Putative mechanisms of drought tolerance in maize (*Zea mays* L.) *via* root system architecture traits

ABSTRACT

Identifying maize genotypes with favorable root architecture traits for drought tolerance is prerequisite for initiating a successful breeding program for developing high yielding and drought tolerant varieties of maize. The aims of the present study were: (*i*) to identify drought tolerant genotypes of maize at flowering and grain filling, (ii) to interpret the correlations between the drought tolerance and root architecture traits and (iii) to identify the putative mechanisms of drought tolerance *via* root system traits. An experiment was carried out in two years using a split plot design with three replications. The main plots were assigned to three water stress levels, namely: well watering (WW), water stress at flowering (WSF) and water stress at grain filling (WSG), and sub-plots to 22 maize cultivars and populations. Drought tolerance index (DTI) had strong and positive associations with crown root length (CRL), root circumference (RC) and root dry weight (DRW) under both WSF and WSG, a negative correlation with brace root whorls (BW), and positive correlations with crown root number (CN) under WSF and brace root branching (BB) and crown root branching (CB) under WSG. These root traits are therefore considered as putative mechanisms of drought tolerance. The cultivars Pioneer-3444, SC-128, Egaseed-77, SC-10 and TWC-324 showed the most drought tolerant and the highest yielding in a descending order; each had a number of such drought tolerance mechanisms. Further investigation should be conducted to determine the underlying root mechanisms contributing to the selection of water-efficient hybrids of maize.

Key words: Corn, Crown and Brace roots, Correlations, Drought tolerance index.

INTRODUCTION

Maize (*Zea mays* L.) in Egypt is mainly used for poultry industry and animal feed. For acreage and production, it ranks second to wheat among cereal crops in Egypt. It is grown as a summer season crop and well irrigated by water coming from Nile River and its branches and canals. Current maize hybrids cultivated in Egypt are selected under well irrigation and therefore are subject to yield losses when grown under water deficit. The irrigation water is reducing, especially at the ends of canals and due to expanding maize cultivation into the deserts, where sandy soils are of low water holding capacity. In order to stabilize maize production in Egypt, there is a need to develop drought tolerant maize hybrids.

Maize is very sensitive to drought during the flowering and grain-filling periods [1]. However, Witt *et al.* [2] reported that "most of yield production happened approximately in the period from two weeks before flowering time until two weeks after flowering time". Developing maize varieties that are tolerant to drought is, therefore considered critical for increasing the maize production. Several investigations have been undertaken across the years to improve drought tolerance in breeding programs. Edmeades *et al*. [3] reported that germplasm developed from drought tolerant source populations performed significantly better under drought stress compared to conventional populations.

Root system traits are very important for productivity of plants under water stress [4]. "Plants avoid drought by increasing their water uptake from the soil and their adaptation to the physical and chemical soil problems, *via* their root system plasticity " [5]. The importance of steep and strong roots for achieving high yield in maize under water stress has been reported by Hund *et al.* [6]. Rauf and Sadaqat [7] stated that "drought tolerant genotypes generally increase the photosynthates allocation for root elongation under drought stress". Rauf *et al.* [8] reported that genetic variation for root elongation has been shown in maize. The effects of root architecture and size on maize yield also depend on the soil water distribution and the competition for water among the plants [9].

Trait interrelationships in particular determine the degree of association among traits and how they may increase selection efficiency. It is useful if indirect selection for root traits gives greater response to selection for grain yield trait than direct selection for the same trait. The main criterion for drought tolerance selection is the association of each root trait with grain yield under stress conditions [9, 10].

To start a successful breeding program for improving drought tolerance, available maize germplasm should be screened for related traits to drought tolerance; *e.g.* root architecture traits under deficit irrigation to identify the best ones for further use in extracting the best parental inbred lines for developing drought tolerant hybrids. The aims of the present study were: (i) to characterize 22 maize genotypes for their root system architecture traits and their drought tolerance in order to identify drought tolerant ones, (ii) to interpret the correlations between the drought tolerance and root traits and (iii) to identify the putative mechanisms of drought tolerance *via* root system architecture.

MATERIALS AND METHODS

This experiment was conducted in 2016 and 2017 maize growing seasons at the Agric. Exper. and Res. Sta. of the Fac. of Agric., Cairo University, Giza, Egypt located at 30° 02'N latitude and 31° 13'E longitude with an altitude of 22.50 m asl.

Plant materials

The plant material of this study consisted of twenty two maize genotypes (*Zea mays* L.), *i.e.* 15 Egyptian cultivars (ten single crosses and five 3-way crosses) and seven populations (Table 1). These materials were kindly provided by Hi-Tec Company (HT-2031, HT-2066, HT-1100), DuPont Pioneer Company (P-30K09, P-3444, P-32D99), Fine Seeds Company (F-1005), Egaseed Company (Ega-77), Wataniya Company (W-11) and Agricultural Research Center-Egypt (the rest of genotypes). The studied genotypes represent the available germplasm in Egypt and some of them could be considered sources for extracting drought tolerant inbred lines.

Table 1. Name, origin, genetic nature and grain color of studied maize genotypes.

Genotype No.	Name	Origin	Genetic nature	Grain colour
1	HT-2031	Hi-Tec Co., Egypt	SC	W
2	P-30K09	DuPont Pioneer Co.	SC	W
3	F-1005	Fine Seeds Co., Egypt	SC	W
4	Ega-77	Egaseed Co., Egypt	SC	W
5	SC-10	ARC, Egypt	SC	W
6	SC-128	ARC, Egypt	SC	W
7	HT-2066	Hi-Tec Co., Egypt	SC	Y
8	P-3444	DuPont Pioneer Co.	SC	Y
9	SC-166	ARC, Egypt	SC	Y
10	P-32D99	DuPont Pioneer Co.	SC	Y
11	HT-1100	Hi-Tec Co., Egypt	TWC	W
12	W-11	Watania Co., Egypt	TWC	W
13	TWC-324	ARC, Egypt	TWC	W
14	TWC-360	ARC, Egypt	TWC	Y
15	TWC-352	ARC, Egypt	TWC	Y
16	Giza Baladi	ARC, Egypt	Pop	W
17	Pop-45	ARC, Egypt	Pop	Y

18	Nubaria	ARC, Egypt	Pop	Y
19	Nebraska Midland	USA	Pop	Y
20	Midland Cunningham	Eldorado,Kansas, USA	Pop	Y
21	Golden Republic	Beltsville,Kansas, USA	Pop	Y
22	Sweepstakes 5303	USA	Pop	Y

ARC= Agricultural Research Center, SC= Single cross, TWC= Three-way cross, Pop= Population, W=White, Y=Yellow

The experimental procedures

The planting date was April 24th and April 30ht in 2016 and 2017 seasons, respectively. Sowing was done in rows; each row was 4 m long and 70 cm width. Seeds were over sown in hills 25 cm apart, thereafter (after 21 days from planting and before the first irrigation) were thinned to one plant/hill to achieve a plant density of 57,120 plants/ha. Each experimental plot included two rows (plot size = 5.6 m^2).

The experimental design

The experiment was conducted using a split-plot design in randomized complete blocks arrangement with three replications. The main plots were assigned to three watering systems, *i.e.* well watering, water stress at flowering and water stress at grain filling. Each main plot was surrounded with a border of 4m width, to avoid water interference from main plot to another. The sub plots were allotted to twenty-two maize genotypes.

Watering systems

1. Well watering (WW): The flood irrigation was used; the second irrigation was applied after 21 days from sowing and subsequent irrigations were given at 12 days intervals.

2. Water stress at flowering stage (WSF): The irrigation was just like well watering, but the 4th and 5th irrigations were prevented, resulting in 24 days drought stress just before and during flowering stage.

3. Water stress at grain filling stage (WSG): The irrigation was just like well watering, but the 6th and 7th irrigations were prevented, resulting in 24 days drought stress during the grain filling stage.

Other agricultural practices

All other agricultural practices were followed according to the recommendations of ARC, Egypt. Triple Superphosphate (46% P_2O_5) at the rate of 70 kg P_2O_5/ha was added to soil before sowing during soil preparation for planting. Urea (46% N) at the rate of 285 kg N/ha was applied in two equal doses before the second and third irrigations. Weed control was done chemically with Stomp herbicide just after sowing and before the planting irrigation and manually by hoeing twice, the first before the second irrigation and the second before the third irrigation. Pest control was done when required by spraying plants with Lannate (Methomyl) 90% (manufactured by DuPont, USA) against corn borers.

