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SOME PHYSICAL PARAMETERS IN RELATION TO WATER EXTRACTION BY ROOTS OF TWO PIGEONPEA GENOTYPES

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Abstract: In modeling water extraction by roots and in whole crop modeling, careful selection of the factors for their parameterization which could differ from genotype to genotype is a prerequisite. Some physical parameters of soil hydraulic resistance, root conductivity, root length density, yield and some yield components in relation to water extraction by roots of two pigeonpea genotypes (ICPL 87 and ICP 1-6) were investigated in the field. Soil hydraulic resistance was found to be negligible in the upper soil layers but concentrated where there was maximum root length density along the profile. Lower soil hydraulic resistance and higher rate permeability was exhibited by ICPL 87 (short duration) than in the medium duration pigeonpea, ICP 1-6. Root permeability was found to be closely associated with the position of the root front, soil moisture status and age of the plant. The most effective part of the root front for water extraction was found to be detemined by the degree of aeration at that zone. Higher plant density, lower soil hydraulic conductivity, and higher root conductivity resulted in higher water extraction by ICPL 87 than for ICP 1-6 when moisture was adequate. Higher water extraction rate by root of ICP 1-6 than ICPL 87 under drought or water stress condition was associated with higher specific leaf area of ICP 1-6 than the latter. The results also indicated an inverse relation between total profile water extraction rate and the total root length density. The extraction rate was directly linked with precipitation. The genotype, ICPL 87 produced higher grain yield than ICP 1-6.

Keywords: physical parameters, pigeonpea

INTRODUCTION

The inherent potentials of the individual genotypes could be enhanced and realised through the understanding and manipulation of the relevant internal and external factors. The most central is the water relations. Understanding the processes that lead to efficient or inefficient water extraction by pigeonpea roots will lead to a better understanding and control of its water requirements, its cultural and mostly agronomic practices and its role in mixed farming and mixed cropping systems.

Water controls the processes of cell division, photosynthesis and transpiration that play an obvious central role in crop physiology, crop growth and development. In the past, many attempts have been made to relate the structure and expansion of leaf canopies to the interception of radiation and related exchanges of water vapour and carbon dioxide in trying to understand the processes involed in water uptake or water requirement of arable crops. Those attempts only yielded more generalised recommendations despite the specific differences encountered in individual crops, species and genotypes. More so, the corresponding processes in the soil parts of a whole plants, and the individul differences in species, cultivars and genotypes have suffered benign neglect. Specifically, the most ignored ones are the soil hydraulic resistance and permeability, roots length density and weight, soil profile water content as they relate to soil water extraction by roots. Some reports support that the dominant resistance to water flow in the soil root system resides in the soil surrounding the roots [3,9,10] while others attributed it to the resistance in the root system [9]. In his recent study, Ogunremi [8], presented a compromise report that shows the two forms of resistances to be important depending on the prevailing circumstances. This area requires further study. Even though many arable crops had been used for test crops in water extraction studies, the processes and the genotypic differences in pigeonpea have been grossly unattended to. The neglected could be traced to the general neglect suffered by pigeonpea among the arable crops, the notoriously time-consuming operation and rare reliable sets of systematic measurements that would relate the physical measurements to the water extraction rates of different pigeonpea genotypes in a sequential and comprehensive manner.

This study therefore attempts to measure some water related soil and plant physical parameters and relate them to water extraction rates by roots of two pigeonpea genotypes.

MATERIALS AND METHODS

Description of field site and experimental plots

The experiment was carried out on the Patancheru (Udic Rhodustalf) series at the International Crops Research Institute for the semi-Arid Tropics, Patancheru India (18°N 78°E, 542 m asl.). The surface 0-20 cm layer of this soil has a sandy loam textue and merges with a more variable sandy clay to clay layer (20-80 cm) which is underlined by a horizon that has gravels in a sandy matrix up to 140 cm depth. This gravelly layer has a calcareous concretions in sandy clay loam below it (Table 1). The different layers have high internal drainage at saturation.

