JARQ 32, 97–103 (1998)

Differences in Root System Morphology and Root Respiration in Relation to Nitrogen Uptake among Six Crop Species

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Abstract

Cereals and legumes that originated from the semi-arid tropics (SAT) are mainly grown in marginal soils with limited water and nutrient resources. Initial root system development is crucial for crop establishment in order to acquire these minimal resources. A comparative study of the root system morphology and of some physiological parameters at initial growth stages was carried out for 3 legumes: pigeonpea, chickpea and groundnut, and 3 cereals: sorghum, pearl millet and maize, the component crops of the semi-arid tropics. Considerable differences were observed for all the root morphological traits among the species. Among the legumes, chickpea produced few thick and lengthy laterals, while pigeonpea produced a high frequency of thinner laterals. However groundnut had a larger root system than the other 2 legumes. Among the cereals, maize formed a large root system followed by sorghum with a high frequency of laterals, while millet displayed a smaller root system with thin roots. The root respiration rate was significantly correlated with the N uptake activity. The legumes showed a higher efficiency of N uptake in terms of respiratory requirement. The transpiration rate showed a significant correlation with total N concentration in shoot, indicating that transpiration may be partly related to nitrogen flow to and accumulation in shoot in case of nitrate nitrogen as a sole nitrogen source. Morphological and physiological characters of the root system using rather simple indices were found to be better criteria for describing functional differences among crop species.

Discipline: Soils, fertilizers and plant nutrition
Additional key words: *Arachis hypogaea, Cajanus cajan, Cicer arietinum, Pennisetum glaucum, semi-arid crop species, Sorghum bicolor, Zea mays*

Introduction

The crops widely grown in the semi-arid tropics (SAT) are exposed to a scarcity of nutrients and water. The morphology and physiology of the root system play a major role in the uptake of minerals and water by crop species especially under stressed conditions, and consequently determine biomass production and crop yield[10]. A well-developed root system is essential for crop establishment at the initial growth stage in order to exploit limited soil resources. The ability of a root system to support crop growth largely depends on its architectural structure and uptake ability[9]. Our previous study[12–14] dealt with the N uptake kinetics under low and high nitrogen availability. Morphological and physiological characterization of the root system is a prerequisite for the genetic improvement of any crops grown under adverse conditions[11]. The information obtained from these studies can be utilized as input parameters for a nutrient uptake model[5] which is a necessary component of the crop growth model. In addition, it is also useful for understanding the competition of roots for soil resources when the crops are grown under intercropping systems[15].

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The present study was undertaken to describe and correlate some morphological and physiological traits of the root system. The experiment was conducted using 2 distinct groups of crops, legumes and cereals. Three crop species were selected to represent each group: for legumes; pigeonpea, chickpea and groundnut, and for cereals; sorghum, pearl millet and maize. These are the major component crops grown under both monocropping and intercropping conditions at SAT.

Materials and methods

1) Plant materials and culture conditions

Three legumes, pigeonpea (*Cajanus cajan* L. millsp. cv. ICPL 87), chickpea (*Cicer arietinum* L. cv. K850) and groundnut (*Arachis hypogaea* L. cv. NCAC 17090) and 3 cereals, sorghum (*Sorghum bicolor* L. Moench cv. CSH5), pearl millet (*Pennisetum glaucum* L. cv. WC 75) and maize (*Zea mays* L. cv. Ganga 5) were grown in a greenhouse for 1 month at an average temperature of 30°C. Twenty seeds of each plant species were sown in a wooden tray (150, 450 and 120 mm depth) filled with sand. The plants were regularly supplied with modified Hoagland nutrient solution[8], with 1/5 strength for legumes and 2/5 strength for cereals.

