Effects of drought and salinity on maize phenology, morphology and productivity in a semi-arid environment

Romdhane Leila[1,2], Dal Cortivo Cristian[3], Vamerali Teofilo[3], Radhouane Leila[2]*

Abstract: *In a field trial in Tunisia, the effects of drought and salinity on maize phenology, shoot and root characteristics, and productivity were examined after the following treatments: two sub-optimal irrigation levels (70% and 35% ETM), with standard water quality; two levels of water salinity (3 and 6 g NaCl L^{-1}) at 100% ETM, compared with optimal water supply (100% ETM, control) and standard quality. We demonstrate here that both drought and salinity greatly change phenology, with the result that both silking and physiological maturity are reached much earlier. The extreme condition is the most severe drought, resulting in 10 and 12 days anticipation respectively, although with compromised yield (-84% vs. controls). Irrigation at 70% ETM turned out to be a sustainable practice, with limited changes in phenology but with a fall in yield of 22%. The vegetative habitus of the plants was very stable towards salinity, although yield losses were considerable, i.e., 25% and 73% at moderate and high salinity, respectively, due to marked reduction of cob fertility. Extreme drought impaired root weight, whereas salinity did not affect this root trait. Principal component and discriminant analyses identified above-ground the number of kernels per ear and kernel weight, and below-ground the number of main roots as the key traits in sustaining maize productivity. We conclude that moderate water or salinity stress allows silking time to be scheduled, for more efficient water management in the sensitive growth stages of maize. Thorough screening of genotypes at below-ground level also seems to be helpful to improve water use efficiency and tolerance to conditions of extreme drought and salinity.*

Keywords: *Drought; shoot growth dynamics; maize; phenology; root growth; salinity.*

Riassunto: *In una sperimentazione di pieno campo condotta in Tunisia sono stati studiati gli effetti dello stress idrico e salino sulla fenologia, sulle caratteristiche morfologiche della parte aerea e radicale, e sulla produttività del mais, considerando i seguenti trattamenti: due livelli sub-ottimali di rifornimento idrico (70 e 35% dell'ETM) con elevato standard qualitativo, due livelli di salinità dell'acqua (3 e 6 g NaCl L^{-1}) applicati al 100% dell'ETM, in raffronto a volumi irrigui e qualità dell'acqua ottimali (100% ETM, controllo). Sia lo stress idrico che salino hanno causato un largo anticipo dell'epoca di fioritura e di maturazione, con effetti più marcati in condizioni di stress idrico severo (-10 e -12 giorni rispetto al controllo, rispettivamente), condizione associata ad una forte contrazione della resa (-84%). L'irrigazione al 70% dell'ETM è risultata una tecnica sostenibile, potendo influenzare solo lievemente la fenologia, ma con una ripercussione negativa sulla resa del 22%. L'accrescimento epigeo è risultato molto stabile nei confronti dello stress salino, ma associato ad una contrazione produttiva marcata, del 25% e 73%, rispettivamente a moderata ed elevata salinità, a causa della modesta fertilità della spiga. A livello radicale si è avuta una contrazione di biomassa con lo stress idrico e nessuna variazione con quello salino. L'analisi delle componenti principali e l'analisi discriminante hanno evidenziato il numero di cariossidi per spiga e il peso delle singole cariossidi a livello epigeo, e il numero di radici a livello radicale, quali fattori chiave per sostenere la produttività della coltura. Si conclude che, la programmazione di uno stress idrico o salino moderato può consentire di modulare il periodo di fioritura permettendo una più efficiente gestione della risorsa idrica nelle fasi più sensibili del mais. Il ruolo dell'apparato radicale nei confronti di questi due stress abiotici, suggerisce di approfondire lo studio sulla caratterizzazione varietale a livello radicale per migliorare l'efficienza d'uso dell'acqua e la tolleranza allo stress salino.*

Parole chiave: *Siccità; dinamica di accrescimento epigeo; mais; fenologia; accrescimento radicale; salinità.*

1. INTRODUCTION

Abiotic stress in agriculture is giving rise to worldwide concern among scientists and farmers, due to its increasing incidence within a context of climate change. There is awareness that variations in rainfall patterns and temperature dynamics can seriously affect field crops and compromise productivity, due to increased drought and salinisation of agricultural land (Sarr *et al.*, 2011). According to scenarios for climate change (IPCC, 2007), all these perturbations are predicted to become more accentuated in semi-arid areas, where competition for water resources for other human activities is also expected.

