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Analysis of Relationship between Root Length Density and Water Uptake by Roots of Five Crops Using Minirhizotron in the Semi-Arid Tropics

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Abstract

Experiments were carried out to analyze the root and water dynamics simultaneously using a minirhizotron on an Alfisol soil in the semi-arid tropics in 1993. Sorghun (CSH 5), pearl millet (ICMV 221), pigeonpea (ICP 1-6), groundnut (ICGS 11) and cowpea (EC 82-7) were used to describe the relationship between the root length density (RLD) and water uptake by roots per day (WU). During the periods from 37 to 46, from 51 to 59 and from 72 to 77 days after sowing, the average values of RLD of sorghum and pearl millet at the soil depth of 15-60 cm were consistently higher than those of pigeonpea, groundnut and cowpea, whereas the average values of WU of the cereals were not always higher than those of the grain legumes. Thus, there was no significant relationship between RLD and WU for the 5 crops due to the higher values of the specific root water uptake (SRWU) of grain legumes than those of cereals in each period. In this study, it was demonstrated that WU and SRWU as well as RLD for the 5 crops could be estimated by using the minirhizotron since dynamic values of the root length of the 5 crops and soil moisture content (SMC) in each soil layer could be quantified from datasets by frequent observations and with limited sampling errors. Therefore the minirhizotron was found to be a suitable tool for simultaneous monitoring of the root and water dynamics in soil layers except for the soil surface.

Discipline: Crop production
Additional key words: cereals, grain legumes

Introduction

The minirhizotron method, which is a nondestructive, rapid and efficient root measurement technique, was applied to observe root development using a microvideo camera in the observation tube[3,8]. In a similar manner, the soil moisture content (SMC) was estimated by a neutron probe method using an aluminum tube. The minirhizotron and the neutron probe methods are nondestructive and allow continuous observations from the same spot in different soil layers. Thus, these methods are suitable for monitoring time-course changes in root development and SMC. Since the tubes using the minirhizotron and the neutron probe methods are usually embedded in soil separately, it is difficult to estimate the relationship between the root and water dynamics due to soil heterogeneity, artifacts of tube installation and so on. As few studies have been carried out to minimize these factors, attempts were made to analyze the root and water dynamics *in situ* simultaneously. In our previous study[9], since there was a close positive correlation of neutron counts between aluminum and acrylic tubes, we were able to estimate SMC even by using the acrylic tube based on the following regression equation:
$y = 0.97x - 0.044$, $r^2 = 0.99$, where x represents the neutron count for the soil moisture measurement using an acrylic tube and y that using an aluminum tube. The objective of this study was to determine whether the minirhizotron was a suitable tool for simultaneous monitoring of the root and soil water dynamics in soil layers.

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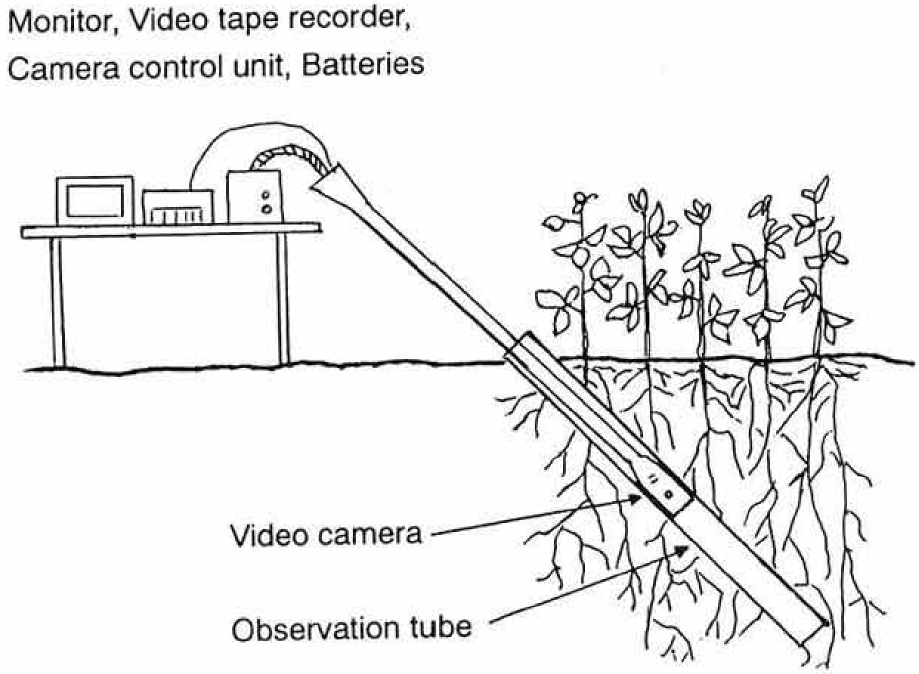

