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RESEARCH PAPER

Genetic variability for root dynamics in sorghum [*Sorghum bicolor* (L.) Moench] for drought tolerance

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Abstract: Plant root related traits offer the potential for increasing soil water accessibility, particularly in water-limited conditions. In the present study, 52 genotypes consisting of 41 improved lines (33 RILs and eight NILs developed for drought adaptation) and 11 released varieties (landraces and elite cultivars) were evaluated for 10 root-related traits at the reproductive stage in PVC pipes in the greenhouse with two replications under well-watered (WW) and water stress (WS) conditions. Moisture stress reduced root volume, root fresh weight and shoot length whereas it increased root length, root dry weight, root:shoot length ratio, number of roots, total root length, root length density and root weight density. Genetic variability and correlation analysis revealed that root length, root volume, root fresh weight, total root length and root:shoot length ratio could be used as a selection criterion for drought tolerance at the reproductive stage. Based on the performance of the genotypes, six genotypes RL 167, RL 34, RV 48, BJV 362, Phule Suchitra and SPV 86 were identified as best performing (root related traits) lines only under water stress condition and STG 44 was identified for both water stress and well-watered conditions.

Key words: Drought tolerance, Genetic variability, Root traits, Sorghum, Water stress

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is one of the staple cereal crops in the world because of its adaptation to a wide range of ecological conditions, suitability for low input cultivation and diverse uses. It is the fifth most important cereal crop globally after wheat, maize, rice and barley in terms of production and utilization (Anon., 2020). It ranks third in the major food grain crops of India. Apart from being a major source of carbohydrates for humans, it also serves as a source of cattle feed and has a high potential to compete with crops like maize under better moisture and inputs conditions. The greatest merit of sorghum is that it can withstand drought better than maize in marginal lands and it does well even in low rainfall areas. It makes comparatively quick growth and gives not only good grain yield but also large quantities of fodder.

In India, sorghum is cultivated over an area of 4.09 million ha with an annual production of 3.47 million tonnes and productivity of 849.1 kg ha^{-1} (FAO, 2020). Three major sorghum producing states in India are Maharashtra, Karnataka and Andhra Pradesh. In India, the area under the *kharif* crop is 1.90 m ha with a production of 1.80 m tonnes with an average yield of 947 kg ha^{-1}. During the *rabi* (post-rainy) season, it covered an area of 3.10 m ha with a production of 2.40 m tonnes and an average yield of 774 kg ha^{-1} (Anonymous, 2020). Though India has the largest area under the *rabi* sorghum, its average productivity is less than the *kharif* sorghum because *rabi* sorghum is typically dependent on the available soil moisture, which gets depleted over a period with the progress in crop maturity.

Terminal drought is the major constraint in the production of the *rabi* sorghum, which affects morphological and physiological activities in plants resulting in an extensive reduction in crop yield (Hallajian, 2016). Drought resistance is accompanied by the interaction of different morphological (earliness, reduced leaf area, leaf rolling, wax content, efficient rooting system, awn, stability in yield and reduced tillering), physiological (reduced transpiration, high water use efficiency, stomata closure and osmotic adjustment) and biochemical (accumulation of proline, polyamine, trehalose) traits. Several shoot related physiological traits have been identified and used as selection criteria (Badigannavar *et al*., 2017) in the identification of drought tolerant genotypes in sorghum. Root related traits also play an essential role in capturing soil water, nutrient uptake in plant growth and adaptation.

Several characterization studies for stay-green and yield traits have been reported on germplasms, local cultivars, landraces and improved sorghum genotypes (Kapanigowda *et al*., 2013, Girish *et al*., 2016 and Badigannavar *et al*., 2017). However, a few studies have been conducted on sorghum root traits due to the difficulty in measuring root-related traits underground for a large number of plants under field conditions. As a result, the majority of root studies have been performed in acrylic root boxes (Tsuji *et al*., 2005), rhizotrons (Rajkumar *et al*., 2013), pots (Liang *et al*., 2016) and PVC pipes (Toure *et al*., 2018). The effectiveness of a deep root system in maintaining yield under drought conditions has been confirmed by simulation studies across several years and environments in the USA (Sinclair and Muchow, 2001). Miller (1916) was the first to carry out an extensive study of the sorghum root system under field conditions and recorded sorghum root growth up to a depth of 180 cm and to lateral distance of about 90 cm. Drought-tolerant sorghum lines had roots that were at least 40 cm deeper than drought-sensitive lines, and stay-green lines had deeper roots under drought conditions (Vadez *et al*., 2005). Tsuji *et al*. (2005) studied the rooting pattern in two sorghum cultivars (Gadambalia, drought-tolerant and Tabat, drought susceptible) in acrylic root boxes under two moisture regimes (irrigation withheld from 55 days after sowing until harvest at