Soil analysis

Soil analyses of the experimental site was done at the Laboratories of Soil and Water Research Institute of ARC, Egypt. Across the two seasons, soil type was clay loam: Silt (36.4%), clay (35.3%), fine sand (22.8%) and coarse sand (5.5%), pH (7.92), EC (1.66 dSm^{-1}), SP (62.5), $CaCO_3$(7.7 %), Soil bulk density (1.2 g cm^{-3}), HCO_3 (0.71 mEqu/l), Cl (13.37 mEqu/l), SO_4 (0.92mEqu/l), Ca^{++} (4.7mEqu/l), Mg^{++} (2.2mEqu/l), Na^{+} (8.0mEqu/l), K^{+} (0.1mEqu/l), N, P, K, Zn, Mn and Fe (371, 0.4, 398, 4.34, 9.08 and 10.14 mg/kg, respectively).

Data recorded:

1. **Grain yield/plant (GYPP) (g)** was estimated from a sample of ten guarded plants/plot (adjusted at 15.5% grain moisture).
2. **Grain yield/ha (GYPH) (ton)** was estimated by adjusting grain yield/plot at 15.5% grain moisture to grain yield/ha.

Root traits:

At the end of each water stress treatment (80 and 100 days from emergence for WSF and WSG, respectively) and just after irrigation, roots of three plants from each experimental plot were excavated by removing a soil cylinder of 40 cm diameter and a depth of 40 cm with plant base as the horizontal centre of the soil cylinder. Excavation was carried out using standard shovels. The excavated root crowns were shaken briefly to remove a large fraction of the soil adhering to the root crown. Most of the remaining soil was then removed by soaking the root crown in running water. In a third step, remaining soil particles were removed from the root crown by vigorous rinsing at low pressure. The clean roots were measured or visually scored (Fig. 1) for the following traits:

3. Number of above-ground whorls occupied with brace roots (BW).

4. Number of brace roots (BN).

5. Angle of 1st arm of the brace roots originating from whorl 1 (BA) (score).

6. Branching density of brace roots (BB) (score).

7. Number of crown roots (CN) (score).

8. Crown roots angle (CA) (score).

9. Branching density of crown roots (CB) (score).

Traits from No. 5 to No. 9 were assigned values from one to nine according to Trachsel *et al*. [10], where one indicates shallow root angles (10°), low root numbers and a low branching density and nine indicates steep root angles (90°), high numbers and a high branching density (Figure 1).

10. Crown root length (CRL) (cm). The root length, measured as the distance between the last node to the end tip of the root.

11. Root circumference (RC) (cm). RC was measured from maximum root system width.

12. Root (crown and brace) dry weight (RDW) (g). The measured root was first spread out in the sun for partial drying and then put in an oven for total drying at 40°C for 24 hours. After drying the roots were weighed using an electronic scale.

Drought tolerance index (DTI):

Drought tolerance index is the factor used to differentiate between the genotypes from tolerance point of view and it is calculated by the equation of Fageria [11] as follows:

$DTI = (Y1/AY1) \text{ X } (Y2/AY2)$

Where, Y1 = trait mean of a genotype at well watering. AY1 = average trait of all genotypes at well watering. Y2 = trait mean of a genotype at water stress. AY2 = average trait of all genotypes at water stress. When DTI is ≥ 1, it indicates that genotype is tolerant (T) to drought. If DTI is <1, it indicates that genotype is sensitive (S) to drought.

Statistical analyses

Analysis of variance of the split plot design was performed on the basis of individual plot observation using the MIXED procedure of MSTAT ®. Combined analysis of variance across the two growing seasons was also performed if the homogeneity test was non-significant. Moreover, combined analysis for each environment separately across seasons was performed as randomized complete blocks design. Least significant difference (LSD) values were calculated to test the significance of differences between means according to Steel *et al.* [12].

Figure 1. Images of brace roots angle (BA), brace roots branching density (BB), crown roots number (CN), crown roots angle (CA) and crown roots branching (CB) displayed were scored with 1, 3, 5, 7 and 9.

Simple correlation coefficients were calculated between pairs of studied traits under well watering (WW), water stress (WS), severe water stress (SWS) and combined across all irrigation treatments according to Singh and Narayanan [13]. Spearman's rank correlation coefficients calculated among studied root traits and other studied traits under studied environments. It was computed by using SPSS 17 computer software and the significance of the rank correlation coefficient was tested according to Steel *et al*. [12].

RESULTS AND DISCUSSION

3.1. Analysis of variance

Combined analysis of variance across seasons of the split plot design (Table 2) indicated that mean squares due to season were significant (P≤0.05 or P≤0.01) for BW, BA, CA, CB, GYPP and GYPH traits. Mean squares due to irrigation regime were significant (P≤0.05 or P≤0.01) for six traits, namely CN, CB, RC, RDW, GYPP and GYPH. Mean squares due to genotype were significant (P ≤ 0.01) for all 12 studied root traits and grain yield.

Table 2. Combined analysis of variance across 2016 and 2017 seasons for studied root traits of 22 maize genotypes under four irrigation regimes.

SOV	Mean squares					
	BW	**BN**	**BA**	**BB**	**CN**	**CA**
Season (S)	*	ns	**	ns	ns	**
Irrigation regime(I)	ns	**	ns	ns	*	ns
I x S	*	ns	ns	ns	ns	ns
Genotype (G)	**	**	**	**	**	**
G x S	ns	ns	ns	**	*	ns
G x I	ns	ns	ns	ns	ns	ns
G x S x I	ns	ns	ns	*	ns	ns
	CB	**CRL**	**RC**	**RDW**	**GYPP**	**GYPH**
Season (S)	**	ns	ns	ns	*	**
Irrigation regime(I)	**	ns	**	**	**	**
I x S	ns	ns	*	**	ns	**
Genotype (G)	**	**	**	**	**	**
G x S	**	ns	ns	**	**	**
G x I	ns	ns	ns	ns	**	**
G x S x I	ns	ns	ns	ns	**	**

BW= Number of above-ground whorls occupied with brace roots, BN= Number of brace roots, BA= Brace root angle, BB= Branching density of brace roots, CN= Number of crown roots, CA=Crown roots angle, CB=Branching density of crown roots, CRL= Crown root length, RC=Root circumference, RDW= Roots dry weight, GYPP= Grain yield/plant, GYPH= grain yield/ha, ns= not significant, * and ** indicate significance at 0.05 and 0.01 probability levels, respectively.

Mean squares due to the 1st order interaction were significant (P ≤ 0.05 or 0.01) for four traits (BN, RC, RDW and GYPH) due to I×S, for six traits (BB, CN, CB, RDW, GYPP and GYPH) due to G×S and two traits (GYPP and GYPH) due to G×I. Mean squares due to the 2nd

order interaction, *i.e.* G×S× I, were significant ($P \leq 0.01$) for three traits, namely BB, GYPP and GYPH (Table 2).

Root system traits are very important for productivity of plants under water stress conditions [4]. In order to improve maize yield, breeders should select genotypes with a root system adapted to the water stress conditions of the target environment. Results of the present study indicated that irrigation regime had a significant effect on six traits (CN, CB, RC, RDW, GYPP and GYPH). Most importantly, genotype had an obvious effect on all studied root traits and grain yield. The role of maize genotype is in agreement with the findings of Trachsel *et al.* [10] for maize root system architecture traits and Al-Naggar *et al.* [14, 15] for grain yield. Mean squares due to the the 1st and 2nd order interactions were significant for some root and yield traits, indicating that for such traits, the rank of maize genotypes differ from irrigation treatment to another, and from one season to another and the possibility of selection for improved root traits and grain yield under a specific drought stressed environment as suggested by Al-Naggar *et al.* [16-20]. Combined analysis of variance of RCBD under each environment (data not presented) indicated the significance of differences among studied genotypes for the majority of studied root traits and grain yield under each irrigation treatment.