Two plots each measuring 10 m x 10 m were established on the 27th of June, 1991 at the 2 sides of a profile pit. A short duration, ICPL 87 (125 days growing period), and a medium duration, ICP 1-6 (170 days growing period) pigeonpea genotypes were sown on the plots. The short duration (SDP) cultivar was sown at 0.3 m x 1 m x 1 plant while the medium duration (MDP) cultivar was planted at 0.6 m x 0.2 m x 1 plant spacing.

Physical measurements

Detailed measurement of the parameters that would permit calculations of water extraction rate from the models in Table 2 were made at: (1) the vegetative stage of the SDP (about 46 DAS), (2) flowering stage of SDP (about 66 DAS), (3) podding stage of SDP and active vegetative/budding stage of MDP (about 80 DAS), (4) second flush flowering of SDP and flowering of MDP (101 DAS), and (5) SDP and MDP at maturity and podding respectively, (122 DAS). The measured parameters are discussed below.

Table 1. The physical and hydrological properties of the soil profile

Depth (cm)	Bulk density (g/cm^3)	Saturated water content (cm^{3}cm^{-3})	Air dry moisture content (cm^{3}cm^{-3})	Saturated hydraulic conductivity (cm/day)	Gravel (%)	Soil texture
0-22.5	1.68	0.323	0.016	30.95	5.65	Sandy loam
22.5-37.5	1.65	0.374	0.089	29.18	4.90	Sandy clay
37.5-52.5	1.56	0.392	0.101	40.61	6.40	Clay
52.5-75	1.54	0.416	0.112	113.98	7.21	Clay
75-105	1.63	0.364	0.099	21.08	10.09	Clay
105-135	1.15	0.360	0.079	23.07	37.33	Clay loam
135-165	1.13	0.406	0.075	31.06	35.88	Sandy clay loam
165-195	1.35	0.408	0.085	22.94	22.97	Sandy clay loam

Table 2. The profile of root length density (cm^{-2}) of two pigeonpea genotypes and unsaturated hydraulic conductivity at 104 days after sowing

Soil layer (cm)	Unsaturated hydraulic conductivity at 104 DAS (cm/day) (SDP)	Root length density (SDP)	Unsaturated hydraulic conductivity at 104 DAS (cm/day) (MDP)	Root length density (MDP)
0-22.5	$1.25x10^{-10}$	0.32762	$9.95x10^{-1}$	0.26189
22.5-37.5	$1.88x10^{-7}$	0.15542	$9.98x10^{-8}$	0.20324
-52.5	$5.92x10^{-11}$	0.28442	$1.55x10^{-11}$	0.24731
-75.0	$7.95x10^{-13}$	0.32682	$2.29x10^{-13}$	0.32677
-105.0	$5.59x10^{-10}$	0.15969	$2.66x10^{-10}$	0.04566
-135.0	$2.59x10^{-5}$	0.08349	$1.84x10^{-5}$	0.04749
-150.0	$4.03x10^{-5}$	0.04937	$2.05x10^{-6}$	0.05829

Characterization of the site

a) Soil moisture characteristics, saturated hydraulic conductivity and particle size

Three soil cores, 300 cm^3 each and bulk soil samples were collected from a profile pit (2.0 m x 2.0 m) excavated mid-way between the two experiemental plots. The sampling depths of the cores and bulk soil were 0-22.5, 22.5-37.5, 37.5-52.5 52.5-75, 75-105, 105-135, 135-165 and 165-195 cm. Soil moisture characteristics were determined on the 3 soil cores at between 0 to 15 bar pressure using pressure plate equipment. The soil were also used to determine the saturated water content and the bulk density of each depth. Three additional monolith samples of cross-sectional are 0.38 m^2 and height 0.15 m were carved from each depth for the determination of saturated hydraulic conductivity described by Bonsu and Laryea [1].