Fig. 1. Diagrammatic representation of the minirhizotron

Materials and methods

The experiment was conducted during the 1993 rainy season on an Alfisol at ICRISAT Asia Center, near Hyderabad, India. The initial characteristics of the soil in the experimental area were as follows: pH, 6.78 (1:2 soil/water ratio); inorganic N content, 22.9 mg kg^{-1} soil and $NaHCO_3$-extractable P, 3.34 mg kg^{-1} soil. Medium duration pigeonpea (*Cajanus cajan* L. Millsp. cv. ICP 1-6), hybrid grain sorghum (*Sorghum bicolor* L. Moench cv. CSH 5), pearl millet (*Pennisetum glaucum* L.R.Br. cv. ICMV 221), groundnut (*Arachis hypogaea* L. ICGS 11) and cowpea (*Vigna sinensis* Endl. cv. EC 82-7), which are staple food crops in the semi-arid tropics, were sown on broad beds on 25 June 1993. Spacing for the sole crops was as follows: for pigeonpea, 75 × 20 cm; sorghum, 50 × 15 cm; pearl millet, 50 × 15 cm; groundnut, 37.5 × 10 cm and cowpea, 50 × 10 cm. All the plots received a uniform basal application of 25 kg N ha^{-1} as urea and 20 kg P_2O_5 ha^{-1} as single superphosphate prior to sowing, which were incorporated into the soil up to 20 cm by disc plowing before sowing. The experimental layout consisted of a randomized complete block design with 3 replications. The size of each plot was 6 × 12 m, consisting of 12 broad beds with a 90 cm width. Heading of pearl millet and sorghum occurred at 51 and 78 days after sowing (DAS) and flowering of groundnut, cowpea and pigeonpea occurred at 30, 51 and 142 DAS, respectively. The crops were harvested at maturity, 85 DAS for pearl millet and cowpea, 114 DAS for groundnut and sorghum and 209 DAS for pigeonpea.

Root length of the crops was measured by the minirhizotron method (CIRCON MV9011 agriculture system with MV9390 color CCD microvideo camera) at 31, 46, 60, 74, 84, 105, 143 and 169 DAS. The transparent plastic minirhizotron tubes (58 mm in diameter and 100 cm in length) were installed at a 45° angle between rows of each crop before sowing (Fig. 1). This experiment was carried out in an Alfisol with a hardpan layer below 60 cm. Root length at 15 cm intervals up to 60 cm depth was calculated from the number of roots observed on a video display[15]. Soil moisture was measured with a soil moisture meter (Model 3332, Troxler Electronic Laboratories Inc., N.C., USA) at 15 cm intervals up to 60 cm depth except at the soil surface using the same transparent acrylic tube as in the minirhizotron method at 7, 23, 37, 46, 51, 59, 72, 77, 93, 107, 119, 143, 157, 172 and 213 DAS. Usually, SMC at the soil surface was measured by the gravimetric method. Thus, we analyzed seasonal changes in SMC at the depths of 15–30, 30–45 and 45–60 cm, where consecutive data could be obtained in the same spot in this study. The values of SMC on a weight basis in each layer were converted to the values on a volume basis by multiplication by the bulk density for an estimation of water uptake by roots per day (WU). The values of the bulk density at the depths of 15–30, 30–45 and 45–60 cm were 1.69, 1.59 and 1.59 Mg m^{-3}, respectively. The WU was estimated based on the volume of water extracted within the respective soil layers per day. The specific root water uptake (SRWU) referred

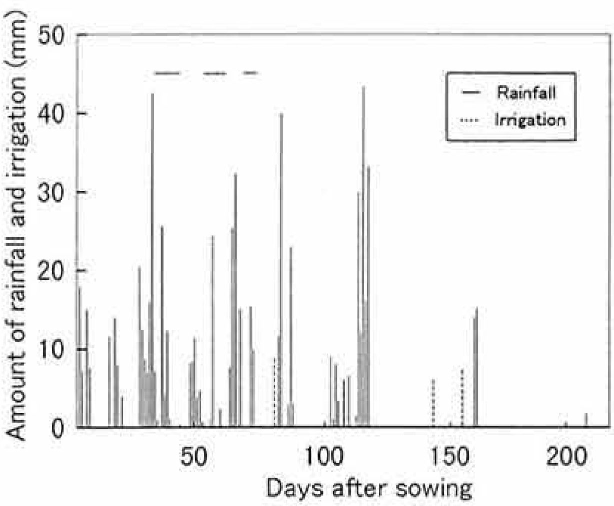

Fig. 2. Distribution of rainfall and irrigation after sowing
Horizontal bars indicate periods when the water uptake by roots was measured.

to the volume of water extracted within a soil layer per unit root length per day[6].