3.3. The effect of genotype

Means and lowest and highest values (Ranges) of all studied traits across all genotypes, all watering treatments and across two seasons are presented in Table (3). Genotypes ranged for grain yield/ha from 13.03 ton/ha (genotype No.8; P-3444) to 2.69 ton/ha (genotype No. 22; Sweepstakes 5303), grain yield/plant from 158.5 g (genotype No. 6; SC 128) to 62.5 g (genotype No. 22; Sweepstakes 5303), number of above-ground whorls occupied with brace roots from 3.0 from (genotype No. 17) to 1.9 (genotype No. 8), number of brace roots from 49.0 (genotype No. 10) to 25.6 (genotype No. 21), angle of 1st arm of the brace roots originating from whorl 1 from 7.7 (genotype No. 19) to 5.5 (genotype No. 1), branching density of brace roots from 6.2 (genotype No. 9) to 3.4 (genotype No. 18), number of crown roots from 4.5 (genotype No. 6) to 1.9 (genotype No. 21), crown roots angle from 8.1 (genotype No. 10) to 5.6 (genotype No. 7), branching density of crown roots from 6.5 (genotype No. 8) to 3.0 (genotype No. 21), crown root length from 26.1 cm (genotype No. 5) to 20.4 cm (genotype No. 18), root circumference from 38.1 cm (genotype No. 7) to 25.9 cm (genotype No. 21) and roots dry weight from 36.8 g (genotype No. 8) to 11.2 g (genotype No. 20).

Table 3. Mean, lowest (Lo) and highest (Hi) values of all studied traits across two seasons and across all watering treatments.

Trait	Unit	Mean	Lowest	Highest	$LSD_{.05}$
Brace root whorls number	**No.**	2.5	1.9 (8)	3.0 (10,11,17)	0.36
Brace roots number	**No.**	37.1	25.6 (21)	49.0(10)	6.8
Brace roots angle	**score**	6.7	5.5 (1)	7.7(19)	0.74
Brace roots branching	**score**	4.9	3.4 (18)	6.2(9)	1.09
Crown roots number	**score**	3.2	1.9 (21)	4.5(6)	0.86
Crown roots angle	**score**	6.7	5.6 (7)	8.1(10)	0.76
Crown roots branching	**score**	4.2	3.0 (21)	6.5 (8)	0.91
Crown roots length	**cm**	22.8	20.4 (18)	26.1 (5)	2.57
Root circumference	**cm**	32.7	25.9 (21)	38.1 (8)	2.85
Roots dry weight	**g**	22.3	11.2 (20)	36.8(8)	6.05
Grain yield/plant	**g**	107.3	62.5(22)	158.5(6)	9.72
grain yield/ha	**ton**	7.18	2.69(22)	13.03(8)	0.39

Lowest and highest values are followed by genotype No. mentioned in Table 1 (Between brackets).

The single cross cultivar Pioneer-3444 developed by DuPont Pioneer Co. exhibited the highest mean values for four traits [grain yield/ha (GYPH), root circumference (RC), crown root branching (CB) and roots dry weight (RDW)] and second highest for GYPP, brace root branching (BB), number of crown roots (CN), crown root length (CRL), *i.e.* most important yield and root traits. The genotype SC-128 developed by ARC-Egypt was the highest in GYPP and number of crown roots and second highest in crown root branching. The genotype Ega-77 developed by Egaseed Co., Egypt showed the third highest in grain yield and the highest in brace root angle (BA). The genotype SC-10 developed by ARC-Egypt showed the highest means for one trait (crown root length; CRL); it gave the fourth highest grain yield per plant and per hectare.

On the contrary, the genotype Pop. Sweepstakes 5303 exhibited the lowest means for two traits, namely GYPP, GYPH. The genotype Pop. Golden Republic exhibited the lowest means for two traits, namely BN and CN. The genotype Pop. Nubaria showed the lowest means for two traits (BB and CRL).

Means of the 22 maize genotypes showed wide ranges of performance (difference between minimum and maximum values) for all studied root and yield traits across all irrigation treatments. Three commercial varieties showing the highest grain yield showed also the highest means for a number of root traits. The superiority of these three commercial varieties in six root traits (RC, CB, RDW, BB, CN and CRL) for Pioneer-3444, two traits (CN and CB) for SC-128, one trait (BA) for Egaseed 77 and one trait (CRL) for SC-10 might be the reason of their superiority in grain yield, because good roots may help the plants to uptake more water and nutrients from the soil for their biological activities, especially under drought conditions [4, 21, 22].

In general, the commercial varieties P-3444, SC-128, Egaseed-77 and SC-10 were the best genotypes in our experiment; they showed the highest grain yield and the best root architectural traits across all studied irrigation treatments; they could be recommended for farmers use under a range of different environments as well as for maize breeding programs. On the contrary, it is observed that most of root and yield traits with undesirable mean values were exhibited by populations and the *vice versa* for traits with desirable means, which were mostly shown by the single crosses.

Genotype × water stress interaction

For root traits (Table 4), data were measured under WWF, WWG, WSF and WSG. Under WWF, WWG, WSF and WSG, for BW the lowest mean was exhibited by genotypes No. 2, 13, 17 and 21 and the highest mean was shown by genotypes No. 17, 19, 4 and 10, for BN the lowest mean by genotypes No. 21, 12, 4 and 21 and the highest mean by genotypes No. 11, 11, 10 and 10, for BA the lowest by genotypes No. 1, 9, 14 and 1 and the highest mean was shown by genotypes No. 19, 21, 21 and 19, for BB the lowest by genotypes No. 18, 18, 13 and 20 and the highest mean was shown by genotypes No. 5, 15, 6 and 9, for CN the lowest by genotypes No. 18, 19, 13 and 13 and the highest mean was shown by genotypes No. 12, 8, 6 and 3, for CA the lowest by genotypes No. 2, 5, 7 and 1 and the highest mean was shown by genotypes No. 10, 10, 21 and 10, for CB the lowest by genotypes No. 21, 17, 19 and 19 and the highest by genotypes No. 8, 8, 6 and 8, for CRL the lowest by genotypes No. 14, 18, 22 and 22 and the highest mean by genotypes No. 8, 5, 9 and 4, for RC the lowest by genotypes No. 18, 19, 19 and 21 and the highest by genotypes No. 7, 8, 7 and 8 and for RDW the lowest by genotypes No. 20, 18, 19 and 21 and the highest by genotypes No. 8, 8, 5 and 8, respectively.

Table 4. Mean, lowest (Lo) and highest (Hi) values of all studied traits across two seasons under each irrigation treatment.

Watering	Mean	Lowest	Highest	LSD.05	Mean	Lowest	Highest	LSD.05
		Brace Root Whorls No.				Brace Roots No.		
WWF	2.52	2 (2)	3.1(17)	0.7	39	27.3 (21)	47(11)	16.58
WWG	2.48	1.66 (13)	3.33(19)	0.81	37.1	22.7 (12)	54.7(11)	14.5

WSF	2.29	1.8 (17)	2.9 (4)	0.57	31.5	23 (4)	43.3(10)	7.3
WSG	2.64	1.5 (21)	3.3(10)	0.81	40.8	25.2 (21)	59(10)	14.76
		Brace Root Angle (Score)				**Brace Root Branching (Score)**		
WWF	6.7	5 (1)	8.3 (19)	1.62	5.3	3.3 (18)	7 (5)	2.38
WWG	6.7	5 (9)	7.3 (21)	1.88	4.7	2 (18)	7 (15)	2.66
WSF	6.9	5.8 (14)	7.5 (21)	1.02	4.9	3 (13)	6.8 (6)	1.66
WSG	6.5	4.7 (1)	7.5 (19)	1.25	4.7	2.3 (20)	6.2 (9)	2.02
		Crown Root Number (Score)				**Crown Root Angle (Score)**		
WWF	3.82	1.7 (18)	6 (12)	2.2	6.8	5.7 (2)	8 (10)	1.6
WWG	2.66	1(19)	4 (8)	1.8	6.5	5.3 (5)	8 (10)	1.92
WSF	3.38	1.8 (13)	5.3 (6)	1.3	6.9	5 (7)	8 (21)	1.2
WSG	3.05	1.8 (13)	5 (3)	1.47	6.5	5.2 (1)	8.5 (10)	1.25
		Crown Root Branching (Score)				**Crown Root Length (cm)**		
WWF	4.6	3 (2)	6 (8)	1.95	22.4	18.6 (14)	25.9 (8)	6.67
WWG	4.1	2 (17)	7.3 (8)	2.35	23.2	18.8 (18)	28.1(5)	5.1
WSF	4.6	3.2 (19)	6.3 (6)	1.49	23.9	21.2 (22)	26.2 (9)	4.1
WSG	3.7	2.2 (19)	6.5 (8)	1.54	21.76	16.9 (22)	26 (4)	4.4
		Root Circumference (cm)				**Root Dry Weight (g)**		
WWF	34.7	28.1(18)	40.4(7)	6.48	26.2	8.2 (20)	40.7 (8)	14.36
WWG	30.7	23.3 (19)	41(8)	6.5	21	8.2 (18)	44.9 (8)	12.96
WSF	34.4	26.5(19)	42.5(7)	4.97	18.8	9.8 (19)	33.6 (5)	9.53
WSG	30.9	23.3(21)	36.6(8)	4.95	23.3	9.9 (21)	40.1(8)	11.53
		Grain Yield/Plant (g)				**Grain Yield/ha(ton)**		
WW	128.2	82.9 (19)	168.1 (1,5)	23	9.03	3.91 (22)	15.25 (8,5,6)	0.75
WSF	91.4	31.8 (22)	156.4 (6,4)	13.3	5.8	1.39 (22)	10.55 (4,8.6)	0.63
WSG	102.2	58.9 (15)	179.7 (8,6,4)	12.7	6.72	2.77 (22)	13.45 (8,6)	0.71

Lowest and highest values are followed by genotype No. (Between brackets).

