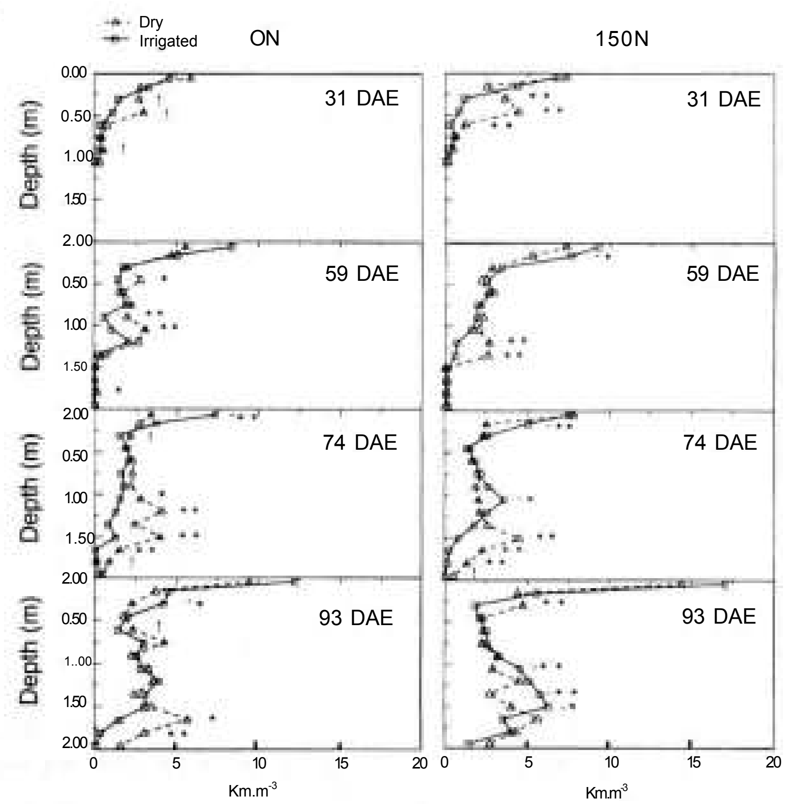

Fig. 3. Root length density as a function of depth for sorghum at the rates of zero N and 150N kg ha^{-1}. The denotation (i), (*) and (**) indicates significant difference at the 10%, 5% and 1% levels respectively, and those accompanied by a minus sign indicate that the irrigation had a significantly higher value. DAE = Days after emergence.

Hoogenboom et al. (1987) observed with soybean that irrigation mainly increased the roots in soil layers above 0.6 m, whereas roots under drought stress conditions penetrated deeper soil layers below 0.6 m. In our study, fertilizer-N increased the root biomass in the top 0.45 m but did not increase the root length. The soil in our study contained about 14 ppm mineral-N before fertilizer-N treatments were applied. We surmise that root length is less sensitive to changes in mineral-N of the soil, and therefore root length did not respond to fertilizer-N applications in the soil of this study. In the 1989/90 postrainy season four sorghum genotypes were examined for their response to fertilizer-N application under dry conditions in another deep Vertisol that contained 7 ppm mineral-N. Root length density in all four genotypes positively responded to fertilizer N application (data not shown). This result supports our conclusion of a more conservative response of root length to fertilizer-N application.

Rooting distribution curve

Gerwitz and Page (1974) obtained a linear relationship for various crops between the soil depth and the logarithms of root percentage of whole root systems within a depth. An exponential distribution with depth has often been reported (e.g., Gregory et al. 1978). Belford et al. (1987) observed that the distribution with depth of nodal and tiller roots of winter wheat was exponential, but that of seminal root was linear.

In our study, the root distribution did not seem to depict a model curve, except the root distribution of young roots (up to 31 DAE) in the irrigated treatment. Except for the top 0.16 m layer, there were layers where root length density was greater than adjacent layers. These layers were more distinct in dry treatment (Fig. 3), and moved down to deeper soil depth with growth stages. We surmise that this phenomenon is due to the death of some roots after water uptake at particular layers and to the growth of new roots at deeper layers where the roots are absorbing water. Blum and Ritchie (1984) proposed that the soil surface moisture controls the number of crown roots and subsequently root distribution along the soil profile. It is also possible in our study that the drier soil surface caused compensatory increased root elongation in deeper soil layers.