Drought and salt stress are common threats for plant growth, development and survival in several

---

[*] Corresponding author's e-mail: teofilo.vamerali@unipd.it

[1] Department of Life Sciences, Faculty of Sciences of Bizerte, Jarzouna 7021, Bizerte, University of Carthage, Tunis, Tunisia.

[2] Laboratory of Agronomic Sciences and Technical, National Institute of Agronomic Research of Tunisia, Hedi Karray Street, Ariana 2049, Tunisia.

[3] Department of Agronomy, Food, Natural Resources, Animals and the Environment, University of Padova, Legnaro (Padova), Italy.

Received 30 March 2016, accepted 10 June 2016

DOI:10.19199/2016.3.2038-5625.043

species (Munns and Tester, 2008; Ouda *et al.*, 2008; Carpici *et al.*, 2010). Maize (*Zea mays* L.) is considered moderately salt-sensitive (Passioura, 2007) but very susceptible to drought, especially in the 2-3 weeks after silking (Ghobadi *et al.*, 2006). Maize is expected to be progressively constrained by reduced water availability in more extensive areas of the world, due to climatic variations and the more rational use of water resources. This is a substantial problem in Tunisia and other Mediterranean countries, where water resources are scarce and competition from other users is gradually increasing. In such conditions, water use efficiency must be improved and plant responses to reduced water supply and quality due to increased salinity must be studied in greater depth. Better understanding of the effects of water availability on crop phenology would thus be helpful in predicting the timing of critical growth stages, in order to schedule agricultural practices more appropriately and reduce damage to yields. At the same time, the consequences of salt water resources supplied to maize must be ascertained, in order to verify if they can replace optimal-quality water.

Within this framework, we studied the influence of both moderate and severe drought and salinity stress on the dynamics of plant growth, productivity and changes in the timing of phenological stages. We also studied related root characteristics and yield components, in order to identify suitable above- and below-ground traits which protect maize productivity in semi-arid environments.

2. MATERIALS AND METHODS

2.1. Experimental set-up

The experiment was carried out between May and September 2013, at the experimental farm of the National Institute of Agronomic Research of Tunisia (INRAT) at Ariana (Tunis) with the Naudi maize hybrid (FAO class 400; Caussade Semences, France), cultivated for about 4 months. Sowing took place on May 14 and harvest on September 15. Five treatments were compared: optimal water supply (control, 100% ETM), two sub-optimal water regimes (70% and 35% ETM) with standard water quality (<1 g NaCl L^{-1}), and two salinity levels (3 and 6 g NaCl L^{-1}) applied through optimal water supply (100% ETM), as follows:

T100: irrigation at 100% ETM;
T70: irrigation at 70% ETM;
T35: irrigation at 35% ETM.
T3: treatment T100 with salty water (3 g L^{-1} NaCl), EC 5.7 mS cm^{-1} and ψ -0.23 MPa;
T6: treatment T100 with very salty water (6 g L^{-1}), EC 10.9 mS cm^{-1} and ψ -0.46 MPa.

The trial was conducted in a typical semi-arid climate with loamy alkaline soil (pH 8.2) (Tab. 1). The experiment had a strip-plot design with three replicates. Each plot covered an area of 2 m^2 (2 m in length, 1 m in width) and was planted with 4 rows 0.5 m apart, with a distance of 1 m between replicates and 3 m between treatments. Sowing density was 25 seeds m^{-2}, thinned to a final density of 9 plants m^{-2} after emergence, giving a distance of 0.22 m between the plants on the row.

The sowing scheme and agronomic practices mimicked local large-scale management in maize cultivation. Soil was ploughed to a depth of 0.3 m in April 2013 and harrowed at 0.2 m just before sowing. Pre-sowing fertilisation of 100 kg N ha^{-1} was incorporated through harrowing, and an additional amount of 100 kg N ha^{-1} was dress-applied at the beginning of stem elongation (4-5-leaf stage). Weeds were

Physical properties (% of DW)	Parameter (%)	Hydraulic properties (%)
Clay = 21	Limestone = 13	Field Capacity (FC) = 35
Fine silt = 48	Total N = 0.08	Wilting point (Wp) = 23
Coarse silt = 6	Total P (as P_2O_5) = 4	Available water = 12
Fine sand = 13	Assimilable P (as P_2O_5) = 0.01	
Coarse sand = 10	Total K (as K_2O) = 3.87	
Gravel = 2	Exchangeable K (as K_2O) = 0.94	

Tab. 1 - Physical, chemical and hydraulic properties of experimental soil at Ariana (Tunis, Tunisia).
Tab. 1 - Principali caratteristiche chimico-fisiche del terreno del sito sperimentale INRAT (Tunisia).