145 days and normal irrigation throughout the experiment). The drought-tolerant genotype exhibited higher root length and recorded more water extraction from the deeper soil than the susceptible genotype. They reported that response of root traits like branching, lateral root growth, nodal root from higher internodes could be associated with drought tolerance. Ali *et al*. (2011) studied 17 sorghum landraces at the seedling stage under limited moisture by watering the plants with 50 % of the water used under normal condition. By evaluating six traits, they found root-related traits (fresh root and shoot weight, dried shoot weight and root:shoot length ratio) and higher grain yield as essential selection factors for drought tolerance. Techale *et al*. (2014) evaluated thirteen accessions under water stress by with holding irrigation from panicle differentiation to flowering (pre-flowering drought stress) and under normal irrigation throughout the growing season, and identified two drought-tolerant genotypes (DA119 and TS217) based on the shoot and root related traits but did not consider yield data. Toure *et al*. (2018) evaluated 100 sorghum cultivars using PVC tubes and irrigation was given every two days until harvest. They observed variability among the genotypes for root length and root density/volume at the maturity stage and found a positive association between root length and root density. To enhance post-flowering drought tolerance of *rabi* sorghum, RILs and NILs were developed with E36-1 as a source of stay green at UAS, Dharwad, India. Near isogenic lines (NILs) carrying different combination of stay-green and water use efficiency QTLs in M35-1, SPV 86 and SPV 570 backgrounds (recurrent parents) using E36-1 as donor. Two recombinant inbred lines (RILs) populations segregating for root length (E36-1 × SPV 570) and root volume (E36-1 × BP) were developed (Rajkumar, 2012). Rajkumar and Fakrudin (2018) evaluated recombinant inbred populations (E36-1 x Basavanapada) and (E36-1 x SPV70) for morpho- physiological, root related and yield component traits. Seven root related traits were recorded at maturity stage under limited moisture condition (irrigation given until flowering) in an above-ground rhizotron and identified five root related traits (root length, root volume, root fresh weight, root dry weight and number of roots) as a selection criterion for drought tolerance. In the present study, selected advanced breeding lines (RILs and NILs and improved lines for drought adaptation) and released varieties (landraces and elite cultivars) were evaluated for root-related traits at the reproductive stage to study the differential response of the genotypes under two water regimes and to identify the genotypes with superior root traits for drought stress tolerance.

Material and methods

A total of 52 sorghum genotypes consisting of eight RILs each from two populations [E36-1× SPV 570, (F12) and E36-1 × BP, (F13)] and eight NILs (SPV86 × E36-1, M35-1 × E36-1, SPV570 × E36-1) selected based on the performance in the previous generations (high, intermediate and low yielding lines), 17 improved lines for drought adaptation and 11 released varieties (landraces and elite cultivars) were evaluated in the current study (Table 1). These lines had been developed to enhance drought tolerance. Single plants of 52 genotypes were evaluated in PVC pipes (20 cm diameter and 150 cm in length) in the greenhouse, Department of Biotechnology, UAS, Dharwad, with two replications during 2019 under two moisture regimes *viz*., water stress (WS) and well-watered (WW) conditions (Fig. 1). Each PVC pipe was filled with thoroughly mixed soil and the bottom of each pipe was covered with a polythene cover as described by Shashidar *et al*. (2012). Appropriate soil moisture was maintained to ensure seed germination.

Three seeds were sown directly in each pipe and only one healthy seedling was retained at 20 days after sowing. Till 30 days after sowing two sets of experiments were treated similarly. Thirty days after sowing, in water stress (WS) treatment water was withheld completely and in the second set (well-watered (WW) treatment) water was given every two days until 55 days. Observations were recorded (at flower bud initiation stage, 55 DAS) for ten root related traits such as root length (RL), root volume (RV), root fresh weight (RFW), root dry weight (RDW), shoot length (SL), root to shoot length ratio (R:S), number of roots (NR), total root length (TRL), root length density (RLD) and root weight density (RWD) under both conditions (WS and WW). The shoot of each plant was separated by cutting at the base of the stem. To retrieve the intact root system, the soil was removed with a very low speed water stream and root was washed carefully to remove any adhering soil without harming the root system. Root traits were analyzed manually and using WinRhizo Tron MF software, an image analysis system specially designed for root measurement (Regent Instruments Inc., Quebec, Canada). Genetic variability analysis was performed on genotypes using Windostat version 8.1. Correlation analysis among the root traits was done using R software (http://CRAN.R-project.org/packege=Hmisc).

Results and discussion

The statistical analysis showed significant differences among the genotypes for all the traits studied under both the conditions (WW and WS). High GCV and PCV were observed for RV under both conditions indicated that selection for this trait in the genotype would be most effective. Moderate values of GCV and PCV were observed for all the traits except shoot length under WW condition. Under WS condition, R:S showed moderate GCV and PCV while remaining traits exhibited low GCV and PCV (Table 2). This indicated the lower environmental influence on these traits and that acceptable improvement could be obtained through the selection of the above traits. Similarly in the previous study (Rajkumar and Fakrudin, 2018) conducted in two RIL populations (E36-1 × SPV 570 and E36-1 × BP) reported low to moderate GCV and PCV for root:shoot length ratio and root length. In this study high heritability coupled with high genetic advance over mean (GAM) was observed for all the traits studied except shoot length under WW condition. All traits recorded high heritability coupled with moderate GAM under WS condition (Table 2). The high heritability and GAM is a sign of additive gene action and ensures high extended genetic gain from the selection of superior genotypes. RL, RFW, RDW, SL, R:S, TRL, RLD and RWD showed higher heritability under water stress condition compared to well-watered condition. Whereas RV and NR showed higher heritability under well-watered condition