For grain yield (Tables 5 and 6), data were measured under WW, WSF and WSG. The lowest mean GYPP was shown by genotypes No. 19, 22 and 15 and the highest by genotypes No. 1, 6 and 8 under WW, WSF and WSG, respectively. For GYPH, the lowest mean was exhibited by Genotypes No. 22, 22 and 22 and the highest mean was shown by Genotypes No. 8, 4 and 8 under WW, WSF and WSG, respectively.

Table 5. Mean grain yield/plant and mean grain yield/ha for each genotype under each watering treatment across two seasons.

Genotype	WW	WSF	Ch%	WSG	Ch%	WW	WSF	Ch%	WSG	Ch%
		Grain yield/plant						**Grain yield/ha**		
1	168.1	78.0	53.6	102.7	38.9	9.95	4.40	55.8	6.30	36.7

2	131.7	73.3	44.3	92.0	30.1	8.51	3.79	55.5	5.51	35.2
3	124.0	75.6	39.1	109.0	12.2	7.98	4.29	46.3	6.29	21.2
4	151.6	147.9	2.5	132.5	12.6	9.56	8.35	12.7	6.36	33.5
5	166.3	123.2	25.9	126.0	24.2	10.22	5.96	41.7	6.65	34.9
6	150.4	156.4	-4.0	168.7	-12.2	10.05	8.14	19.1	8.38	16.6
7	128.5	131.2	-2.1	106.8	16.9	7.34	6.41	12.6	4.76	35.2
8	150.4	137.6	8.5	179.7	-19.5	12.11	8.21	32.2	10.67	11.9
9	134.4	105.6	21.4	121.0	9.9	8.12	5.64	30.6	6.69	17.7
10	134.3	98.9	26.4	117.7	12.3	8.32	5.31	36.2	6.43	22.8
11	125.5	78.5	37.4	84.7	32.5	7.61	4.02	47.2	4.50	40.9
12	119.4	91.0	23.8	111.5	6.6	7.79	5.12	34.2	6.09	21.8
13	149.4	111.1	25.6	120.7	19.2	9.28	5.96	35.8	7.16	22.8
14	133.6	89.7	32.9	81.9	38.7	5.65	4.15	26.5	3.86	31.7
15	125.4	84.7	32.5	58.9	53.1	4.96	3.79	23.6	3.05	38.5
16	118.6	56.2	52.6	81.9	30.9	4.30	2.84	33.9	4.12	4.1
17	110.9	65.0	41.4	70.8	36.2	4.86	2.80	42.4	3.62	25.6
18	110.5	74.2	32.9	85.8	22.4	5.37	3.22	40.1	4.54	15.4
19	82.9	59.4	28.4	75.8	8.5	3.83	2.33	39.1	3.38	11.9
20	106.6	79.7	25.2	91.4	14.3	4.64	3.00	35.4	3.63	21.9
21	100.8	61.8	38.7	70.4	30.2	3.79	2.60	31.5	3.04	19.8
22	96.9	31.8	67.2	58.9	39.3	3.10	1.11	64.2	2.19	29.4
Average	128.2	91.4	28.7	102.2	20.3	7.15	4.61	35.5	5.33	25.5
Lowest	82.9	31.8		58.9		3.10	1.11		2.19	
Highest	168.1	156.4		179.7		12.11	8.35		10.6	
LSD$_{.05}$	23	13.3		12.7		0.6	0.5		0.6	

Change percentage (Ch%) = 100(WW-WSF or WSG)/WW , WW=Well watering, WSF= Water stress at floweing, WSG= Water stress at grain filling.

On the contrary, the worst genotypes were No. 22 (Sweepstakes) in 3 traits (GYPP, GYPH, CRL) under WSG, 3 traits (GYPP, GYPH, CRL) under WSF and one trait (GYPH) under WW, the genotype No. 21 (Golden Republic) in 4 traits (BW, BN, RC, RDW) under WSG, two traits (BN,CB) under WWF, the genotype No. 19 (Nebraska) in one trait (CB) under WSG, and 3 traits (CB, RC, RDW) under WWG and the genotype No. 18 (Nubaria) in two traits (CN, RC) under WWG and one trait (GYPP) under WW.

The four highest and the four lowest performing genotypes under water stress at flowering (WSF) and grain filling (WSG) across seasons are presented in Table (6**).** Under WSF conditions, the highest mean grain yield/ha was achieved by the single cross Egaseed-77 (developed by Egaseed Co.), followed by P-3444 (developed by Pioneer Co.), SC 128 (developed by ARC, Egypt) and HT-2066 (developed by Hi Tec Co.) in a descending order. The single cross Egaseed-77 was amongst the four highest genotypes under WSF for GYPH, GYPP, BA and CRL. The single cross P-3444 was amongst the four highest genotypes under WSF for GYPH, GYPP, CN, CB and CRL. The single cross SC-128 was amongst the four highest genotypes under WSF for GYPH, GYPP, BB, CN, CB, RC, and RDW. The single cross HT-2066 was amongst the four highest genotypes under WSF for GYPH, GYPP, CN and RC.

Table 6. The three highest and the three lowest genotypes for studied traits across seasons under drought stress at flowering (WSF) and at grain filling (WSG).

Water stress	Highest			Lowest		
			Brace root whorls No.			
WSF	Pop-45	HT-1100	32D99	Fine 1005	SC-128	Eg-77
WSG	32D99	HT-1100	TWC-360	Eg-77	P-3444	30K09
			Brace root No.			
WSF	32D99	TWC-352	Pop-45	Fine 1005	Midland	Golden
WSG	32D99	TWC-352	HT-1100	P-3444	Eg-77	30K09
			Brace root angle (score)			
WSF	Nebraska	Golden	Fine 1005	SC-128	HT-2066	SC-166
WSG	Nebraska	SC-10	Golden	TWC-352	Giza	TWC-324
			Brace root branching (score)			
WSF	SC-128	TWC-352	SC-166	Golden	Giza	Nebraska
WSG	SC-166	SC-128	P-3444	Nubaria	Wat- 11	Golden
			Crown root number (score)			
WSF	SC-128	P-3444	HT-2066	Eg-77	Sweep	TWC-324
WSG	Fine 1005	HT-2031	SC-128	SC-166	Midland	TWC-324
			Crown root angle (score)			
WSF	Golden	32D99	Midland	TWC-360	P-3444	HT-2031
WSG	32D99	Nebraska	Midland	P-3444	HT-1100	HT-2031
			Crown root branching (score)			
WSF	SC-128	P-3444	TWC-352	Fine 1005	Eg-77	TWC-324
WSG	P-3444	HT-1100	HT-2066	Golden	32D99	TWC-324
			Crown root length (cm)			
WSF	P-3444	SC-166	SC-10	Pop-45	HT-2066	Midland
WSG	Eg-77	P-3444	HT-1100	Nubaria	Golden	Giza
			Root circumference (cm)			
WSF	HT-2066	TWC-352	TWC-352	Nubaria	Midland	Golden
WSG	P-3444	30K09	TWC-352	Nebraska	Midland	Nubaria
			Root dry weight (g)			
WSF	SC-10	Fine 1005	SC-128	Midland	TWC-324	Golden
WSG	P-3444	HT-1100	SC-128	Nebraska	Midland	Nubaria
			Grain yield/plant (g)			
WSF	SC-128	Eg-77	P-3444	Golden	Nebraska	Giza
WSG	P-3444	SC-128	Eg-77	Pop-45	Golden	TWC-352
			Grain yield/ha			

WSF	Eg-77	P-3444	SC-128	Pop-45	Golden	Nebraska
WSG	P-3444	SC-128	TWC-324	Nebraska	TWC-352	Golden

Under WSG conditions, the highest mean grain yield/ha was achieved by the single cross P-3444 (developed by Pioneer) followed by SC-128 (developed by ARC), TWC-324 (developed by ARC) and SC-166 (developed by ARC) in a descending order. The single cross P-3444 was amongst the four highest genotypes in GYPH, GYPP, BB, CB, CRL, RC and RDW, i.e. most important grain yield and root architecture traits. The single cross SC-128 was amongst the four highest genotypes in GYPH, GYPP, BB, CN, CB and RDW (the most important grain yield and root architecture traits). The single cross SC-166 was amongst the four highest genotypes in GYPH and BB.