	T100	T70	T35	T3	T6
May 20	25	25	25	25	25
June 1	25	25	25	25	25
June 11	50	34	15	50	50
June 21	50	34	15	50	50
July 1	50	34	15	50	50
July 10	50	34	15	50	50
July 17	50	34	15	50	50
July 24	50	34	15	50	50
July 31	50	34	15	50	50
August 7	50	34	15	50	50
August 14	50	34	15	50	50
August 21	50	34	15	50	50
August 28	50	34	15	50	50
TOTAL	600	424	215	600	600
% ETM	100	70.7	35.8	100	100

Tab. 2 - Irrigation time and water amount (mm) under contrasting irrigation regimes and water salinity.
Silking time (50% of plants): 14 July (T100), 12 July (T70), July 7 (T35), July 9 (T3) and July 4 (T6).
T100: irrigated at 100% ETM; T70: irrigated at 70% ETM; T35: irrigated at 35% ETM; T3: moderate salinity (3 g NaCl L^{-1}) at 100% ETM; T6: severe salinity (6 g NaCl L^{-1}) at 100% ETM

Tab. 2 - Date e volume di irrigazione nei diversi trattamenti di stress idrico e salino.
Emissione delle sete fiorali (50% delle piante): 14 Luglio (T100), 12 Luglio (T70), 7 Luglio (T35), 9 Luglio (T3) e 4 luglio (T6).
T100: apporto irriguo al 100% ETM; T70: apporto irriguo al 70% ETM; T35: apporto irriguo al 35% ETM; T3: salinità moderata (3 g NaCl L^{-1}) al 100% ETM; T6: salinità elevata (6 g NaCl L^{-1}) al 100% ETM.

controlled manually, by hoeing the experimental area twice, the first after crop emergence and the second at N supply.

In the water stress treatments, the required water rate was applied according to the level of drought. The theoretical amount of water needed for optimal maize growth and full productivity was estimated following Sarr *et al.*, (1999) at 600 mm (ETM=100%). Irrigation water in treatments T100, T70 and T35 had <1 g NaCl L^{-1}, corresponding to electrical conductivity (EC) <2 mS cm^{-1} and osmotic pressure (y) of about -0.08 MPa; for treatments T3 and T6, EC was 5.7 and 10.9 mS cm^{-1}, respectively.

Uniform distribution of irrigation water in each plot was achieved by surface flooding, thanks to small banks surrounding each plot. Water was delivered to the plots directly from the tap for drought stress and from a pump connected to a tube for salt stress, after the experimental levels of salinity in a large tank had been established. From sowing to the 4-leaf stage (about June 11), when water and salinity stresses started, all plots received two irrigations of 25 mm. Thereafter, they were irrigated at 10-day intervals until silking, and thereafter weekly, each time with 50 mm (T100, T3 and T6), 34 mm (T70) or 15 mm (T35) (Tab. 2). In the case of salt stress, treatments T3 and T6 received the same amounts of water (100% ETM) but at different levels of salinity.

Total rainfall during the crop cycle was 133 mm, but was negligible from sowing to mid-August (only 14 mm). As most rain fell very close to moment for harvest (Fig. 1), precipitation was not included in the water balance. The mean daily temperature across the crop cycle was 25.7 °C, with maximum temperatures greatly exceeding 30 °C for most of July and August.