Table 1. List and features of 52 sorghum genotypes selected for this study

Improved lines			Features
RL 142	RL 167	RL 34	High yielding lines over M35-1 from RIL (E36-1 x SPV 570) population
RL 183	RL 21		Intermediate yielding lines over M35-1 from RIL (E36-1 x SPV 570) population
RL 83	RL 146	RL 127	Low yielding lines over M35-1 from RIL (E36-1 x SPV 570) population
RV 146	RV 48	RV 129	High yielding lines over M35-1 from RIL (E36-1 x BP) population
RV 150	RV 114		Intermediate yielding lines over M35-1 from RIL (E36-1 x BP) population
RV 60	RV 193	RV 84	Low yielding lines over M35-1 from RIL (E36-1 x BP) population
STG 44 (RP: SPV570; DP: E36-1)			High yielding lines over M35-1 from stay-green NIL population
STG 25 (RP: SPV570; DP: E36-1)			
STG 21 (RP: SPV86; DP: E36-1)			
STG 5 (RP: SPV570; DP: E36-1)			Intermediate yielding lines over M35-1 from stay-green NIL population
STG 15 (RP: SPV86; DP: E36-1)			
STG 4 (RP: SPV86; DP: E36-1)			Low yielding lines over M35-1 from stay-green NIL population
STG 43 (RP: SPV86; DP: E36-1)			
STG 26 (RP: M35-1; DP: E36-1)			
RSV 1736	RSV 1910	RSV 2121	Improved lines for drought adaptation
RSV 2138	CRS 65	CRS 66	
CRS 67	CRS 68	BJV 125	
BJV 129	BJV 362	BJV 371	
SPV 2544	SPV 2405	SVD 1352	High yielding *rabi* sorghum entry having superior grain yield
SVD 1365			
Released varieties			
B35			Resistant to drought, stay green, dwarf, purple-coloured, awned, semi-open panicle, grains with yellow pericarp and thick mesocarp, short plant height, small panicle, size and low grain number per panicle.
Phule Suchitra			It has non-tan plant pigment, white midrib, medium leaves, semi-compact cylindrical panicle and medium bold pearly white grains. It has medium plant stature and is medium in maturity (120-125 days). It is tolerant to shoot fly, charcoal rot and drought.
SPV 570			This variety has a high yield, good fodder quality, tall and thick stem, pale yellow leaves, semi-compact, oval- shaped panicle straw-colored glumes, creamy and lustrous seed with pink spot with long roots and promising restorer line on Milo cytoplasm.
BJV 44			High grain and fodder yielding variety with good *roti* quality and fodder quality. Bold, round, lustrous, creamy white grains. Tall, dark purple pigmented stem, semi- compact and cylindrical panicle.
Basavanapada (BP)(Landrace)			High number of trichomes, known for good fodder quality, better adaptability, semi-compact elliptic panicle, dark green leaves, thick stem covered with wax, high root volume, a popular variety of *rabi* sorghum in the North Karnataka region.
CSV 29R			High grain and fodder yielding variety, grains with good *roti* quality.
E36-1			Resistance to drought, charcoal rot and susceptible to striga.
SPV 86			High yielding variety, highly susceptible to charcoal rot, moderately tolerant to shoot fly, leaves yellowish-green, medium drooping, more leaf sheath waxiness, semi-compact cylindrical ear, seeds round, bold and creamy, grain texture of endosperm is half vitreous.
Phule Anuradha			Non-tan plant pigment, green colored midrib, narrow leaves, semi-compact oval panicle and medium bold pearly white grains. Short plant stature and is early in maturity (105-110 days), tolerant to shoot fly, charcoal rot and drought. It is recommended for shallow soil in post-rainy season growing areas.
SPV 2217			High grain yielding variety with bold and pearly white round seeds. *Roti* quality is on par with M35-1. Fodder quality is good with stay- green character, non-lodging and charcoal rot tolerant.
M35-1			A long-standing variety, good quality grain, tolerant to drought and moderately susceptible to charcoal rot.

RP: Recurrent parent DP: Donar parent

compared to water stress condition (Table 2). These results suggested that the selection of these traits in the genotypes would be most effective under water stress and well-watered condition.

Highly significant correlations were observed among the root related traits except for shoot length. The shoot length was negatively correlated with R:S under both conditions (Table 3a and 3b). Similarly, the previous studies (Girish *et al*., 2016 and Rajkumar and Fakrudin, 2018) reported strong positive correlation among root traits such as root length, root volume, root dry weight and root fresh weight. The same trend was also observed in wheat (Sanguineti *et al*., 2007) and chickpea (Serraj *et al*., 2004). Shoot length was not associated with any of the root traits, similar observations were reported by

Water stress condition   Well-watered condition

Fig. 1. Root experiment using PVC pipes at 45 days after sowing under water stress and well-watered condition under greenhouse

(McPhee, 2005) in the field pea, and there was no association between shoot length with total root length and weight. Because total root length is determined by length and number of lateral roots there may be an independent genetic basis for the shoot and root traits as reported in wheat (Sanguineti *et al*., 2007). Even though shoot length was not positively correlated with other root traits, a negative correlation was found between shoot length and root: shoot length ratio, this may be due to an increased shoot biomass production. Similarly, in wheat (Narayanan *et al*., 2014) no correlation was found between plant

Table 2. Estimates of genetic parameters for root traits in 52 sorghum genotypes under (a) well-watered and (b) water stress conditions

Traits	Range	Average	GCV (%)	PCV (%)	h^2_b (%)	GA as % of the mean
(a) Well-watered condition						
RL	92.50 - 225.00	175.39	14.65	16.87	75.35	26.23
RV	18.89 - 40.76	31.66	81.26	93.61	86.80	26.32
RFW	55.76 - 96.94	79.72	12.98	14.84	76.51	27.01
RDW	4.94 - 12.01	9.34	14.48	16.75	74.66	25.81
SL	150.00 - 284.50	224.27	8.15	9.68	70.92	14.15
R:S	0.38 - 1.03	0.78	16.21	19.44	69.56	27.86
NR	10.55 - 20.00	15.94	13.27	14.19	87.56	25.58
TRL	206.13 - 536.17	414.31	15.30	19.13	63.99	25.20
RLD	446.16 - 11660.54	897.57	15.30	19.13	63.94	25.20
RWD	10.68 - 24.77	20.10	14.58	16.87	74.63	25.94
(b) Water stress condition						
RL	125.00 - 245.50	201.28	9.02	10.00	80.72	21.61
RV	14.87 - 27.09	22.29	81.45	90.65	89.84	16.63
RFW	34.01 - 88.85	68.91	10.58	11.61	83.07	22.33
RDW	7.24 - 13.10	10.70	9.24	10.64	77.88	22.33
SL	151.50 - 261.00	199.24	8.55	9.98	73.36	19.59
R:S	0.74 - 1.42	1.02	11.17	12.78	77.95	27.34
NR	13.92 - 23.23	19.64	10.10	11.69	74.64	23.36
TRL	400.65 - 683.68	559.69	9.03	10.05	80.72	16.72
RLD	874.03 - 1479.82	1218.28	9.06	10.02	81.86	16.89
RWD	15.67 - 28.36	23.17	9.41	10.66	77.90	17.12