Results from Tables (4 and 5) concluded that the best genotypes were No. 8 (P-3444) in 5 traits (GYPP, GYPH, CB, RC, RDW) under WSG, 4 traits (CN, CB, RC, RDW) under WWG, 3 traits (CA, CRL, RDW) under WWF and one trait (GYPH) under WW, the genotype No. 6 (SC 128) in 4 traits (GYPP, BB, CA, CB) under WSF, the genotype No.5 (SC 10) in two traits (BB and CRL) under WWF and WWG, respectively, the genotype No. 7 (Hi-Tec 2066) in one trait (RC) under WSF and RC under WWF, the genotype No. 4 (Egaseed 77) in one trait (GYPH) under WSF, and the genotype No. 2 (30K09) in one trait (GYPH) under WSF.

The best genotypes in grain yield under drought at either flowering or grain filling were characterized by one or more desirable root architecture traits. Accumulating genes of more desirable root characteristics in one genotype might help plants to search water and nutrients in the soil and consequently help plant to accomplish its biological activities and achieve almost its potential grain yield under drought stress at flowering or grain filling stages [4, 10, 21-24]. The studied single-cross hybrids P-3444, Egaseed-77 and SC-128 were considered drought tolerant genotypes under drought stress at flowering and/or grain filling stages and would be offered to future breeding programs to utilize their genes of desirable root architecture and grain yield traits in improving maize drought tolerance under Egyptian conditions. It should be mentioned that the hybrid P-3444 was characterized in this experiment by its ability to stay green even under water stress, which might help it to tolerate water stress at grain filling stage in a way much better than other tested hybrids and populations.

3.2. Drought tolerance index

Drought tolerance index (DTI) values of studied genotypes under the stressed environments WSF and WSG are presented in Table (7). According to our scale, when DTI is ≥1.0, it indicates that genotype is tolerant (T), if DTI is 1.0, it indicates that genotype is moderately tolerant (MT) and if DTI is <1.0, it indicates that genotype is sensitive (S).

Based on DTI values, the 22 studied maize genotypes were grouped into three categories under water stress at flowering, namely tolerant (10 genotypes), moderately tolerant (two genotypes) and sensitive (10 genotypes) (Table 7). Under water stress conditions at grain filling, number of tolerant (T), and sensitive (S) genotypes were 11, and 11, respectively.

Table 7. Drought tolerance index (DTI) of studied genotypes across seasons under WSF and WSG.

Genotype	DTI		Genotype	DTI	
	WSF	WSG		WSF	WSG
G1	1.30	1.60	**G12**	1.20	1.20
G2	1.00	1.20	**G13**	1.70	1.70
G3	1.00	1.30	**G14**	0.70	0.60
G4	2.40	1.60	**G15**	0.60	0.40
G5	1.80	1.80	**G16**	0.40	0.50
G6	2.50	2.20	**G17**	0.40	0.50
G7	1.40	0.90	**G18**	0.50	0.60
G8	3.00	3.40	**G19**	0.30	0.30
G9	1.40	1.40	**G20**	0.40	0.40
G10	1.30	1.40	**G21**	0.30	0.30
G11	0.90	0.90	**G22**	0.10	0.20

The highest DTI under both the two stressed environments (WSF and WSG) was exhibited by the genotype No. 8 (P-3444). The 2nd and 3rd highest genotypes in DTI were SC-128 and Egaseed-77 under WSF and SC-128 and SC-10 under WSG. For productivity (grain yield/plant) under WSF, the genotype Egaseed-77 ranked 1st , but P-3444 and SC-128 ranked 3rd. Under WSG, P-3444, SC-128 and SC-10 ranked 1st, 2nd and 3rd, for productivity as well as drought tolerance index.

On the contrary, the most drought sensitive genotypes were the open-pollinated populations Sweepstakes 5303, Golden Republic and Nebraska Midland under both water stress environments (WSF and WSG); their grain yield were the lowest.

3.3. Superiority of drought tolerant (T) to sensitive (S) genotypes

Based on grain yield/plant and drought tolerance index (DTI) the best three genotypes were the single cross hybrids P-3444, SC-128 and Egaseed-77 under WSF and P-3444, SC-128 and SC-10 under WSG, while the most drought sensitive and lowest yielding genotypes were the populations Sweepstakes, Golden Republic and Nebraska Midland under both water stress environments (WSF and WSG). Data averaged for each of the two groups (T and S) under WSF and under WSG indicated that GYPP of drought tolerant (T) was greater than that of the sensitive (S) genotypes by 189.0and 131.3 % under drought at flowering (WSF) and grain filling (WSG), respectively (Table 8).

Table 8. Superiority (Sup.%) of the three most tolerant (T) to the three most sensitive (S) genotypes for selected traits under WSF and WSG across two seasons.

	WSF			WSG		
Trait	**S**	**T**	**Sup. %**	**S**	**T**	**Sup. %**
Root dry weight	10.70	20.10	86.7*	14.60	33.10	126.3**
Crown root number	2.40	4.20	76.7**	2.30	3.40	45.2*
Crown root branching	3.80	5.40	42.6*	2.50	4.60	84.4**
Crown root length	22.90	25.60	11.3*	18.60	23.30	25.4*
Root circumference	28.40	35.60	25.4**	26.40	32.60	23.6*
Grain yield/plant	51.00	147.30	189.0**	68.30	158.10	131.3**

* and ** indicate significance at 0.05 and 0.01 probability levels, respectively.

Significant superiority of drought tolerant (T) over sensitive (S) genotypes in GYPP under drought at flowering and grain filling was associated with significant superiority in higher CN (76.7 and 45.2%), CB (42.6 and 84.4%), higher CRL (11.3 and 25.4 %), higher RC (25.4 and 23.6%) and higher RDW (86.7 and 126.3%), respectively.

3.4. Correlations among drought tolerance index and root traits

Drought tolerance index (DTI) showed a strong, significant ($p \leq 0.01$) and positive correlation with grain yield/plant (r= 0.912** and 0.941**) under WSF and WSG conditions, respectively (Table 9). DTI was significantly and positively correlated with crown root length (r = 0.693** and 0.561**), root circumference (0.440* and 0.499*), root dry weight (r = 0.410* and 0.592**) under WSF and WSG conditions, respectively. Moreover, DTI had a significant and positive correlation coefficient with brace root branching (0.506*) and crown root branching (0.489*) under WSG and with Crown root branching (0.469) under WSF. On the contrary, DTI had a significant and negative correlation coefficient with brace root whorls; BW (-0.598**).

Table 9. Correlation coefficients between DTI and selected studied traits under water stress at flowering (WSF) and at grain filling (WSG) across seasons.

Trait	**WSF**	**WSG**
Crown root number	0.469*	0.320
Crown root branching	0.381	0.489*
Crown root length	0.693**	0.561**
Brace root whorls number	-0.598**	-0.288
Brace root Branching	0.169	0.506*

Root circumference	0.440*	0.499*
Root dry weight	0.410*	0.592**
Grain yield/plant	0.912**	0.941**

* and ** indicate significance at 0.05 and 0.01 probability levels, respectively.

3.5. Correlations among grain yield and root traits

Estimates of rank correlation coefficients among GYPP and selected root traits across two seasons are presented in Table (10). Under WW, GYPP had a significant (p≤0.01) and positive association with the root dry weight (RDW) (0.42), root circumference (RC) (0.43), crown root length (0.26), crown root branching (CB) (0.27), number of crown roots (CN) (0.23) and brace root branching (BB) (0.34). Under WSF, GYPP had significant (P ≤ 0.01) and positive correlation with each of RC (r=0.33) and CN (r=0.27). Under WSG, GYPP was significantly and positively correlated (p≤0.01 or p≤0.05) with CRL (r=0.33), CB (r=0.25), RDW (r=0.23), BB (r=0.18) and RC (r=0.17).