During this study, rainfall which amounted to 695.2 mm was mainly distributed at the onset of the rainy season (June-November) (Fig. 2). Nine, 6 and 7 mm of water were used for irrigation at 79, 143 and 155 DAS, respectively.

Results

1) Seasonal changes in SMC

Seasonal changes in SMC at the soil depths of 15–30, 30–45 and 45–60 cm determined with a minirhizotron for 5 crops are depicted in Fig. 3–a, b and c, respectively. Water flow was assumed to be one-dimensional with the increase in SMC on successive dates being attributed to rainfall and irrigation and the decrease attributed to the root uptake. Fluctuation range in SMC was lower at the soil depth of 15–30 cm, followed by the soil depth of 30–45 cm and the widest range in SMC was obtained at the soil depth of 45–60 cm during the sampling period, presumably due to the presence of a hard layer below 60 cm depth. Since a decrease in SMC on successive dates was obtained during 3 periods from 37 to 46, from 51 to 59 and from 72 to 77 DAS before the harvest of pearl millet and cowpea as shown in Fig. 3, these periods were selected to estimate the WU of the 5 crops.

2) Estimation of total root length (TRL), RLD, WU and specific root water uptake (SRWU) of 5 crops using the minirhizotron

The seasonal changes of TRL of the 5 crops are depicted in Fig. 4. The values of TRL of pearl millet and sorghum were higher than those of cowpea, groundnut and pigeonpea except at 31 DAS. During the periods from 37 to 46, from 51 to 59 and from 72 to 77 DAS, the average values of RLD of sorghum and pearl millet at the soil depth of 15–60 cm were consistently higher than those of pigeonpea, groundnut and cowpea, whereas the average values of WU of cereals were not always higher than those of the grain legumes (Table 1). Thus, there was no significant difference between the RLD and WU of the 5 crops in each period (Fig. 5–a, b and c) due to the

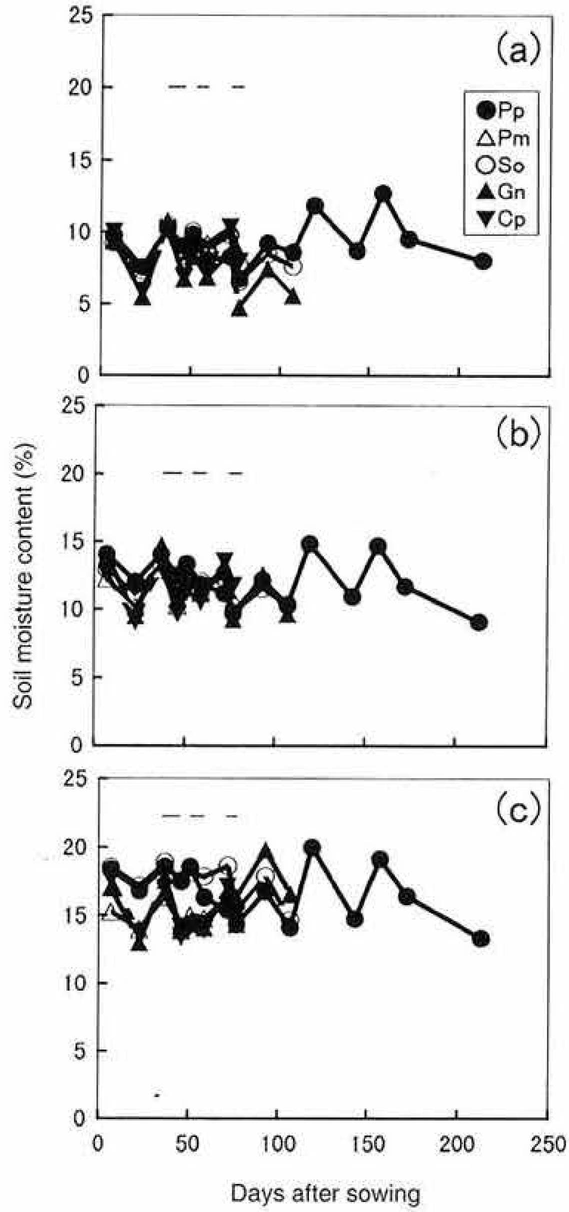

Fig. 3. Seasonal changes in soil moisture content at the depths of 15–30 (a), 30–45 (b) and 45–60 (c) under the 5 crops after sowing
Horizontal bars indicate periods when water uptake by roots was measured.