RL: Root length, RV: Root volume, RFW: Root fresh weight, RDW: Root dry weight, SL: Shoot length, R:S : Root to shoot length ratio, NR: Number of roots, TRL: Total root length, RLD: Root length density, RWD: Root weight density, GCV: Genotypic coefficient of variation, PCV: Phenotypic coefficient of variation, h^2_b: Heritability in broad sense, GAM: Genetic advance as per cent of mean height and root traits (root depth and root dry weight) while a negative correlation was observed between shoot length and root: shoot length ratio.

In the WS condition increased values for seven root traits (RL, RDW, R:S, NR, TRL, RLD and RWD) and decreased values for three root traits (RV, RFW and SL) were observed in comparison to WW condition (Table 4a, 4b and Fig. 2, Fig. 3a and 3b). The highest value of RL under WS condition was 245.50 cm whereas in WW condition it was 225 cm. Similarly, for TRL (536.17 m and 683.68 m) and R:S (1.03 and 1.42) higher values were observed under WW and WS condition. Whereas, values for traits like RV (40.76 cm^3 and 27.09 cm^3) and RFW (96.94 g and 88.85 g) were increased under WW condition compared to WS condition (Table 4a, 4b and Fig. 2). The ability of roots to acquire soil water increased exponentially with root length or root length density in sorghum and in other cereal crops such as wheat, barley under drought conditions (Monti and Zatta, 2009 and Carvalho *et al*., 2014). The amount of water extracted from the soil is mostly governed by root traits such as rooting depth, root length density and root angles (Singh *et al*., 2012; Wasson *et al*., 2012 and Comas *et al*., 2013). Under high plant density narrow root angle may increase water accessibility in deep soils whereas under low plant density wide root angle may increase water accessibility (Borrell *et al*., 2014). In the present study, root length, root volume, root fresh weight, root dry weight, root: shoot length ratio, total root length, root length density and root weight density showed variation between WW and WS conditions. The increased root length, total root length, root length density and root weight density was observed under WS condition than compared to WW condition, however, root volume and root fresh weight values were comparatively higher under WW condition than WS condition. A similar trend was observed by Tsuji *et al*. (2005) in two sorghum varieties from Sudan. Drought stress increased root depth/fine roots or decreased root volume/ root diameter, which improved soil water extraction when water was scarce. The drought tolerant genotypes showed longer root depth whereas drought sensitive genotypes exhibited higher horizontal roots (root volume) and less depth at reproductive stage (Tomar *et al*., 2016).

In the present study, the majority (36.53 %) of genotypes had RL values between 171-190 cm and 30.76 % of the genotypes showed RL varied from 191-210 cm (Fig. 4a). The maximum number of genotypes (53.84 %) had RV values between 32-37 cm^3 and 23.07 % of genotypes varied from 27 to31 cm^3 (Fig. 4b). The longest RL was observed in STG 44 (225 cm) followed by CRS 66 (209 cm) and RL 34 (205 cm). The highest RV was observed in STG 44 (40.74 cm^3) followed by CRS 66 (38.86 cm^3) and RL 34 (37.14 cm^3) under WW condition. Under WS condition, the majority of the genotypes (44.23 %) had RL varied from 201- 220 cm followed by 28.84 % of the genotypes showed RL varied from 181-200 cm (Fig. 4c). The maximum number of genotypes (69.23 %) had RV varied from 21-30 cm^3 and 30.76 % of the genotypes had RV of 10-20 cm^3 (Fig. 4d). Highest RL was recorded in RV 48 (245.50 cm) followed by RL

Table 3. Phenotypic correlation coefficient among root traits in 52 sorghum genotypes under (a) well-watered (WW) and (b) water stress (WS) conditions

(a) Well - watered condition

	RL	RV	RFW	RDW	SL	R:S	NR	TRL	RLD	RWD
RL										
RV	0.68**									
RFW	0.99**	0.67**								
RDW	0.99**	0.67**	0.99**							
SL	0.03	- 0.09	0.03	0.04						
R:S	0.84**	0.64**	0.84**	0.83**	- 0.48**					
NR	0.61**	0.59**	0.62**	0.61**	- 0.12	0.60**				
TRL	0.94**	0.60**	0.94**	0.94**	0.00	0.81**	0.54**			
RLD	0.94**	0.60**	0.94**	0.94**	0.00	0.81**	0.55**	0.99**		
RWD	0.65**	0.99**	0.65**	0.64**	- 0.10	0.63**	0.59**	0.58**	0.58**	

(b) Water stress condition

RL	RV	RFW	RDW	SL	R:S	NR	TRL	RLD	RWD	
RL										
RV	0.64**									
RFW	0.99**	0.65**								
RDW	0.97**	0.71**	0.97**							
SL	0.12	0.06	0.12	0.13						
R:S	0.69**	0.46**	0.68**	0.65**	- 0.62**					
NR	0.69**	0.51**	0.68**	0.71**	0.11	0.44**				
TRL	1.00**	0.64**	0.99**	0.97**	0.12	0.69**	0.69**			
RLD	0.99**	0.64**	0.99**	0.96**	0.13	0.67**	0.68**	0.99**		
RWD	0.67**	0.97**	0.67**	0.73**	0.02	0.52**	0.53**	0.67**	0.67**	