2.2. Study parameters

Phenological stages including tasselling (VT), silking (R1) and physiological maturity (R6) were recorded in each replicate when 50% of the plants had reached the specific stage, according to the leaf collar method (Abendroth *et al.*,

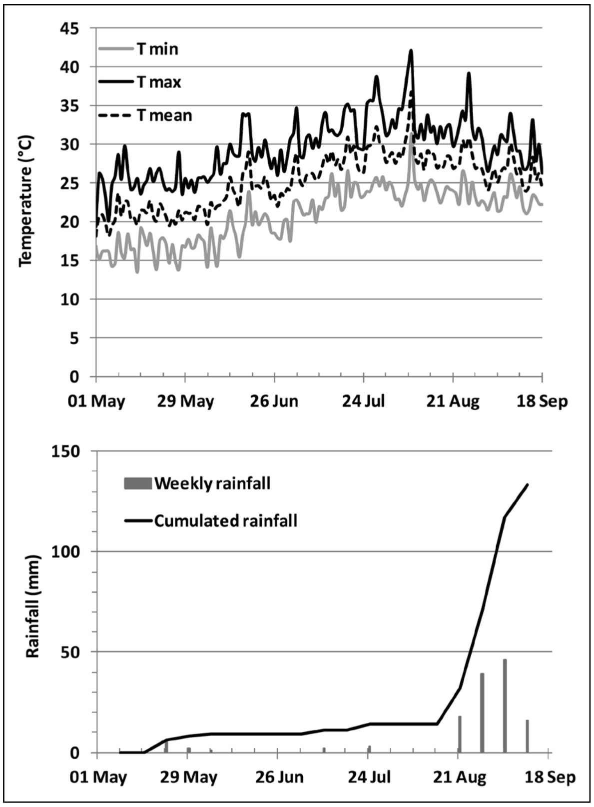


Fig. 1 - Dynamics of daily minimum, maximum and mean temperatures (above) and rainfall (below) during maize cycle at experimental site of Ariana (Tunis) in 2013.
Fig. 1 - Andamento delle temperature minime, massime e medie giornaliere (sopra) e piovosità (sotto) presso il sito sperimentale di Ariana (Tunisi) durante il ciclo colturale del mais nel 2013.

2011). In order to model maize growth, plant height was measured weekly until 13 August in 5 plants per plot (n = 3). Data were regressed with the Gompertz model, which explained >99% of variance in all treatments (Fig. 2). The equation estimates plant height (H) as a function of time (x) as follows:

$$H = a + ce^{-e^{-b^{(x - m)}}}$$

where a, b and m are empirical coefficients.

At harvest, all the plants from the two central rows of each plot (n = 3) were collected, to calculate grain yield per hectare. Five ears from each plot (n = 3) were used to determine the main yield components, i.e., length, diameter, and the thousand kernel weight (TKW) and total kernel weight per ear. Ears were manually shelled and a seed-counter was used to measure TKW.

At the same time, the root system of two plants per plot (n = 3) was studied with the destructive monolith destructive method, applied to a soil surface area of 0.2 × 0.2 m (with a plant in the centre) and a depth of 0.2 m. Samples were washed in a centrifuge device to separate roots from soil particles. Roots were collected in a sieve (500-µm mesh), to determine the number and length of the main roots, which were measured automatically by KS300 software (Carl Zeiss Vision GmbH, München, Germany) in 1-bit 400 DPI TIFF images acquired through a flatbed scanner (Epson Expression 10000XL, Canada), according to the method of Vamerali *et al.*, (2003). Thereafter, root weight was recorded after sample drying (105°C, 48 h). The specific root length (SRL) was calculated as the ratio between root length and weight.