Rooting depth

In our study with sorghum, rooting depth, the depth of containing 90% of the roots, increased with growing period up to 93 DAE (maturity) and then leveled off at harvest (Fig. 4). The rooting depth increased almost linearly up to 93 DAE. There was no significant difference in rooting depth between N levels. Up to 31 DAE, differences in rooting depth were not observed between dry conditions and irrigated conditions except at 60 N (data not shown). After 31 DAE, rooting depth was consistently greater under dry conditions than under irrigated conditions.

Borg and Grimes (1986) showed that time course of rooting depth can be described by a sine function. The rooting depth with time in our study may fit a sine function with

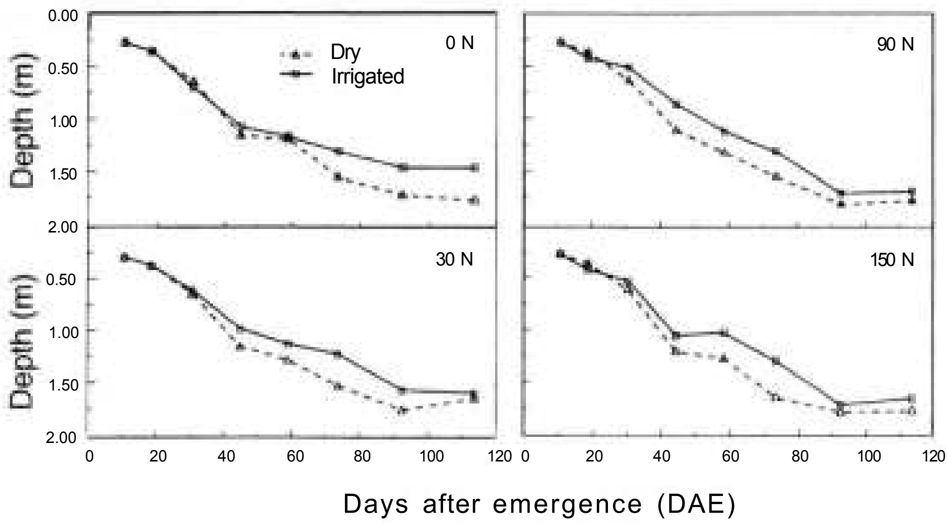

Fig. 4. Changes of root depth, the depth of the soil containing 90% of the root, with growth stages for sorghum grown at the rates of 0, 30, 90 and 150 kg N ha^{-1} under dry and irrigated conditions.

certain errors if the root depth data at harvest (114 DAE) are included. However, a linear function also fits if the data at harvest are not included, because the root growth ceased at 94 DAE (physiological maturity). Assuming that root depth increase linearly with growing days, the rate of root depth ranges from 1.9 to 2.0 cm day^{-1} under dry conditions and from 1.5 to 1.8 cm day^{-1} under irrigated conditions.

Soil moisture and water uptake

The plants grow and survive by coordinating the operation of roots and shoots. Both irrigation and fertilizer-N application influence the canopy size, root length, and rooting depth, and consequently influence seasonal water use by the plants. A much larger combined effect of fertilizer-N and irrigation than the sum of their separate effects was observed with wheat (Gajri et al. 1989). Comfort et al. (1988) described that high rates of N-fertilization may inhibit deeper root growth and hence potentially decrease the use of deeper soil water reserves.

We measured soil water content in the field planted with sorghum during the 1988/89 postrainy season, and then estimated the evapotranspiration from the change in soil water content, the amount of irrigation and the amount of precipitation. Soil evaporation was calculated using the soil water balance model of Ritchie (1972). Transpiration was calculated as the difference between observed evapotranspiration and soil evaporation.

Changes in soil moisture in soil profile as the plants grew were greater in irrigated conditions than in dry conditions (Fig. 5). Within an irrigation treatment, changes in soil