The bulk samples from each depth were used for particle size analysis.

b) Daily soil water content and suction

Soil water suction changes in the cropped area were calculated from daily reading of tensiometcrs installed at 0.15, 0.30, 0.45, 0.60, 0.90, 1.20 and 1.50 m depths. In addition, water content measurement were made at the same depth with a neutron moisture meter. Two sets of tensiometers were installed in the rows and at mid-points between the rows of pigeonpeas at the depths specified above. Also, four sets, of access tubes were installed in similar locations in each pigeonpea plot to measure the volumetric water content changes during crop growth.

c) Unsaturated hydraulic conductivity

Four bare microplots located between the 2 cropped plots were used for *in situ* determination of unsaturated hydraulic conductivity. In each microplot, an access tube installed for neutron moisture measurement was surrounded at a distance of 0.30 m radius by tensiometers whose porous cups were located at 0.15 m depth increment down to 0.60 m depth and thereafter at depth increment of 0.30 m down to 1.80 m. The microplots were mulched (dry grass) and ponded continously for 7 days when the tensiometer readings indicated that the soil profile was saturated to 1.80 m depth. The microplots were then covered with tarpaulin sheets with a white surface to reflect radiation.

*Neutron probe measurements and the ten-*siometric readings continued for 50 days after drainage to allow for a wide range for unsaturated hydraulic conductivity. Unsaturated hydraulic conductivity was calculated according to the metod of Hillel *et al.* [5].

Plant parameters measurement

a) Root length density

The SD and MD pigeonpeas were sampled

for root growth and root development during the week commencing 46, 66, 80, 101, and 122 DAS. In order to obtain representative samples of root, an area (A) associated with lm row length and another adjoining area (B) of similar dimension were demarcated in each pigeonpea plot. The plants in A were cut at the root/stem junction.

The plants in B were discarded and the soil removed to create a working space for a systematic and progressive removal of successive soil layer of A. The big roots in each soil layer were carefully picked manually. The soil was weighed and about 10 % by weight of the thoroughly mixed soil, replicated thrice from each layer was taken and soaked overnight to facilitate the recovery of the very fine roots using number 36 mesh sieves. The big and fine roots were washed separately, the dead roots and debris were then removed mannually.

Root length were measured using Comair root length scanner (Commonwealth Aircraft Corporation Limited, Australia). The total root length and the root length density for each layer was then estimated.

b) Daily average plant water potentials

Daily average plant water potential during these five periods were determined on 6 to 8 plants per plot using the pressure chamber method [2].

The plant stems close to the ground as possible were used for the determination of the plant water potential, so that the values could be assumed to be approximated to either the crown or the root water potential.

Estimation of water extraction by roots

Water extraction rate is the rate of change of water content and the net capillary flux between the bottom and top of that layer. Thus, upon integration and rearrangement, the water extraction rate (cm/day) is:

$$M - O_{vf} = -\int_{z_1}^{z_2} (\partial\theta/\partial t)dz + K_{(\theta)}(\partial H/\partial z)/z_2 - K_{(\theta)}(\partial H/\partial z)/z_1 \qquad (1)$$

when vertical flux is considered and

$$M - O_{ovf} = \int_{z_1}^{z_2} (\partial\theta)/H)dz \qquad (2)$$

for no vertical flux conditions, where θ - volumetric water content (cm^3/cm^3). t - time in days, H - total hydraulic head (cm), K - soil hydraulic conductivity (cm/day) and z - soil depth (cm). Mathematical integrations were carried out using PCSMP on IM PC's using field measured parameters.