2) Morphological measurements

Five randomly selected plants of each species were used for the measurements of morphological parameters. The root parameters observed varied between legumes and cereals as their morphology was completely different[16]. The terminology used in this study for each group of species was as follows: In legumes, (1) the tap root, (2) the first order roots on the tap root with further branches were designated as primary roots and (3) second and third order roots as secondary and tertiary roots, respectively; in cereals, (1) the seminal root system which developed from root primordia, (2) the adventitious roots from the first primordia node were designated as nodal-1 roots and (3) the adventitious roots from the second node as nodal-2 roots. The further orders of the roots on nodal roots were designated as secondary and tertiary roots as in legumes. The schematic description of these root systems is given in Fig. 1.

The number and length of each class of roots were measured manually. The diameter of thin roots was measured with a binocular microscope using an eyepiece micrometer. For precise observation up to the tertiary root level, only the well developed 5 primary/nodal roots were used from each plant. The total root length was measured with a Comair root length scanner. From these preliminary data the following parameters were derived as follows: branching frequency (branches cm^{-1}) = number of branches of each order root/length of higher order root; surface area (cm^2) = 1/3 × 3.143 × diameter × length; and specific root length (mg DW^{-1}) = root length/root dry weight. In cereals the frequency of nodal roots was the same as the number per plant because of their origin from nodes. Some shoot

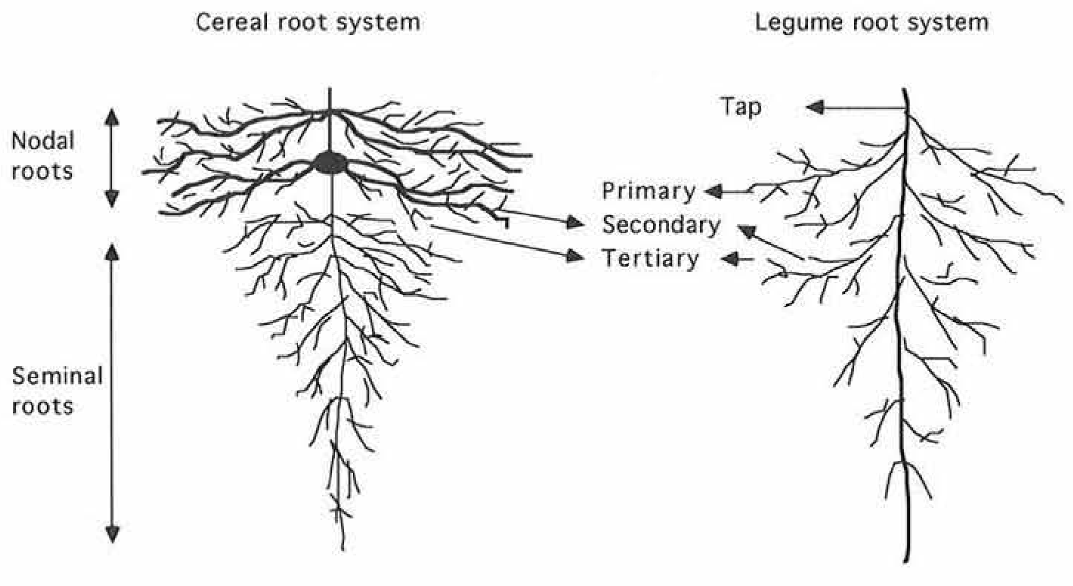

Fig. 1. Schematic representation of root systems of legumes and cereals in relation to the difference in the order of roots

parameters have been included for a brief description of plant as a whole and to explain their functional significance. The changes of various parameters of individual groups in the crop species were analyzed by 2-way ANOVA (CRD) and post-ANOVA comparisons were made using Fisher-PLSD test.