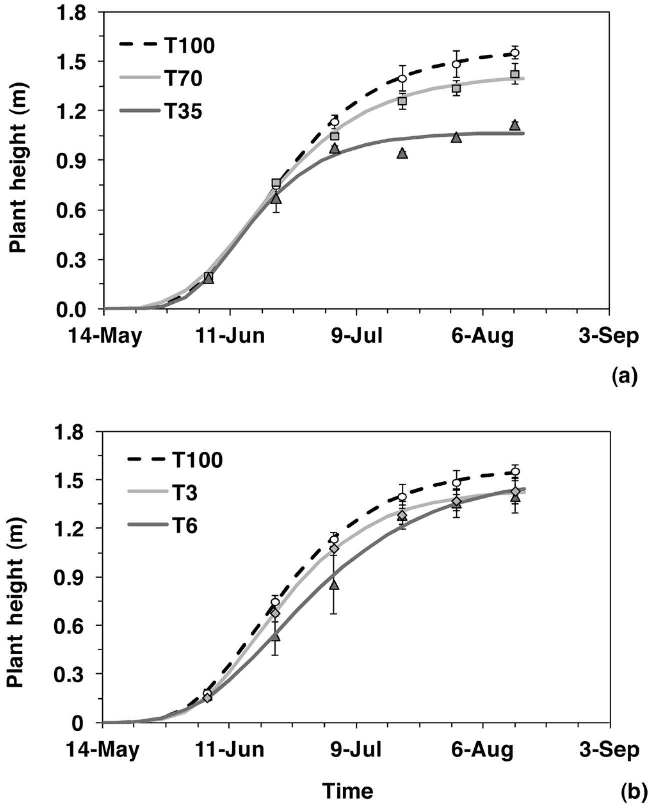
2.3. Statistical analysis

Statistical analysis was applied to the whole data set, which included 3 replicates for each parameter and treatment. After data normality and variance homogeneity had been checked, ANOVA and the Newman-Keuls test ($P \leq 0.05$) were used to evaluate differences among means for all parameters.

In order to facilitate the interpretation of plant responses to drought and salinity, multivariate statistical analysis was used to reduce the number of variables by PCA (principal component analysis). Data were preliminarily standardised by subtracting the means and dividing by the standard deviations within each variable. Factorial discriminate analysis (MDA, Multigroup Discriminate Analysis, with Wilks' lambda and Pillai's trace tests) and PCA were applied to describe treatments based on yield components (cob size and productivity), shoot parameters (height and biomass), root characteristics (weight, number of roots, SRL) and duration of ripening. Multivariate data normality was preliminarily verified by the Shapiro test. All analyses were performed with MS Excel XLSTAT (Addinsoft, Paris, France).

3. RESULTS AND DISCUSSION

Phenological changes in plants are generally the most important detectable effects in adverse environmental conditions. Under stress, plants generally tend to reduce yield losses by changing the duration of their vegetative and reproductive growth (Golabadi *et al.*, 2008). The period of each developmental stage depends on several factors, such as genotype, temperature, day length and sowing date. As Tab. 3 shows, phenological traits,



	T100	T70	T35	T3	T6
c	1.58±0.01	1.42±0.03	1.07±0.04	1.44±0.01	1.53±0.08
b	0.0668±2.03×10^{-3}	0.0672±5.92×10^{-3}	0.0907±0.0155	0.0713±2.24×10^{-3}	0.0537±7.47×10^{-3}
m	46.0±0.30	44.0±	41.0±1.46	46.0±	50.6±1.58
R^2 (%)	99.9	99.9	99.7	99.9	99.8

Fig. 2 - Dynamics of plant height over time (Gompertz model) under reduced water supply (a) and salinity stress (b). Vertical bars: standard error. Regression coefficients (±S.E.) and coefficient of determination reported below.
T100: irrigated at 100% ETM; T70: irrigated at 70% ETM; T35: irrigated at 35% ETM; T3: moderate salinity (3 g NaCl L^{-1}) at 100% ETM; T6: severe salinity (6 g NaCl L^{-1}) at 100% ETM.

Fig. 2 - Dinamica dell'accrescimento epigeo (altezza) nel corso della stagione di crescita in condizioni di stress idrico (a) e salino (b).Barre verticali: errore standard. Coefficienti di regressione (±S.E.) e di determinazione riportati sotto.
T100: apporto irriguo al 100% ETM; T70: apporto irriguo al 70% ETM; T35: apporto irriguo al 35% ETM; T3: salinità moderata (3 g NaCl L^{-1}) al 100% ETM; T6: salinità elevata (6 g NaCl L^{-1}) al 100% ETM.

including days to silking (R1) and physiological maturity (R6), were shortened in both drought treatments T70 and T35, with maximum effect in the most intense stress conditions, plants in treatment T35 reaching R1 almost 7 days earlier than well-watered plants (T100).

Various environmental stresses, particularly heat, but also water deficit and salinity, may shorten growth phases in maize (Acevedo *et al.*, 2002). Some studies have shown similar results to those presented here, confirming that drought shortens the duration of vegetative growth and that maturity is also anticipated if the stress persists (Neumann, 1995; Ghobadi *et al.*, 2006; Moriondo and Bindi, 2008).

The influence of salinity on the growing dynamics of the Naudi hybrid (Tab. 3) was slightly greater than that of the lack of water, with longer anticipation of silking under severe salt stress (6 g NaCl L^{-1}). At this salinity level, silking occurred 10 days earlier than in controls and 3 days earlier than in severe drought conditions (35% ETM).