** Significant at 1 % level of probability with n-2 degrees of freedom

RL: Root length, RV: Root volume, RFW: Root fresh weight, RDW: Root dry weight, SL: Shoot length, R:S : Root to shoot length ratio, NR: Number of roots, TRL: Total root length, RLD: Root length density and RWD: Root weight density

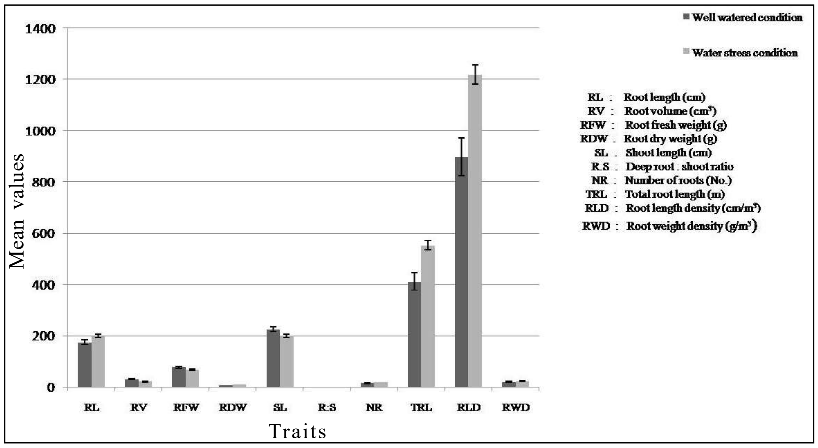

Fig. 2. Mean performance of 52 sorghum genotypes for root related traits under well-watered and water stress condition

34 (242 cm) and RL 167 (240.50 cm). Similarly highest RV was observed in RV 48 (27.09 cm^3) followed by STG 44 (25 cm^3).

Under WW condition, compared to intermediate and low yielding lines, high yielding lines showed higher values for RL (8.71 % and 22.57 %), RFW (11.8 % and 16.33 %), R:S (9.47 % and 27.15 %) and TRL (8.87 % and 22.55 %). The similar trend was observed for RDW, NR, RLD and RWD, while SL showed decrease of 0.65 % and 6.25 % in high yielding lines compared to intermediate and low yielding lines respectively. The same trend was also seen in WS condition. RV showed more differences between high and intermediate/low yielding lines, RFW showed less difference between high and intermediate lines and more difference between high

a) Root length and volume of two high yielding lines (RL 167 and RL 142) along with stay green donor parent (E36 -1) under well- watered (left) and water stress condition (right)

b) Root length and volume of the high yielding line (STG 44) under well-watered (left) and water stress condition (right)

c) Root length and volume of a low yielding line (STG 43) under well-watered (left) and water stress condition (right)
Fig.3. Root length and volume of sorghum genotypes

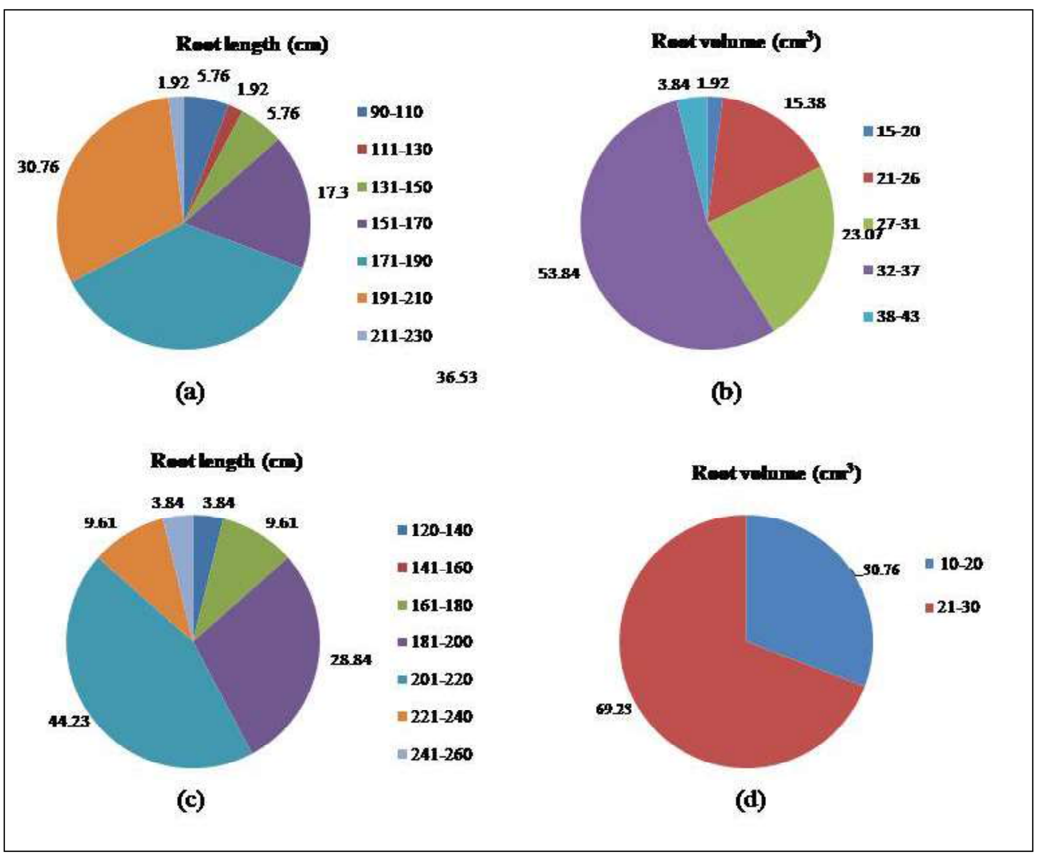

Fig. 4. Distribution of root length and root volume of 52 genotypes: (a) Root length under well-watered condition, (b) Root volume under well-watered, (c) Root length under water stress condition and (d) Root volume under water stress condition.