3) Physiological determinations

Root respiration rate (μmole O_2 g root FW^{-1}), total N content of shoot and root (% on a dry weight basis), and N uptake activity (mgN g root FW^{-1}) and transpiration rate (cm^3 m^{-2} h^{-1}) were determined as physiological indices. Root respiration was determined by placing whole root detached from the plant in a gas-tight container whose size ranged from 10 to 50 ml depending on the volume of the root and incubated at 30°C for 2 h. Oxygen concentration inside the container was determined after the incubation period using an oxygen analyzer (Toray LC700F). Total N was analyzed in the same way as described previously[12]. The N uptake activity was calculated in terms of the amount of N acquired per gram root fresh weight. Transpiration was calculated from the weight difference of the container where an intact plant was placed with culture medium for 2 h at 30°C and expressed on a leaf area basis.

Results

Among the legumes, although chickpea produced thick and long lateral roots, the frequency of these laterals was very low compared to the other 2 legumes (Table 1). Groundnut had a larger number and high frequency of primary and secondary roots as well as a larger total root length and leaf area

Table 1. Root and shoot characteristics of 3 legumes; pigeonpea (*Cajanus cajan* L.), chickpea (*Cicer arietinum* L.) and groundnut (*Arachis hypogaea* L.)

		Pigeonpea	Chickpea	Groundnut	Mean	SEM	LSD
Number	Pri.	14.6	17.0	53.8	28.5**	2.12	6.54
($plant^{-1}$)	Sec.	19.8	8.4	42.3	23.5**	1.20	3.71
	Ter.	2.20	0.96	0.68	1.28*	0.50	1.55
Length	Tap	11.5	25.9	22.1	19.8**	2.38	7.32
(cm)	Pri.	9.98	15.0	17.1	14.0	0.84	2.58
	Sec.	2.94	7.66	2.98	4.52**	0.38	1.16
	Ter.	0.41	0.65	0.33	0.46**	0.15	0.47
	Total	214	596	895	568**	41.3	27.3
Diameter	Tap	1.82	2.72	2.76	2.43**	0.18	0.32
(mm)	Pri.	0.51	0.78	0.62	0.64*	0.05	0.16
	Sec.	0.34	0.54	0.38	0.42**	0.02	0.06
	Ter.	0.27	0.39	0.32	0.33**	0.01	0.04
Frequency	Pri.	1.29	0.67	2.45	1.47**	0.10	0.30
(branch cm^{-1})	Sec.	2.07	0.56	2.49	1.70**	0.07	0.22
	Ter.	0.66	0.09	0.19	0.32**	0.10	0.31
Surface area	Tap	2.21	7.25	6.41	5.29**	0.62	1.90
(cm^2)	Pri.	0.54	1.24	1.09	0.96**	0.12	0.37
	Sec.	0.11	0.43	0.12	0.22**	0.02	0.06
	Ter.	0.01	0.02	0.01	0.01	0.01	0.02
Specific root length (mg DW^{-1})		39.8	51.2	45.8	45.6*	2.36	7.28
Root shoot ratio		0.21	0.40	0.31	0.31**	0.03	0.09
Water (%)	Root	94.5	97.7	94.4	95.5**	0.19	0.59
	Shoot	73.3	83.8	82.9	80.0	0.67	2.06
Leaf area (cm^2)		37.4	49.7	92.0	59.7**	5.79	17.8

Pri.: primary, Sec.: secondary, Ter.: tertiary, SEM: standard error of mean, LSD: least significant difference (at 5%)
** Significant at 1% level ($P<0.01$).
* Significant at 5% level ($P<0.05$).

than the other 2 species. Pigeonpea exhibited a lower root mass with thinner roots, and a shorter and smaller surface area for primary and secondary roots, whereas the other 2 species showed high values for these parameters and the difference among the two was negligible. Although pigeonpea had a low profile for all orders of roots, it had a very high frequency of tertiary roots (Table 1). The value of specific root length was highest in chickpea, though the difference was negligible. Water content and root/shoot ratio were also found to be high in chickpea.