Treatment	Time to silking (days)	Time to physiological maturity (days)	Ripening time (days)	Plant height (m)	Shoot DW (stem+leaves) (g plant^{-1})
T100	60 a	101 a	41 a	1.56 a	56.5 (a)
T70	58 a	92 b	34 b	1.43 b	45.3 (a)
T35	53b	84 c	31 b	1.09 c	36.8 (b)
T3	55b	86 c	31 b	1.44 b	51.1 (a)
T6	50 c	89 c	39 a	1.41b	38.8 (b)

Tab. 3 - Duration of two main phenological phases (from sowing), ripening time, and final plant height and biomass (harvest time). Letters: statistically significant differences between treatments within same parameter (Newman-Keuls test, P≤0.05). T100: irrigated at 100% ETM; T70: irrigated at 70% ETM; T35: irrigated at 35% ETM; T3: moderate salinity (3 g NaCl L^{-1}) at 100% ETM; T6: severe salinity (6 g NaCl L^{-1}) at 100% ETM.

Tab. 3 - Durata di due fasi fenologiche (dalla semina) e del periodo di riempimento, e altezza e peso finale delle piante (raccolta). Lettere: differenze statisticamente significative tra i trattamenti per ciascun parametro (Test Newman-Keuls test, P≤0,05). T100: apporto irriguo al 100% ETM; T70: apporto irriguo al 70% ETM; T35: apporto irriguo al 35% ETM; T3: salinità moderata (3 g NaCl L^{-1}) al 100% ETM; T6: salinità elevata (6 g NaCl L^{-1}) al 100% ETM.

These results match those of previous researches, as one response of many cereals under salinity is reaching maturity earlier than unstressed plants, although the stages of both silking and maturity are generally anticipated more with drought than with salinity. Matching our results, Azizian and Sepaskhah (2014) reported a stronger effect of salinity than drought on phenology in a maize crop studied over a two-year period. In our trial, the time difference for reaching physiological maturity between controls and maize plants subjected to salinity, regardless of its intensity, was almost 2 weeks, and even more (17 days) between controls and the most severe drought (T35).

Under salinity, accelerated flowering has also been observed in other cereals, such as wheat, by various authors (Francois *et al.*, 1986; Grieve *et al.*, 1994; Kafi, 2001; Argentel *et al.*, 2008). In wheat, the effects of salt stress depend on the growth stage at which it occurs, high salinity levels reducing the time from sowing to maturity by shortening the duration of specific growth stages, i.e., spikelet initiation, booting, heading, and anthesis (Grieve *et al.*, 1994; Acevedo *et al.*, 2002). On the contrary, a delay in flowering with increased salinity has been found in *Sinapis arvensis* (Stanton *et al.*, 2000) and *Brassica napus* (Bybordi, 2010; Valiollah and Mahyar, 2015), although the period to maturity tended to decrease. In maize, germination and early growth are more sensitive to salinity than during later developmental stages, because of reduced water uptake and embryo toxicity by sodium (Farooq *et al.*, 2015). Although the supply of salt water started after plant establishment in our study, the toxic effects of sodium are expected to change plant ontogeny by reducing shoot internode growth and suppressing leaf initiation and expansion, as well by accelerating leaf abscission (Rios-Gonzale *et al.*, 2002).

As regards growth evolution during leaf formation, plant height was observed to remain unaffected under moderate drought (T70) until tasselling VT (about end-June). However, after two weeks of stress, plant height was about 0.1 m lower than controls, forming the final plateau at 1.42 m compared with 1.58 m for controls (Fig. 2a). Instead, severe drought reduced plant height from the beginning of water stress, and the plants achieved their final height (1.07 m) very slowly (Fig. 2a). The sensitivity of maize to intense drought stress was responsible for the marked reduction in plant height, which is commonly related to reduced photosynthetic activity. The depressive effect of water shortage on plant height has previously been reported in C_4 cereals (Radhouane, 2008), especially in maize (Farré and Faci, 2009; Aydinsakir *et al.*, 2013). According to Poss *et al.*, (1988), the greatest sensitivity of this crop towards drought ranges from 20 days before silking to 10-15 days after it, and water deficits in this crucial phase lead to yield losses generally exceeding 60%.