Table 4a. Performance of 52 sorghum genotypes for root related traits under well-watered condition

Genotypes	RL(cm)	RV(cm^3)	RFW(g)	RDW(g)	SL(cm)	R:S	NR(No.)	TRL(m)	RLD (cm/m^3)	RWD (g/m^3)
RL 142	163.50	29.62#	81.74	8.72	218.50	0.75	18.37#*	400.62	843.32	18.88
RL 167	199.50	36.14#	94.97#*	10.65	237.00*	0.84	19.10#*	475.40	1029.00	23.04
RL 34	205.00	37.14#	95.56#*	10.44	208.50	0.98#	17.21*	488.51#	1057.00	22.60
RL 183	188.50	34.15#	81.34	10.06	243.50*	0.77	15.76	449.19	972.27	21.77
RL 21	182.00	36.97#	76.01	9.71	237.00*	0.77	15.69	433.70	938.74	21.02
RL 83	171.00	30.98#	69.89	9.12	228.50*	0.75	13.05	407.49	882.01	19.75
RL 146	147.00	26.63	76.61	7.84	240.50*	0.61	13.33	350.30	758.22	16.98
RL 127	156.00	32.26#	69.30	8.32	245.00*	0.64	10.55	371.74	804.64	18.02
RV 146	195.00	35.32#	80.95	10.41	225.50	0.86	17.92#*	464.68	1005.00	22.52
RV 48	202.00	36.59#	96.94#*	10.78	203.50	0.99#	16.56*	481.36	1041.00	23.33
RV129	201.00	36.41#	87.66	10.73	239.50*	0.84	14.10	478.98	1010.00	23.22
RV150	192.00	34.78#	78.18	10.25	227.50	0.84	16.22	457.53	990.32	22.18
RV114	172.00	31.16#	77.79	9.18	224.50	0.77	13.47	409.87	887.17	19.87
RV 60	154.00	32.90#	69.10	8.22	235.50*	0.65	12.87	366.98	794.32	17.79
RV 193	180.00	33.33#	71.08	9.82	250.00*	0.74	14.37	438.47	949.06	21.25
RV 84	92.50	26.76	75.03	4.94	245.50*	0.38	12.72	220.42	477.11	10.68
STG 44	225.00#	40.76#*	89.44#	12.01#	235.00*	0.96#	19.08#*	536.17#	1160.00	25.99#
STG 25	201.50	36.50#	84.11	10.75	204.00	0.99#	18.10#*	480.17	1039.00	23.27
STG 21	157.50	28.53#	74.63	8.40	222.50	0.71	15.65	375.32	812.38	18.19
STG 5	151.50	27.44	78.18	8.08	202.00	0.75	15.54	361.02	781.43	17.50
STG 15	179.00	32.61#	70.68	9.60	203.50	0.88	15.96	428.93	928.43	20.79
STG 4	130.00	33.55#	75.42	6.94	212.50	0.61	11.79	309.79	670.53	15.02
STG 43	200.00	33.51#	81.34	9.87	228.50*	0.81	12.26	490.85#	954.22	21.37
STG 26	139.50	30.27#	69.89	7.44	241.00*	0.58	13.31	332.42	719.53	16.11
RSV1736	199.00	36.05#	83.12	10.62	218.00	0.91#	16.26	474.21	1026.00	22.98
RSV 1822	160.00	28.98#	84.11	8.54	174.50	1.00#	16.41*	381.27	825.27	18.48
RSV 1910	172.00	25.16	79.37	9.18	205.00	0.84	17.64#*	409.87	887.17	19.87
RSV2121	180.00	32.61#	71.87	9.60	232.50*	0.77	17.35*	428.93	928.43	20.79
RSV2138	172.00	31.16#	82.53	9.18	220.00	0.78	18.67#*	409.87	887.17	19.87
CRS 65	158.50	28.71#	82.53	8.46	238.50*	0.67	16.81*	206.13	446.16	18.31
CRS 66	209.00	38.86#	84.53	11.45	209.50	1.03#	17.97#*	511.15#	1106	24.77
CRS 67	193.00	24.96	77.99	9.80	195.00	0.99#	17.29*	459.91	995.48	21.21
CRS 68	204.00	36.95#	87.07	10.89	243.00*	0.84	16.92*	486.13#	1052.00	23.56
BJV125	195.00	25.32	81.94	10.41	230.00*	0.85	20.00#*	464.68	1005.00	22.52
BJV 129	187.00	18.89	81.99	9.48	253.50*	0.74	17.12*	445.61	964.53	20.52
BJV362	185.50	33.60#	88.85#	9.90	243.00*	0.76	17.72#*	442.04	956.80	21.43
BJV371	182.00	32.97#	81.74	9.71	232.50*	0.78	15.63	433.70	938.74	21.02
SPV2544	188.50	34.15#	76.01	10.06	262.50*	0.72	15.83	449.19	972.27	21.77
SPV2405	180.00	32.61#	79.76	9.60	220.50	0.82	17.99#*	428.93	928.43	20.79
SVD1352	174.00	21.52	78.97	9.28	222.50	0.78	17.85#*	414.64	897.48	20.10
SVD1365	150.00	27.17	80.55	8.00	223.50	0.67	14.88	357.45	773.69	17.33
B35	95.00	22.21	55.76	5.07	150.00	0.40	12.85	226.38	490.00	10.97
Phule Suchitra	184.00	33.33#	88.85#	9.82	199.50	0.92#	17.13*	438.47	949.06	21.25
SPV570	168.00	30.43#	82.92	8.96	236.50*	0.71	15.78	400.34	866.53	19.40
BJV44	192.00	34.78#	81.74	10.25	284.50#*	0.67	18.12#*	457.53	990.32	22.18
Basavanapada	198.50	35.96#	84.92	10.59	237.00*	0.84	14.81	475.02	997.85	22.93
CSV 29R	167.50	30.34#	77.59	8.94	206.50	0.81	15.18	399.15	863.95	19.35
E36-1	100.00	28.12#	62.19	5.34	194.00	0.52	12.32	238.30	515.79	11.55
SPV 86	180.00	32.61#	86.87	9.60	207.50	0.87	18.19#*	428.93	928.43	20.79
Phule Anuradha	192.00	34.78#	79.57	10.25	206.00	0.93#	18.62#*	457.53	990.32	22.18
SPV2217 (Check 1)	187.00	23.88	76.80	9.98	254.00	0.74	15.87	389.61	964.53	21.60
M35-1 (Check 2)	197.00	35.69	79.76	10.51	204.00	0.97	14.69	469.44	1016.00	22.75
C.D. at 5%	29.54	3.84	11.51	1.58	23.51	0.16	1.60	96.03	207.05	3.42