Table 10. Correlation coefficients between grain yield/plant and selected root traits of maize under WW, WSF and WSG across two seasonss.

Trait	WW	WSF	WSG
Branching density of brace roots (BW)	0.34**	0.13	0.18*
Number of crown roots (CN)	0.23**	0.27**	0.21**
Branching density of crown roots (CB)	0.27**	0.08	0.25**
Crown root length (CRL)	0.26**	-0.03	0.33**
Root circumference (RC)	0.43**	0.33**	0.17*
Roots dry weight (RDW)	0.42**	0.13	0.23**

* and ** indicate significance at 0.05 and 0.01 probability levels, respectively, WW= Well watering, WSF= Water stress at flowering, WSG= Water stress at grain filling.

Grouping genotypes

Based on drought tolerance and grain yield

Mean grain yield/ha of studied genotypes under water stress at flowering (WSF) and grain filling (WSG), was plotted against drought tolerance index of the same genotypes under WSF and WSG; respectively (Fig. 2), which made it possible to distinguish between four groups, namely tolerant and high- yielding, tolerant and low-yielding, sensitive and high-yielding and sensitive and low-yielding according to Sattelmacher *et al.* [25], Worku *et al.* [26] and Al-Naggar *et al.* [27, 28].

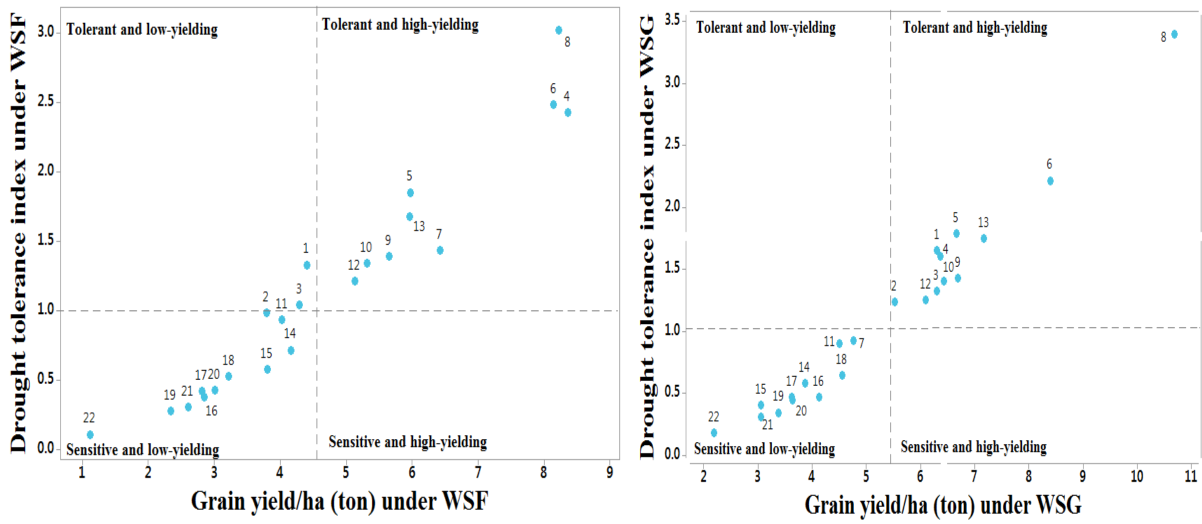


Figure 2. Relationships between drought tolerance index (DTI) and means of GYPH of genotypes (from No.1 to No.22) under water stress at flowering (WSF) and grain filling (WSG) combined across seasons. Broken lines represent mean grain yield/ha and DTI.

Under water stress at flowering (WSF), the genotypes No 8 followed by No. 4, 6, 5, 7, 13, 9, 10 and 12 were classified as the drought tolerant and high yielding genotypes, *i.e.* they could be considered as the most water stress tolerant and the most responsive genotypes to water stress at flowering in this study (Fig. 2). There was no genotype belonging to the group of sensitive and high yielding genotypes under WSF. The genotypes No. 1 and 3 occupied the group of tolerant and low yielding under WSF. The genotypes No 22, 19, 21, 16, 17, 20, 18, 15, 14, 11 and 2 were classified as water stress sensitive and low yielding and therefore could be considered sensitive and low yielding.

Under water stress at grain filling (WSG), the genotypes No. 8 followed by 6, 13, 5, 1, 4, 9, 10, 3, 12 and 2 were classified as drought tolerant and high yielding, they could be considered as the most water stress tolerant and the most responsive genotypes to water stress at grain filling in this study (Fig. 3). On the contrary, genotypes No. 22, 21, 15, 19, 20, 17, 16, 14, 18, 11 and 7 were classified as water stress sensitive and low yielding (Fig. 2).

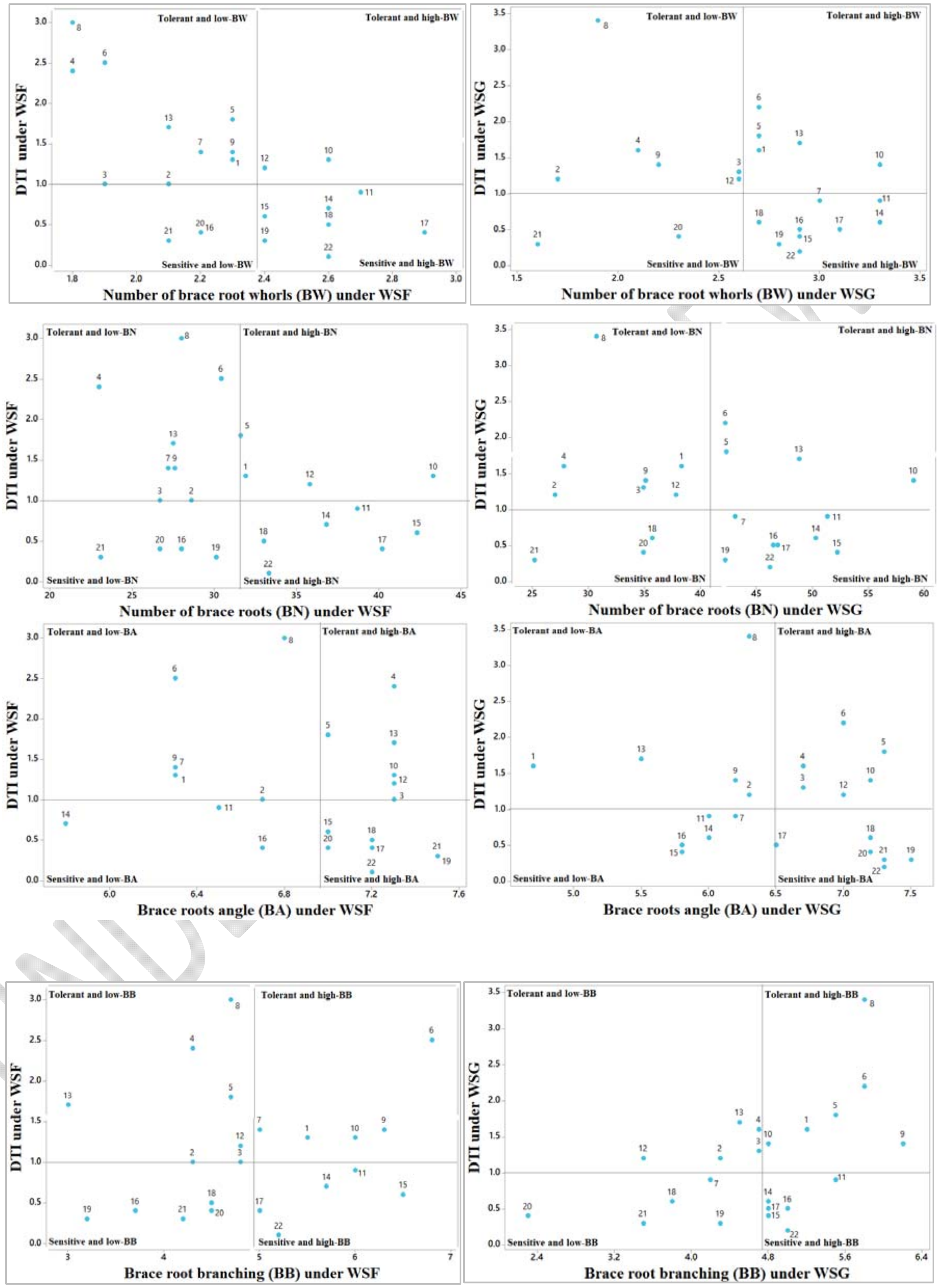
According to Fageria and Baligar [29-31], genotypes belonging to the 1st group "tolerant and high yielding" (above all) and 2nd group "tolerant and low yielding" (to a lesser extent) (we did not have) appear to be the most desirable materials for breeding programs that deal with adaptation to water stress. It was observed that the genotypes No. 8, 6, 4, 13, 5, 9, 10 and 12 occupied the first group (E-R) under both WSF and WSG conditions; they had genes of high water efficiency; i.e. drought tolerance to both WSF and WSG stages and genes for high yield under well watering conditions.