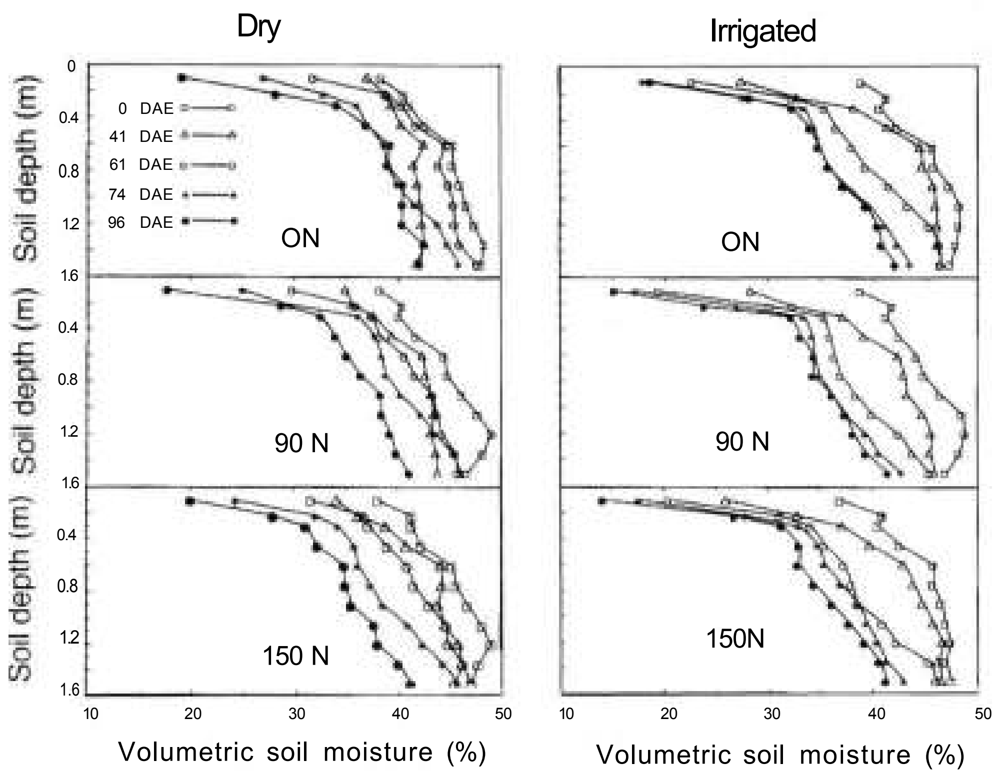

Fig. 5. Soil moisture as a function of depth for sorghum at the rates of 0, 90 and 150 kg N ha^{-1} under dry and irrigated conditions.

moisture increased with fertilizer-N levels. These data indicate that sorghum plants suffer from moisture stress in dry conditions and that increasing biomass production of sorghum with fertilizer-N levels demanded more water.

Water uptake was greater in the irrigated treatment than in the dry treatment at all nitrogen levels (Table 3). In the dry treatment, water uptake increased with N-fertilizer application up to 60 N, and beyond this N-level it did not differ significantly. In the irrigated treatment, the increases in water uptake were observed up to 30 N and beyond this N-level the water uptake did not increase significantly. Water uptake is not controlled by root growth alone, but by coordinated function of root and shoot growth. However, increased root length in corresponding treatments can increase the capacity of water uptake. The observation in our study shows that increased root length due to fertilizer-N or irrigation increased water uptake by field-grown sorghum, but interactive effects of fertilizer N and irrigation were not observed.

Conclusion

The effects of fertilizer-N and irrigation on root biomass, root length, root depth, and water uptake of field-grown sorghum were investigated on a deep Vertisol during the postrainy

Table 3. Effects of irrigation and N fertilizer on evapotranspiration, transpiration, and soil evaporation in various treatments.

	Evapotranspiration (mm)		Transpiration (mm)		Soil evaporation (mm)	
N level (kg ha^{-1})	Dry	Irrigation	Dry	Irrigation	Dry	Irrigation
0	199	367	151	273	48.6	94.5
30	202	397	154	308	48.7	89.5
60	237	392	188	306	48.6	85.3
90	220	379	172	295	48.5	84.4
120	201	416	152	331	48.5	85.0
150	195	396	147	314	48.5	82.4
SE(1)	15.6		15.89		0.92	
SE(2)	17.9		17.87		0.93	

SE(1): To compare N level; SE(2): To compare irrigation.

season. These results were collated with those in other reports. The responses of total root biomass and root biomass distribution with soil depth were consistent with those in other published reports. The root depth under dry and irrigated conditions increased linearly with time. Therefore, these root parameters can be readily modeled by using or modifying existing models. On the other hand, the length distribution with soil depth in our study does not seem to fit well to existing mathematical models. This length distribution may has to be taken into account for modeling of root development, which will be the case for modeling of water uptake because root length distribution is closely related to water uptake.

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