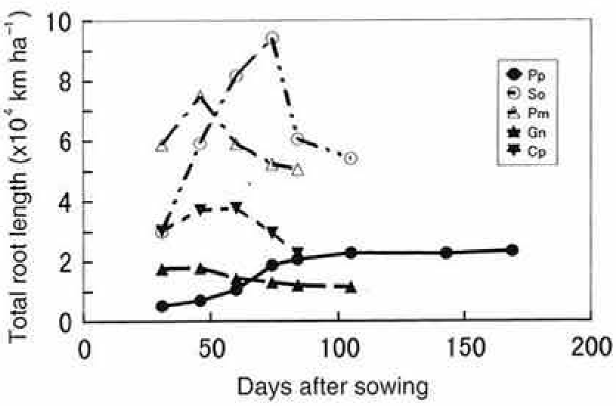

Fig. 4. Seasonal changes in total root length (TRL) of 5 crops after sowing

higher values of SRWU of grain legumes than those of cereals. The average values of SRWU for groundnut, cowpea and pigeonpea were higher than those for pearl millet and sorghum, namely 2.5 to 5.8 times higher during the period from 37 to 46 DAS, 2.4 to 8.0 times during the period from 51 to 59 DAS and 2.5 to 5.8 times during the period from 72 to 77 DAS.

Discussion

The main advantage of the minirhizotron method is the ability to monitor root growth and death throughout the growing period[3,8]. On the other hand, one disadvantage is the quantitative discrepancy with the conventional destructive method in the soil surface layers[1,2]. Katayama et al.[10] showed that in the surface soil layers, the ratios of RLD observed using the minirhizotron compared with the monolith method were below unity, indicating that the RLD value obtained by the minirhizotron is likely to be underestimated. Underestimation at the soil surface may be due to the effects of light leaking through the top of the minirhizotron tubes above the soil surface[11] and to temperature differences at the glass-soil interface[7,12,15]. Katayama et al.[10] reported that the values of TRL of pearl millet and sorghum were significantly higher than those of cowpea, groundnut and pigeonpea when the monolith method was used due to the higher RLD values of cereals compared with grain legumes at the soil surface. Polley et al.[14] reported that the root biomass of the C_4 monocots is concentrated in the upper 20 cm layer of soil. Thus, it is assumed that the values of TRL of the 5 crops shown in Fig. 4 were underestimated.

In this experiment, it was found that the WU of pearl

Table 1. Root length density (RLD), water uptake by roots per day (WU) and specific root water uptake per RLD per day (SRWU) of pigeonpea(Pp), sorghum(So), pearl millet(Pm), groundnut(Gn) and cowpea (Cp) at the soil depths of 15–30, 30–45 and 45–60 cm during the periods from 37 to 46, from 51 to 59 and from 72 to 77 days after sowing (DAS)

Crop	depth	37–46 DAS			51–59 DAS			72–77 DAS		
	(cm)	RLD[a)]	WU[b)]	SRWU[c)]	RLD	WU	SRWU	RLD	WU	SRWU
Pp	15–30	0.16	2.29	23.1	0.19	1.48	7.8	0.42	9.16	22.1
	30–45	0.16	2.79	27.6	0.19	0.54	2.8	0.38	6.95	18.3
	45–60	0.07	1.77	17.7	0.10	1.35	13.5	0.27	6.25	23.6
	AVG	0.13	2.28	22.8	0.16	1.12	8.0	0.36	7.45	21.3
So	15–30	0.80	3.90	4.9	1.48	2.61	1.8	2.67	10.88	4.1
	30–45	1.03	3.77	4.0	2.16	0.92	0.4	2.43	8.36	3.4
	45–60	0.54	2.47	5.3	0.81	0.58	0.8	0.75	7.95	10.6
	AVG	0.79	3.38	4.7	1.48	1.37	1.0	1.95	9.06	6.0
Pm	15–30	1.41	5.23	4.4	1.43	1.19	1.2	1.29	6.26	4.9
	30–45	1.62	4.62	3.2	1.39	1.19	1.5	0.97	5.73	6.0
	45–60	1.10	3.71	4.2	1.08	0.41	0.6	1.00	6.14	6.2
	AVG	1.37	4.52	3.9	1.30	0.93	1.1	1.09	6.04	5.7
Gn	15–30	0.47	7.07	15.3	0.40	2.92	7.5	0.30	12.80	44.1
	30–45	0.37	7.10	20.6	0.30	2.63	10.7	0.23	12.52	55.6
	45–60	0.28	7.07	26.4	0.27	0.70	2.7	0.26	0.08	0.3
	AVG	0.37	7.08	20.8	0.32	2.08	7.0	0.26	8.47	33.3
Cp	15–30	0.81	6.23	8.3	1.11	2.14	1.9	0.69	8.04	12.0
	30–45	0.80	6.53	8.9	0.79	1.34	2.4	0.64	5.73	9.9
	45–60	0.36	6.24	18.1	0.27	0.61	3.4	0.30	6.46	22.6
	AVG	0.66	6.33	11.8	0.72	1.36	2.6	0.54	6.74	14.8