Soil hydraulic resistance

Soil hydraulic resistance Rs was estimated from the relations [6]:

$$Rs = 1/\mathrm{B}\, K\, Lp \qquad (3)$$

where B is a constant taken as 1 here; Lp - partial root length density defined as the ratio of the product of root length in layer and root profile depth to the volume of soil in the rooting profile zone. Both K and Lp were from field measured data. The second method used for the estimation of Rs is from taken from Rowse *et al* [9]:

$$Rs = [(ln(r_s^2/r_r^2)]/4\pi\bar{K} \qquad (4)$$

where r_s - half the mean distance between roots, $r_s = (1/\pi Li)^{0.5}$; Li - root length density; r_r - root radius and $\bar{K} = (Kr\, Ks)^{0.5}$ where Ks and Kr are the hydraulic conductivity in the bulk soil and at the root surface, respectively. The root radius was estimated by determining the volume of roots using water displacement method. Assuming that the roots were cylindrical, an average radius (cm) was estimated from:

$$r_r = [(TRV_{(i)})/\pi\, TRL_{(i)})]^{0.5} \qquad (5)$$

where $TRV_{(i)}$ - total root volume in the ith layer (cm^3) and $TRL_{(i)}$ is the total root length in the ith layer (cm).

Root permeability (cm/day)

The root permeability (ρ) was estimated according to Herkelrath *et al.* [4] from:

$$\rho = (-\partial\theta/\partial t)\,(\theta s/\theta)\,(1/Hr_s - Hp)\,(1/Li)^{\cdot} \qquad (6)$$

using multiple data set and average the parameter values for a day wtere θ and θs - bulk soil water content and saturated soil water content. Hr_s - water potential at the root surface (cm) approximated by field measured soil matric potential between plant stands within the row (tensiometric) and *Hp* - average water potential of plant stems close to the ground as possible (pressure chamber) *Li* - root length density (cm of root/cc of soil).

Leaf area and specific leaf area

Leaf area was determined using *Li* - 3100 area meter and the specific leaf area (SLA) calculated as $\frac{\text{Area of leaf (cm}^2\text{)}}{\text{Dry weight of leaf (Kg)}}$.

RESULTS AND DISCUSSION

Soil hydraulic resistance

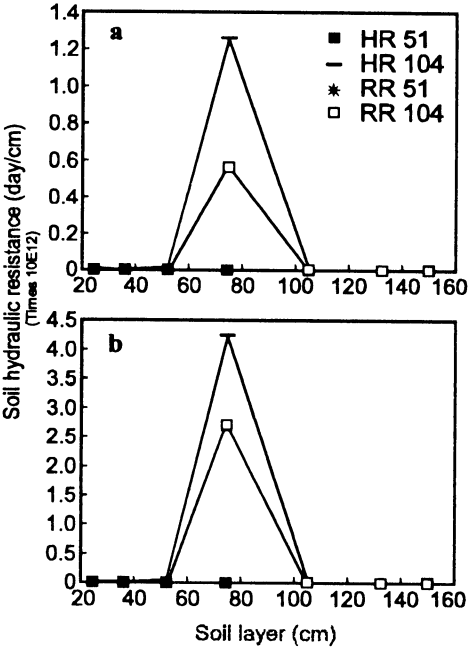

Fig. 1. Comparison between Hillel *et al.* [6] (HR) and Rowse *et al.* [9] (RR) soil hydraulic resistances for short SDP (a) and medium MDP (b) duration pigeonpea at 51 and 104 days after sowing.

Figure 1 shows soil hydraulic resistance as a function of soil layers using Hillel *et al.* [6] (HR) and Rowse *et al.* [9] (RR) methods at 51 and 104 days after sowing (DAS). Figure 1 do not show differences in soil hydraulic resistances at 51 DAS in the different layers. At 104 DAS and at 75 cm layer, the highest values obtained, irrespective of the genotype is linked up with where root length density peaked and the least unsaturated hydraulic conductivity along the profile (Fig. 1 and Table 2). There is an indication also that soil hydraulic resistance to water flow in plants is negligible in the upper soil horizons irrespective of the growth stage. Higher resistances are offered by MDP than for SDP. The higher resistance offered by MDP than the SDP has no relationship with the root length density in the individual soil compartment but it might have with the total profile root length density; for the SDP with lower soil resistance (Fig. 1) has higher total profile root length density (Fig. 2). The total