Among the cereals, the root diameter in each order was smallest in millet followed by sorghum and maize (Table 2). The trend in branching frequency differed depending on the order of roots. The highest frequency of seminal branching was found in maize. In the higher order of roots, however, the frequency was highest in sorghum. The surface area of roots is considered to be closely related to the uptake capacity of nutrients and water by plants. Millet showed the smallest surface area, while there was no significant difference between sorghum and maize. The 3 cereal plants tested here had a similar specific root length. Maize showed a very large leaf area followed by sorghum and millet. Though there was no significant difference in the water percentage of roots among the cereals, millet

Table 2. Root and shoot characteristics of 3 cereals; sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* L.) and maize (*Zea mays* L.)

		Sorghum	Pearl millet	Maize	Mean	SEM	LSD
Number	S.bran.	52.4	49.0	57.8	53.1**	13.8	4.00
(plant^{-1})	Nod-2	8.6	4.8	14.5	9.30**	1.43	4.46
	Nod-1	7.8	2.60	2.75	4.38**	0.82	2.54
	Sec.	12.8	1.74	3.80	6.13**	1.19	3.70
	Ter.	9.60	2.96	4.75	5.77**	1.04	3.25
Length	Sem.	37.7	37.8	20.0	31.8	8.52	27.3
(cm)	Nod-2	21.7	13.3	19.8	18.3	2.42	7.53
	Nod-1	11.7	1.30	14.8	9.30**	2.60	8.08
	Sec.	4.46	2.63	3.49	3.53**	0.39	1.22
	Ter.	0.56	0.58	0.38	0.51	0.08	0.26
	Total	459	100	643	4.01**	64.3	198
Diameter	Sem.	1.08	0.51	1.51	1.04**	0.11	0.35
(mm)	Nod-2	0.93	0.83	1.17	0.98**	0.06	0.18
	Nod-1	0.18	0.11	0.74	0.35**	0.07	0.23
	Sec.	0.31	0.21	0.38	0.30**	0.02	0.06
	Ter.	0.17	0.14	0.21	0.17**	0.01	0.03
Frequency	S.bran.	1.38	1.38	3.37	2.04**	0.29	0.94
(branch cm^{-1})	Sec.	0.65	0.11	0.19	9.32**	0.07	0.22
	Ter.	1.87	0.77	1.22	1.29**	0.22	0.70
Surface area	Sem.	4.51	1.99	3.23	3.24	1.20	3.83
(cm^2)	Nod-2	1.97	1.10	2.40	1.82**	0.21	0.67
	Nod-1	0.20	0.02	1.36	0.52**	0.23	0.71
	Sec.	0.15	0.06	0.15	0.12**	0.01	0.05
	Ter.	0.01	0.01	0.01	0.01	0.03	0.01
Specific root length (mg DW^{-1})		31.7	29.7	25.8	29.1	4.37	13.5
Root shoot ratio		0.58	0.26	0.56	0.47**	0.05	0.15
Water (%)	Root	93.6	94.4	94.3	94.1	0.23	0.71
	Shoot	81.3	88.5	86.1	85.3**	0.35	1.06
Leaf area (cm^2)		41.2	27.7	10.20	57.0**	4.50	13.9

S.bran.: seminal branches, Nod-1, -2: nodal roots, Sem.: seminal.
** Significant at 1% level ($P < 0.01$).
* Significant at 5% level ($P < 0.05$).

Table 3. Rates of root respiration, transpiration, total nitrogen content in root and shoot, and nitrogen uptake activity for 3 legumes and 3 cereals

	Pigeonpea	Chickpea	Groundnut	Sorghum	Pearl millet	Maize
Root respiration rate (μmole O_2 g root FW^{-1})	17.1	10.3	16.3	14.1	16.3	9.10
Transpiration rate (cm^3 m^{-2} h^{-1})	223	340	155	99.4	97.1	84.2
Root-N (% on DW)	1.7	1.5	1.8	0.57	0.87	0.70
Shoot-N (% on DW)	1.8	2.7	1.9	0.87	0.97	0.67
N uptake activity (mgN g root FW^{-1})	4.83	2.48	4.14	2.03	2.39	1.05

FW: fresh weight. DW: dry weight.