a): $\times 10^4 mm^{-3}$. b): $\times 10^{-3} m^{-3} m^3 day^{-1}$. c): SRWU = WU/RLD, $\times 10^{-7} m^2 day^{-1}$.

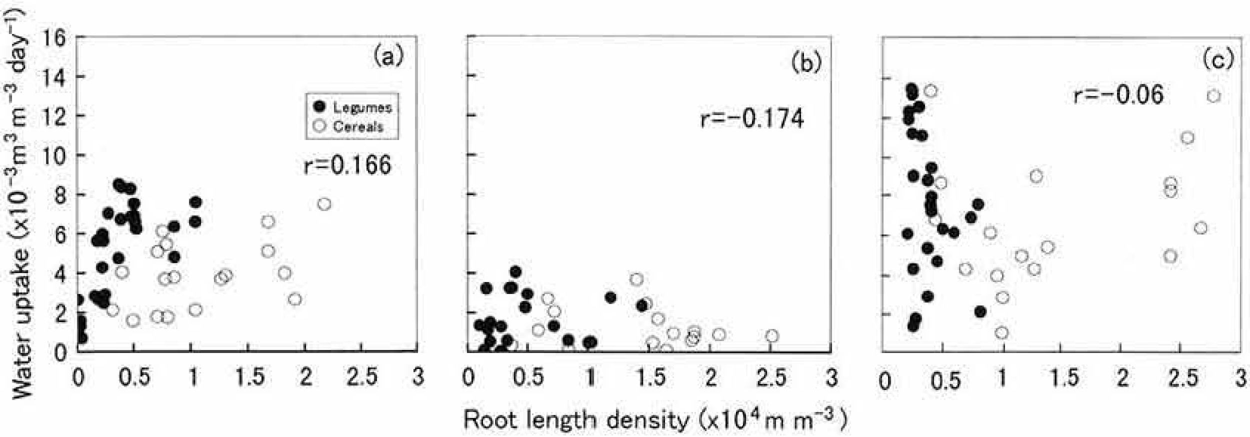

Fig. 5. Relationship between root length density and water uptake of 5 crops during the periods from 37 to 46 (a), from 51 to 59 (b) and from 72 to 77 (c) days after sowing

millet and sorghum with higher RLD values was not always greater than that of groundnut, cowpea and pigeonpea with lower RLD values due to the higher values of SRWU of grain legumes than those of cereals. Difference in stomatal conductance between C_3- and C_4-pathway species may be partially responsible for the variation in water use[4]. However, the discrepancy between RLD and WU of cereals and legumes in this study was in agreement with the results obtained in cereals and legumes of C_3-pathway species by Hamblin and Tennant[6]. They reported that cumulative uptake water by roots for wheat from the soil profile over the period from 70 to 110 DAS was very similar to that of lupin, although the value of the TRL per unit ground area of wheat was 9 times as high as that of lupin[6]. They also showed that the apparent water uptake per RLD per day was greater for lupin than wheat since lupin had large and abundant metaxylem vessels in roots, which give a much lower axial resistance of roots, compared with wheat[6]. Moreover, the discrepancy between RLD and WU in monocotyledonous and dicotyledonous species consisting of maize, sorghum and sunflower, was also reported elsewhere[5,13].

In this study, it was demonstrated that WU and SRWU as well as RLD for 5 crops could be estimated using the minirhizotron since the dynamic values of the root length of the 5 crops and SMC in each soil layer could be quantified based on data-sets by frequent observations and with limited sampling errors. Therefore the minirhizotron was found to be a suitable tool for simultaneous monitoring of the root and water dynamics in soil layers except for the soil surface.

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