Summarizing the above-mentioned classifications, it is apparent that the genotypes No. 8 (P-3444) followed by 6 (SC-128), 4 (Egaseed-77), 5 (SC-10),13 (TWC-324), 7 (Hi Tec-2066), 9 (SC-166), 10 (P-32D99) and 12 (Watania 11) were the best genotypes that occupied the first group (best one) in both classifications; they are the most efficient, most drought tolerant, the highest yielder under WSF as well as WW. The genotypes No. 8 (P-3444) followed by 6 (SC-128), 13 (TWC-324), 5 (SC-10),1 (Hi Tec-2031),4 (Egaseed-77), 9 (SC-166),10 (P-32D99), 3 (Fine 1005), 12 (Watania 11) and 2 (P-30K09) were the best genotypes that occupied the first group (best one) in both classifications; they are the most efficient, most drought tolerant, the highest yielder under WSG as well as WW.

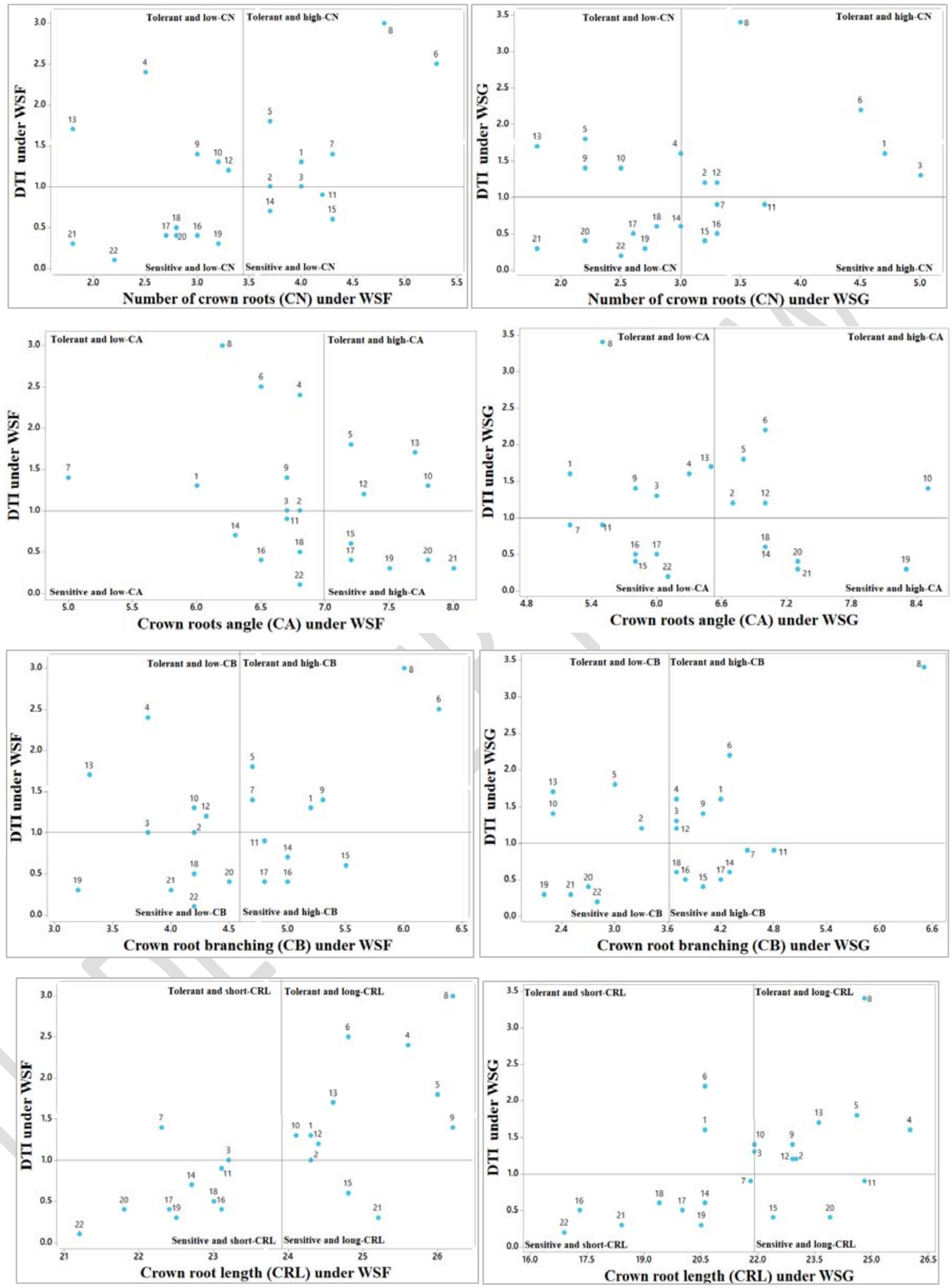
It was observed that the genotypes No 8 (P-3444) followed by 6 (SC-128), 4 (Egaseed-77), 5 (SC-10), 13 (TWC-324), 7 (Hi Tec-2066), 9 (SC-166), 10 (P-32D99) and 12 (Watania 11) were the best in the first group for both stresses WSF and WSG; they are the most efficient, most drought tolerant and the highest yielders under WSF and WSG as well as WW. In accordance to these results, a previous study by Al-Naggar *et al*. [17], proved that the single cross hybrid SC-128 (genotype No. 6 in the present study) was the most water efficient (drought tolerant) under WSF and the most responsive to WW based on grain yield, ears/plant, kernels/ plant, ASI and leaf senescence.

Based on drought tolerance and root traits

Means of root traits of studied genotypes under water stress at flowering (WSF) and grain filling (WSG), were plotted against drought tolerance index (DTI) of the same genotypes under WSF and WSG; respectively (Fig. 3), which made it possible to distinguish between four groups, namely tolerant and high value of root trait, tolerant and low value of root trait, sensitive and high value of root trait and sensitive and low value of root trait. According to Fageria and Baligar [30], genotypes belonging to the 1st group "tolerant and high value of root trait" (above all) appear to be the most desirable materials for breeding programs.



Tolerant and low-BW
Tolerant and high-BW
Sensitive and low-BW
Sensitive and high-BW
DTI under WSF
Number of brace root whorls (BW) under WSF
DTI under WSG
Number of brace root whorls (BW) under WSG
Tolerant and low-BN
Tolerant and high-BN
Sensitive and low-BN
Sensitive and high-BN
Number of brace roots (BN) under WSF
Number of brace roots (BN) under WSG
Tolerant and low-BA
Tolerant and high-BA
Sensitive and low-BA
Sensitive and high-BA
Brace roots angle (BA) under WSF
Brace roots angle (BA) under WSG
Tolerant and low-BB
Tolerant and high-BB
Sensitive and low-BB
Sensitive and high-BB
Brace root branching (BB) under WSF
Brace root branching (BB) under WSG