Genotypes significantly superior than SPV 2217; * Genotypes significantly superior than M35-1

RL: Root length (cm), RV: Root volume (cm^3), RFW: Root fresh weight (g), RDW: Root dry weight (g), SL: Shoot length (cm), R:S : Root to shoot length ratio, NR: Number of roots (No.), TRL: Total root length (m), RLD: Root length density (cm/m^3) and RWD: Root weight density (g/m^3)

Table 4b. Performance of 52 sorghum genotypes for root related traits under water stress condition

Genotypes	RL(cm)	RV(cm^3)	RFW(g)	RDW(g)	SL(cm)	R:S	NR(No.)	TRL(m)	RLD (cm/m^3)	RWD (g/m^3)
RL 142	207.00	20.85	64.56	11.05	200.50#	1.03	21.23*	576.46#	1247	23.91
RL 167	240.50#*	20.85	78.78	12.83#*	217.50#	1.11	21.67*	669.75#*	1449#*	27.78#*
RL 34	242.00#*	24.71	80.95#	12.91#*	171.00	1.42#*	20.72*	673.93#*	1458#*	27.95#*
RL 183	206.00	18.73	74.43	10.99	211.00#	0.98	21.13*	573.68#	1241	23.79
RL 21	192.50	21.25	71.87	10.27	195.50	0.99	17.76	536.08#	1160	22.23
RL 83	177.00	19.53	67.52	9.44	179.00	1.01	17.15	492.92#	1066	20.44
RL 146	194.00	21.41	58.05	10.35	206.50#	0.94	18.36	540.26#	1169	22.41
RL 127	175.50	19.37	61.60	9.36	236.00#*	0.74	18.00	488.74#	1057	20.27
RV 146	205.00	22.62	77.00	10.94	172.00	1.19*	20.72*	570.89#	1235	23.68
RV 48	245.50#*	27.09#*	78.26	13.10#*	206.50#	1.19*	21.74*	683.68#*	1479#*	28.36#*
RV129	222.00#*	24.50	79.37	11.85#*	170.50	1.30#*	20.72*	618.24#*	1338#*	25.64#*
RV150	198.00	21.85	75.82	10.57	180.50	1.10	21.85*	551.40#	1193	22.87
RV114	197.00	21.74	64.42	10.51	203.50#	0.97	20.41*	548.61#	1187	22.75
RV 60	175.00	16.31	60.81	9.34	204.00#	0.86	17.23	487.35#	1054	20.21
RV 193	184.00	14.87	72.66	9.60	196.50	0.92	14.96	501.27#	1085	20.79
RV 84	190.00	20.97	36.53	9.14	199.00	0.95	18.71	529.12#	1145	19.78
STG 44	226.50#*	25.00#	88.85#*	12.09#*	201.00#	1.13*	23.23#*	630.77#*	1365#*	26.16#*
STG 25	213.00#	23.51	79.57	11.37	194.00	1.10	20.58*	593.17#	1283#	24.60
STG 21	189.00	20.86	62.19	10.09	192.50	0.99	18.38	526.34#	1139	21.83
STG 5	198.00	17.85	59.82	10.57	202.00#	0.98	20.51*	551.40#	1193	22.87
STG 15	180.00	19.76	66.08	9.55	204.00#	0.88	18.36	498.49#	1078	20.67
STG 4	191.00	21.08	51.33	9.19	204.50#	0.94	16.09	531.91#	1151	19.90
STG 43	245.00#*	22.73	73.05	10.99	202.00#	1.02	15.23	573.68#	1241	23.79
STG 26	177.00	19.53	55.08	9.44	206.50#	0.86	20.31*	492.92#	1066	20.44
RSV1736	210.50	23.23	78.58	11.23	202.50#	1.04	19.22	586.21#	1268	24.31
RSV 1822	213.00#	23.51	63.18	11.37	203.50#	1.05	19.27	593.17#	1283#	24.60
RSV 1910	201.00	22.18	67.92	10.73	188.00	1.07	21.13*	559.75#	1211	23.22
RSV2121	182.00	20.09	71.08	9.71	194.00	0.94	18.67	506.84#	1097	21.02
RSV2138	209.00	23.07	67.92	11.15	200.50#	1.04	21.95*	582.03#	1259	24.14
CRS 65	209.00	23.07	62.59	11.15	217.50#	0.96	21.44*	582.03#	1259	24.14
CRS 66	214.50#	23.07	82.70#	11.15	190.00	1.10	22.97#*	582.03#	1259	24.14
CRS 67	197.50	21.80	76.21	10.54	172.00	1.15*	18.79	550.01#	1190	22.81
CRS 68	220.50#*	24.34	80.55#	11.77#	193.00	1.14*	21.64*	614.06#*	1329#*	25.47#
BJV125	207.50	22.90	77	11.07	189.50	1.10	21.28*	577.86#	1250	23.97
BJV 129	216.50#	23.89	73.84	11.05	219.50#	0.99	21.21*	602.92#	1305#	23.92
BJV362	225.00#*	24.83	71.75	12.01#*	202.00#	1.11	22.09*	626.59#*	1356#*	25.99#*
BJV371	207.00	22.85	69.37	11.05	218.00#	0.95	21.23*	576.46#	1247	23.91
SPV2544	192.50	21.25	74.43	10.27	220.00#	0.88	18.24	536.08#	1160	22.23
SPV2405	202.00	22.29	71.08	10.78	219.50#	0.92	20.23*	562.54#	1217	23.33
SVD1352	200.00	20.07	68.71	11.17	204.00#	0.98	20.87*	556.97#	1205	24.18
SVD1365	204.00	22.51	59.23	10.89	202.00#	1.01	20.92*	568.11#	1229	23.56
B35	125.00	16	34.01	7.24	151.50	0.96	13.92	403.80	874.03	15.67
Phule Suchitra	225.00#*	24.83	71.66	11.01	186.00	1.21#*	20.58*	626.59#*	1356#*	23.82
SPV570	215.00#	23.18	66.34	11.21	173.00	1.21#*	18.91	584.82#	1265	24.26
BJV44	207.00	22.85	75.82	11.05	197.50	1.05	20.54*	576.46#	1247	23.91
Basavanapada	210.00	23.18	76.88	11.21	232.50#*	0.90	18.14	584.82#	1315#	24.26
CSV 29R	196.50	21.69	66.14	10.49	261.00#*	0.75	18.68	547.22#	1184	22.70
E36-1	127.50	15.38	39.49	8.40	178.00	0.88	14.95	438.61	949.38	18.19
SPV 86	220.00#*	24.28	71.08	11.74#	199.00	1.11	20.21*	612.67#*	1326#*	25.41#
Phule Anuradha	201.50	22.24	75.82	10.75	209.00#	0.96	22.21*	561.15#	1214	23.27
SPV2217 (Check 1)	194.50	21.47	73.84	10.38	178.50	1.09	20.10	400.65	1172.00	22.46
M35-1 202.00 (Check 2)	22.29	77.79	10.78	203.00	1.00	17.22	562.54	1217.00	23.33	
C.D. at 5%	17.80	3.41	6.61	1.07	20.60	0.12	2.32	49.59	104.35	2.30