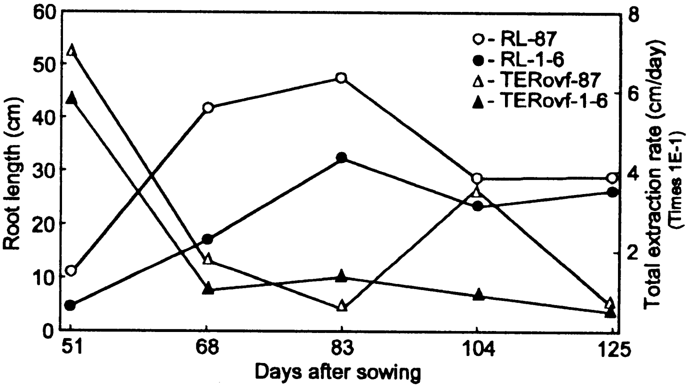

Fig. 2. Relationship between total root length (RL) and extraction rate (TER) for two pigeonpea genotypes as a function of days after sowing. 87 and 1-6 = SDP and MDP, TER_{ovf} - total extraction rate for no vertical flux.

sum of the soil hydraulic resistances could be said to be expressed at the layer of highest concentration of root length somewhere along the profile. A direct comparison of the resistances presented from HR and RR showed that the parameter B in HR taking RR as standard could be approximated to 2 and not 1 as assumed. This could then be used to improve upon the Hillel *et al.* [6] water extraction model.

Root conductivity

Figure 3 presents root conductivity per unit length estimated as a function of soil layer in SDP and MDP at 51, 68, 83, 104 and 125 DAS, respectively. The data show the roots of SDP to be more permeable to water than the MDP. This could be a worthy parameter to breeders in their selection processes.

The depths at which maximum root permeability ocurred are associated with the position of the root front (Fig. 3), availability of water (Table 3) and age of the plant (Fig. 3). The root permeability of the two genotypes at 83 DAS was almost nil in the different layers of the profile (except 150 cm layer). This could be attributed to lack of precipitation (Fig. 3 and Table 3). Root permeability is not just a function of the soil profile water content but also of age of the plant as evidenced in the genotypes, because at 104 DAS when precipitation was much, root permeability was not correspondingly high compared with the earlier periods. Root permeability peaked with age to 68 DAS after which it declined. The decline with age after 68 DAS could be due to secondary thickening of the roots (Tables 5 and 6). The higher root permeability in the SDP compared to the MDP also explained the lower soil hydraulic resistance (as explained in the previous section) in the former than the latter.

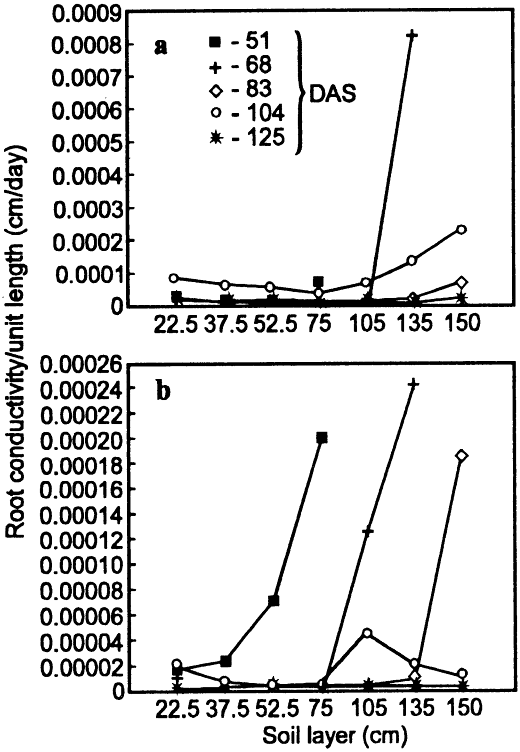

Fig. 3. Root conductivity per unit length estimated from Herkelrath *et al.* [4] model as function of soil layer in short SDP (a) and medium MDP (b) duration pigeonpea at 51, 68, 83, 104 and 125 days after sowing.