Tolerant and low-CN
Tolerant and high-CN
Sensitive and low-CN
Sensitive and low-CN
DTI under WSF
Number of crown roots (CN) under WSF
Tolerant and low-CN
Tolerant and high-CN
Sensitive and low-CN
Sensitive and high-CN
DTI under WSG
Number of crown roots (CN) under WSG
Tolerant and low-CA
Tolerant and high-CA
Sensitive and low-CA
Sensitive and high-CA
DTI under WSF
Crown roots angle (CA) under WSF
Tolerant and low-CA
Tolerant and high-CA
Sensitive and low-CA
Sensitive and high-CA
DTI under WSG
Crown roots angle (CA) under WSG
Tolerant and low-CB
Tolerant and high-CB
Sensitive and low-CB
Sensitive and high-CB
DTI under WSF
Crown root branching (CB) under WSF
Tolerant and low-CB
Tolerant and high-CB
Sensitive and low-CB
Sensitive and high-CB
DTI under WSG
Crown root branching (CB) under WSG
Tolerant and short-CRL
Tolerant and long-CRL
Sensitive and short-CRL
Sensitive and long-CRL
DTI under WSF
Crown root length (CRL) under WSF
Tolerant and short-CRL
Tolerant and long-CRL
Sensitive and short-CRL
Sensitive and long-CRL
DTI under WSG
Crown root length (CRL) under WSG

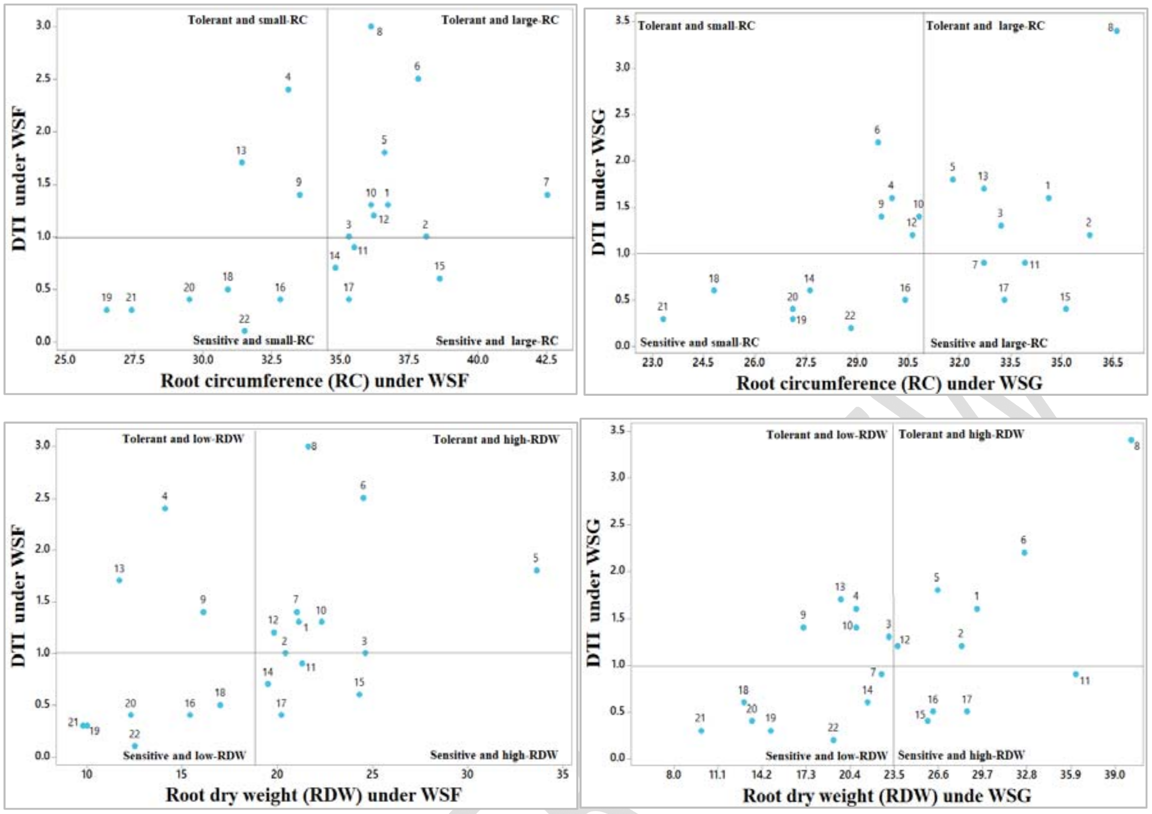


Figure 3. Relationships between drought tolerance index (DTI) and means of number of whorls carrying brace roots, brace root branching, crown root number, crown root branching, root circumference, crown root length, and root dry weight, of genotypes (from No. 1 to No.22) under water stress at flowering (WSF) and grain filling (WSG) combined across seasons. Broken lines represent mean DTI and root trait.

Figure (3) indicates that the 1st group "tolerant and high value of root trait" included the genotypes No. 10 and 12 under WSF, No. 10, 13, 6, 5 and 1 under WSG for number of whorls carrying brace roots, No. 10, 12, 1 and 5 under WSF, No. 10, 13, 1, 5 and 6 under WSG for number of brace roots, No. 4, 13, 10, 12, 3 and 5 under WSF, No. 5, 6, 10, 12, 4 and 3 under WSG for brace root angle, No. 6, 9, 10, 1 and 7 under WSF, No. 9, 6, 5, 1 and 10 under WSG for brace root branching, No. 6, 8, 7, 1, 5, 3 and 2 under WSF, No. 3, 1, 6, 8, 12 and 2 under WSG for number of crown roots, No. 10, 13, 12 and 5 under WSF, No. 10, 6, 12, 5 and 2 under WSG for crown root angle, No. 6, 8, 9, 1, 7 and 5 under WSF, No. 8, 6, 1, 9, 4, 3 and 12 under WSG for crown root branching, No. 8, 4, 5, 6, 9, 12, 1, 10 and 2 under WSF, No. 8, 4, 5, 13, 9, 2, 3, 10 and 12 under WSG for crown root length, No. 7, 6, 8, 5, 1, 10, 12, 2 and 3 under WSF, No. 8, 2, 1, 3, 13 and 5 under WSG for root circumference and No. 5, 6, 8, 10, 7, 1, 12, 3 and 2 under WSF, No. 8, 6, 1, 5, 2 and 12 under WSG for root dry weight.

Mechanisms of drought tolerance of the most tolerant and high-yielding genotypes:

The above-mentioned results (Figs. 2 and 3) helped us to identify the root traits that characterize the most drought tolerant and high-yielding genotypes, in descending order, as follows:

1. Genotype No. 8 (SC-P-3444): Five traits (high CN, CB, large RC, long CRL and heavy RDW) under both WSF and WSG.

2. Genotype No. 6 (SC-128): Four traits (high CN, CB, BB, large RC and heavy RDW)under both WSF and WSG.

3. Genotype No. 4 (SC-Egaseed-77): Two traits (steep brace root; i.e. large BA and long CRL) under both WSF and WSG.

4. Genotype No. 5 (SC-10): Six traits (high CN, CB, BA,RC, long CRL and heavy RDW) under WSF and five traits (high BA, CA, large RC, long CRL and heavy RDW) under WSG.

5. Genotype No. 13 (TWC-324): Two traits (steep brace root; i.e. large BA and long crown root (CRL) under WSF and two traits (large RC and long CRL) under WSG.

6. Genotype No. 9 (SC-166): Two traits (high CB and long crown root CRL) under both WSF and WSG.

7. Genotype No. 10 (SC-P-32D99): Four traits (steep crown root; CA steep brace root; BA, long crown root; CRL and heavy root dry weight; RDW) under both WSF and WSG and one trait (heavy RDW) under WSF.

8. Genotype No. 12 (Watania TWC-11): Seven traits (BW, BN, BA, CA, CRL, RC and RDW) under WSF and six traits (BA, CN, CA, CB, CRL and RDW) under WSG.

The present study suggested that further investigation should be conducted to determine the underlying root mechanisms contributing to the selection of water-efficient hybrids of maize. In a recent study [32], maize genotypes with less variation in root size, medium root size, medium broad root system and more inter-row root distribution help to reduce root-to-root competition and tend to have higher yield at high planting density.

CONCLUSIONS

Correlation analysis of the present study concluded that drought tolerance in maize had a strong and positive association with crown root length, root circumference and root dry weight under both WSF and WSG, a negative correlation with brace root whorls, and a positive correlation with crown root number under WSF and brace root branching and crown root branching under WSG. These root traits could be considered as putative mechanisms of drought tolerance. The present study suggested that further investigation should be conducted to determine the underlying plant mechanisms contributing to the selection of water-efficient hybrids of maize. The cultivars Pioneer-3444, SC-128, Egaseed-77, SC-10 and TWC-324 showed the most drought tolerance and the highest yielding in a descending order; each had a number of such drought tolerance mechanisms. These cultivars should be retested for drought tolerance and grain productivity under drought stress and could be offered to plant breeding programs for improving tolerance to drought and high grain yield.

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