Genotypes significantly superior to SPV 2217; * Genotypes significantly superior to M35-1

RL: Root length (cm), RV: Root volume (cm^3), RFW: Root fresh weight (g), RDW: Root dry weight (g), SL: Shoot length (cm), R:S: Root to shoot length ratio, NR: Number of roots (No.), TRL: Total root length (m), RLD: Root length density (cm/m^3) and RWD: Root weight density (g/m^3)

and low yielding lines. However, traits such as RL, RDW, SL, R:S, NR, TRL, RLD and RWD showed more differences between high and intermediate yielding lines and less difference between high and low yielding lines under WS condition compared to WW condition. Liang *et al*. (2016) reported that not only drought tolerant genotypes but drought sensitive genotypes also produced longer roots under water-limited condition. In the present study STG 43 (drought susceptible and low yielding genotype) showed increased root length in WS condition (Fig. 3c). This indicated that water acquisition from deeper soil layers might be determined not only by the root length or root surface area but also by the physiological function of the roots such as hydraulic conductivity of the roots and available water in the soil gradient. The difference between high and low yielding lines was less under WS condition than compared to WW condition for traits like root length, root dry weight, shoot length, root:shoot length ratio, number of roots, total root length, root length density and root weight density. Root length density increased the capacity of soil water capture in sorghum (Monti and Zatta, 2009). Hence, deep roots may be beneficial in terminal drought, but the benefit may be reduced in intermittent drought, shallow rooting could help extract water from the top soil and reserving moisture at a deeper level in the soil for grain filling (Tron *et al*., 2015). Therefore increased root depth may be a drought adaptive trait of the genotypes grown under terminal drought conditions and has been reported in many crop species (O'Toole and Bland, 1987).

In the analysis of 52 genotypes based on root related traits, among improved lines for drought adaptation under WW condition STG 44 was significantly superior over the checks (M35-1 and SPV 2217) for RV and NR. Three genotypes (RL 167, RL 34 and RV 48) were significantly superior over the checks for RFW. Among released varieties, BJV 44, SPV 86 and Phule Anuradha were significantly superior over the checks for NR. Under WS condition, out of 41 improved lines RV 48 was significantly superior over the checks for RL, RV, TRL, RLD and RWD. STG 44 was significantly superior over the checks for RL, RFW, RDW, NR, TRL, RLD and RWD. Three genotypes (RL 167, RL 34 and BJV 362) were significantly superior over the checks for RL, RDW, TRL, RLD, and RWD. Out of 11 released varieties, Phule Suchitra and SPV 86 were significantly superior over the checks for RL, TRL and RLD.

Conclusion

Screening of 52 genotypes for root related traits under limited moisture condition and correlation analysis revealed that root length, root volume, root fresh weight, total root length and root:shoot length ratio could be used as a selection criterion for post-flowering drought tolerance. These traits benefit genotypes in an environment with limited irrigation; hotter and drier growing seasons. Genotypes showing good field performance can be used in the breeding programme. By considering the response of the genotypes, NIL STG 44 was identified as the best performing genotype under well-watered and water stress conditions whereas under water stress condition, six genotypes (RL 167, RL 34, RV 48, BJV 362, Phule Suchitra and SPV 86) were identified as best performing genotypes. However, since this result is limited to data collected for root related traits only and not grain yield, further determination of grain yield in PVC pipes under greenhouse/ rain protected conditions is needed to find the correlation between root traits and grain yield.

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