Soil water extraction by roots and some associated physical and hydrological parameters

Figure 4 presents data on the water extraction rate by roots as a function of soil layers in two pigeonpea genotypes. The two forms of the traditional water extraction Eqs (1) and (2) predicated the same rate of water extraction by roots up to 105cm layer and irrespective of the genotype (Fig. 4). The influence of vertical water flux could be said to be negligible in the upper (105 cm) layers wich are drier than the layers below.

The higher rates at 104 than at 125 DAS could be attributed to higher root coductivity per unit length in the former than in the latter (Figs 3 and 4). This was brought about by the higher precipitation during the 104 DAS period than 125 DAS (Table 3). Another possible explanation is that both genotypes were at one flowering stage or the other at 104 DAS and where as, MDP and SDP were at podding and maturity stages of growth, respectively at 125 DAS. Not much water extraction is required at these latter stages of growth. At 104 DAS, the

Table 3. Total rainfall (mm) and number of raindays during five days to and five days from each sampling date

Sampling date	Days after sowing	Total rainfall	No. of raining days
17/8/91	51	96.5	7
3/9/91	68	1.0	1
18/9/91	83	0.0	0
9/10/91	104	29.8	2
30/10/91	125	5.0	1

Table 4. Root weight density (mg/cm^3) of ICPL 87 (SDP) within the different soil compartments and at various growth stages

Soil compartment (cm)	Root weight density			
	Days after sowing			
	46	66	80	122
0-22.5	0.12569	0.1212	0.3175	0.4877
22.5-37.5	0.03894	0.0465	0.0961	0.0645
37.5-52.5	0.01818	0.0410	0.0915	0.0655
52.5-75	0.00247	0.0181	0.0725	0.0783
75-105	-	0.0027	0.0509	0.0572
105-135	-	0.0008	0.0125	0.0420
135-165	-	-	0.0054	0.0231
165-195	-	-	-	0.0081

Table 5. Root weight density (mg/cm^3) of ICP 1-6 (MDP) in the different soil compartments and at various growth stages

Soil compartment (cm)	Root weight density			
	Days after sowing			
	46	66	80	122
0-22.5	0.0580	0.3935	0.4539	0.3627
22.5-37.5	0.0082	0.0994	0.0684	0.0611
37.5-52.5	0.0033	0.0596	0.0610	0.0468
52.5-75	0.0008	0.0468	0.0559	0.0575
75-105	-	0.0229	0.0129	0.0474
105-135	-	0.0167	0.0109	0.0135
135-165	-	0.0022	0.0071	0.0194
165-195	-	-	-	0.0179

Table 6. Yield and yield components of two pigeopea genotypes

Parameters	Genotypes ICPL 87 (SDP)	ICP 1-6 (MDP)
Average no. of plants/ha	330,952	93,750
Stover yield (t/ha)	2.55	4.36
Fallen leaves yield (t/ha)	2.24	3.47
Total pod yield (t/ha)	2.30	2.04
1000 grain weight (g)	97.55	99.20
Grain yield (t/ha)	1.67	0.93
Shelling (%)	72.61	45.32
Specific leaf area (cm^2/g) 104 DAS	114.64	197.00
Specific leaf area (cm^2/g) 125 DAS	160.34	225.33