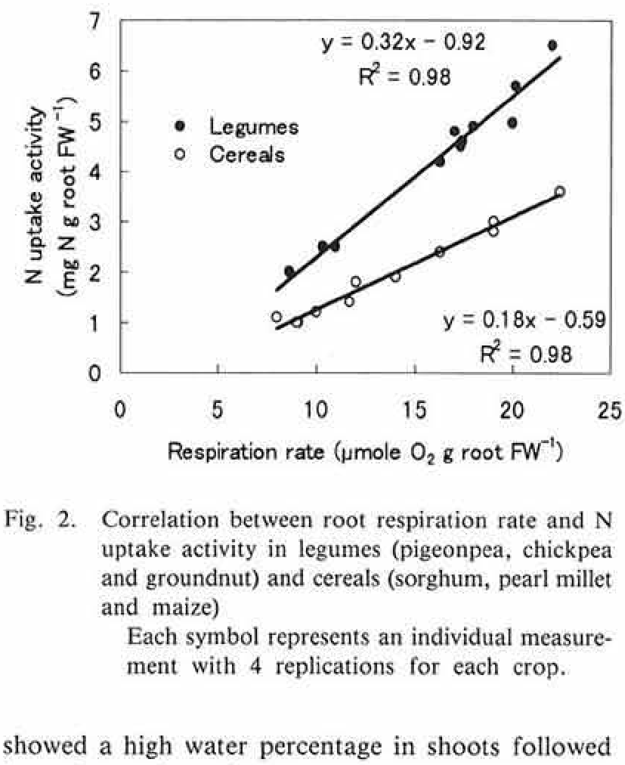

Fig. 2. Correlation between root respiration rate and N uptake activity in legumes (pigeonpea, chickpea and groundnut) and cereals (sorghum, pearl millet and maize)
Each symbol represents an individual measurement with 4 replications for each crop.

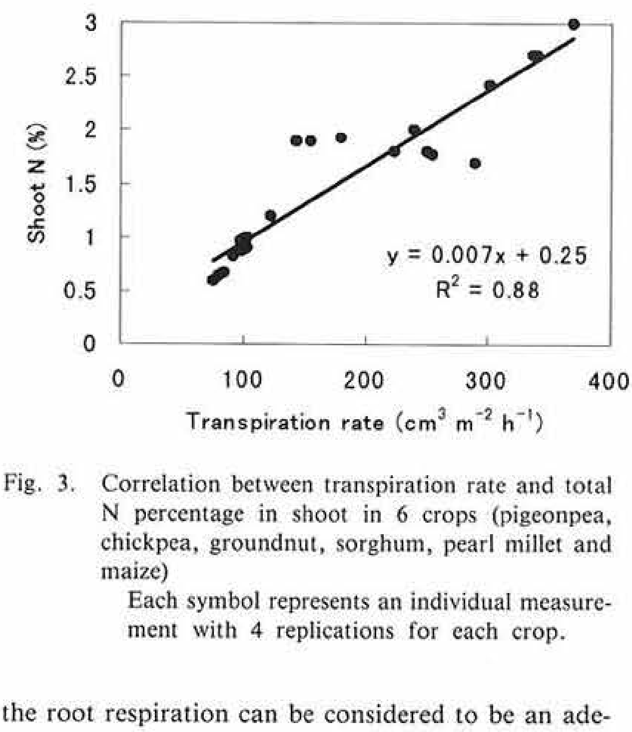

Fig. 3. Correlation between transpiration rate and total N percentage in shoot in 6 crops (pigeonpea, chickpea, groundnut, sorghum, pearl millet and maize)
Each symbol represents an individual measurement with 4 replications for each crop.

showed a high water percentage in shoots followed by maize and sorghum.

Root respiration was significantly low in chickpea and maize among the respective crop groups (Table 3). Total N content was significantly higher in legumes than in cereals in both parts of the plant. The N uptake activity was high in pigeonpea and groundnut among the legumes while high in sorghum and millet among the cereals. Transpiration rate was significantly high in legumes compared to cereals.

There was a significantly high correlation between the root respiration rate and N uptake activity among the crop groups (Fig. 2). Since N uptake should be one of the major functional activities of the root, the root respiration can be considered to be an adequate index to estimate the capacity of root function. The slope of the regression line indicates the N uptake efficiency in terms of requirement of respiratory energy, which is 1.8 times higher in legumes than in cereals.

A significant correlation was also found between the transpiration rate and the shoot-N percentage (Fig. 3). Since the plants were provided with nitrate-N as a sole nitrogen source in this experiment, the major proportion of absorbed N is considered to be translocated to the shoot along with the transpiration stream. The rate of transpiration may be partly responsible for the N deposition in leaves.

Discussion

The remarkable morphological and anatomical differences in the component roots of the complex root system are related to their activity and functional differentiation[16]. Mia et al.[11] reported the presence of large intra-specific and varietal differences in a number of root traits. They found that chickpea produces thick and long laterals compared to other legumes. Our study revealed that the branching frequency of laterals was lower in chickpea than in groundnut and pigeonpea. Since branching leads to a higher level of architectural structure in the root system[6], the lower branching frequency may be a disadvantage for the exploitation of water and nutrient resources spread over in soil. Bray[4] emphasized the significance of the root system structure in the uptake of soil resources with a difference in the mobility in the solid-liquid phases within soils[5]. In this concept, sorption zones were divided into root sorption zone (rooting zone) and root surface sorption zone (total surface area of root), where the former has a functional significance for the uptake of water and mobile nutrients, while the latter is the major factor for the uptake of less mobile nutrients.

The finding that pigeonpea and groundnut were more efficient in the uptake of nitrogen compared to chickpea[13], could be related to the high proliferation of the thin lower order roots. Similarly in cereals, sorghum and maize could exploit a larger amount of resources compared to pearl millet due to the production of a larger root system. However thin roots may be more efficient than thick roots in nutrient absorption, especially at lower concentrations[1]. Pigeonpea and groundnut among the legumes and sorghum and millet among the cereals had a relative advantage in the acquisition of low available nutrients due to the large proliferation of thin higher order lateral roots.

Rao et al.[13] reported that simulated uptake of nitrogen using the thin roots was close to the observed uptake. In the present study, the relative root activity for the total nitrogen status in the plants reflected the same condition by revealing the superiority of pigeonpea, groundnut, sorghum and millet. Root respiration could be used as an index of the root activity which was positively correlated with the N uptake activity (Fig. 2), indicating the importance of the role played by root respiration in the total nitrogen status of the plant[3]. The respiratory efficiency for N uptake can be calculated from the slope of the regression and does not seem to be significantly different among the groups of crops. Using field-grown crops, Ito et al.[7] reported that pigeonpea exhibited an extremely low efficiency of N uptake in terms of respiration requirement. Transpiration could be a suitable index for the shoot nitrogen status based on the significantly positive correlation (Fig. 3), due to the positive correlation with the translocation of nitrogen[13].

Based on the sensitivity analysis using the mechanistic mathematical model for nutrient uptake, Barber and Silberbush[2] reported that Imax (maximal influx) displays a similar degree of influence on nitrate uptake to that of the root growth rate and the root radius. In case of phosphorus and potassium, however, total uptake is mostly determined by the morphological traits of roots and soil nutrient status. These findings emphasize the importance of physiological factors in nitrate acquisition by upland crops from soil. Root system characterization based on both morphological and physiological parameters should be more precisely carried out at species and variety levels for more efficient acquisition of nitrogen from soils by crops.

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(Received for publication, September 18, 1997)