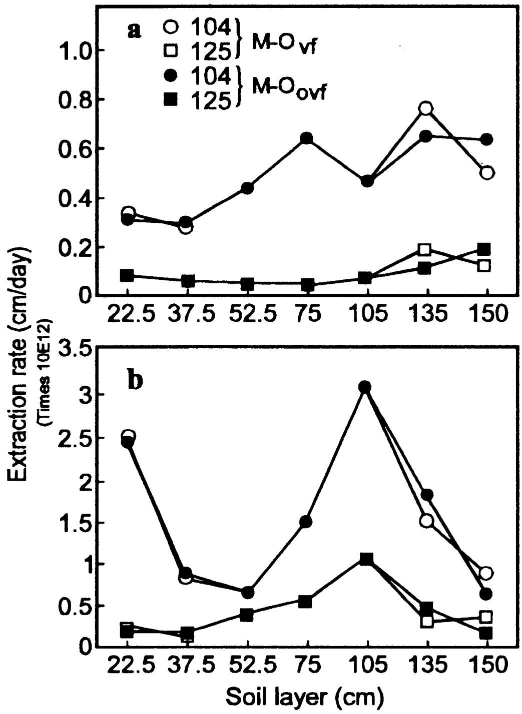

Fig. 4. Comparison of vertical flux root extraction rate with (M-O_{vf}) and without (M-O_{ovf}) as a function of soil layer in short (a) and medium (b) duration at 104 and 125 days after sowing.

extraction pattern followed the trend of root length density along the profile except at the lower end of the rooting depth (Fig. 4 and Table 2). The peculiarity at 135 cm and 105 cm layer for SDP and MDP, respectively indicated that aeration was very poor beyond these layers despite that the lower layers contained the root fronts which should be the water absorption zone. The layers expressed by 135 and 105 cm depth then become the effective water extraction root front zone (EWERZ). This, expressed at lower depths in SDP than MDP is an indication of the faster root growth and proliferation of the former which has to complete its life cycle within a shorter time. The systematic way at which MDP grows and extract water from the soil makes it to exhibit and maintain semi-perrenial life cycle.

Water uptake is higher in SDP than MDP at all depths and irrespective of the growth stages except at 83 DAS (Figs 2 and 4). The higher rate by SDP would be attributed to its higher plant density (Table 6), faster growth rate thereby placing it ahead of MDP along the life-cycle line. Lower soil hydraulic resistance values (Fig. 1), higher root condutivity (Fig. 3) and probably higher total root length density in SDP than MDP (Fig. 2). However, the extraction rate (Fig. 2) indicated an important phenomenon when precipitation was nil (Table 3). The unusual higher total extraction rate enjoyed by MDP indicated its capacity and capability to survive and prolong its life cycle more than SDP under water stress or drought.

Another potential index of drought resistance in the two genotypes could be the specific leaf area (SLR) which is higher in MDP than SDP (Table 6). It then implies that the higher the SLA the better the plant adapts to water stress and droughty conditions. Other data relating to yield and yield components (Table 6) indicated higher grain and pod yields, and higher shelling percentage in SDP than MDP. It then implies that given the same precipitation and other crop production environments, SDP would exhibit higher water use efficiency than MDP. It then mean the higher the SLA, the better it is for the plant to adapt to water stress or droughty condition, the thinner the leaf and lesser the water use efficiency. The pieces of information could as well be relevant when breeders carry out selection work in their breeding processes.

Figure 2 and Table 3 indicate that within a genotype, the total profile water extraction rate at the different growth stages is inversely proportional to the total root length density and directly associated with the pattern of precipitation.

SUMMARY AND CONCLUSION

The influence of vertical water flux could be neglected in the top soil layer when treating the standard traditional water flow equation. The rate of soil water extraction by roots was found to be a function of pigeonpea genotype, soil moisture regime, stage of growth, root conductivity and soil hydraulic resistance which invariably influenced the type of yield obtained.

In modelling total crop growth and productivity, there was an indication that specific leaf area, total root length density, root conductivity, soil hyraulic resistance, yield and some yield components could be used to parametrize such models.

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