Fig. 2b shows the response of maize growth to salinity. The moderate level (3 g NaCl L^{-1}) slightly reduced plant height (-0.05 m vs. controls) in the vegetative phase, although the difference became more accentuated in the tasselling stage, forming a linear plateau at 1.44 m vs. 1.58 m in controls. The final effect of severe salinity was similar to that of the moderate level, but the dynamics differed, since the plants were almost 0.2 m shorter for most of the vegetative phase until tasselling.

Salinity is known to have a negative impact on maize growth and development (Chaum and Kirdmanee, 2009; Farooq *et al.*, 2015) and plant height (Hasanuzzaman *et al.*, 2013), although there are few reports on the effects of salt on the reproductive phase and yield in this species (Kaya *et al.*, 2013; Azizian and Sepaskhah, 2014; Farooq *et al.*, 2015). Excessive salinity and extreme drought often shorten the crop cycle and reduce plant growth (Henry *et al.*, 2015). The sudden decrease in turgor pressure are certainly responsible for growth inhibition induced by rapid increases in external solute concentrations (Volkmar *et al.*, 1998). Saline solutions also affect cell growth directly, although the exact mechanism involved is still unclear (Ashraf and McNeilly, 2004). Under salinity stress, sodium and chloride are taken up to excess, causing severe nutritional imbalances of essential mineral elements such as potassium, calcium, nitrogen, phosphorus, magnesium, iron, manganese, copper and zinc, which alter growth (Turan *et al.*, 2010).

Final plant height, as estimated by the Gompertz model, was very similar to the actual values found (Tab. 2). The fitting model provided further information on the growth rate; coefficient m (time needed to reach 50% of maximum height) generally fitted the hierarchy in flowering time, being greater in T100 controls than in drought treatments, but similar to moderate salinity T3. This coefficient was higher in T6 than controls only, because of the slow initial growth rate which characterised the severe salinity treatment.

Shoot biomass (stem + leaves) at harvest followed almost the same trend as plant height (Tab. 3), with reduced values in conditions of extreme drought (T35) and salinity (T6).

In the below-ground compartment, root biomass in the top 0.2-m soil layer was unaffected by moderate water stress, but significantly reduced (-30%) under severe drought (Tab. 4), a result frequently found in maize (Farré and Faci, 2009; Yamaguchi and Sharp, 2010) and other crops, such as sugar beet (Vamerali *et al.*, 2009). Under salinity, root weight did not differ from that of controls, regardless of stress intensity, although stressed plants had slightly greater root biomass. A similar response was found for other root parameters, e.g., length, number of main roots and specific root length (SRL) (Tab. 4). The condition most similar to that of controls was verified under moderate salinity and concerned the number of roots per plant.

Several studies report inhibition of root growth after salinity stress in various crops (Bernstein *et al.*, 1993; Jamil *et al.*, 2005; Tas and Basar, 2009), although at salt levels which inhibit shoot growth, root growth is often unaffected, causing an increase in the root-to-shoot ratio (Cheeseman, 1988; Munns *et al.*, 2006). Salinity also promotes root suberisation of the hypodermis and endodermis, and the Casparian strip develops closer to the root tip than in non-saline environments (Shannon *et al.*, 1994). Plant species differ greatly in their tolerance to salinity (Jamil *et al.*, 2007) and, in the range of 5.7-10.9 mS cm^{-1} tested here, maize roots were probably not greatly affected, as confirmed by the low sensitivity to salinisation of the most apical

Treatment	Root weight (g DW plant^{-1})	Length of main roots (m plant^{-1})	Specific root length (m g^{-1})	N. of main roots (n. plant^{-1})
T100	14.4 (a)	4.19 (a)	0.29 (a)	27.3 (a)
T70	14.2 (a)	3.27 (ab)	0.24 (a)	23.2 (ab)
T35	10.1 (b)	2.28 (b)	0.24 (a)	17.7 (b)
T3	18.3 (a)	4.23 (a)	0.29 (ab)	27.3 (a)
T6	17.7 (a)	3.46 (a)	0.20 (b)	20.3 (a)

Tab. 4 - Main root characteristics at harvest time (monolith method: 0.2×0.2×0.2 m). Letters: statistically significant differences between treatments within same parameter (Newman-Keuls test, P≤0.05).
T100: irrigated at 100% ETM; T70: irrigated at 70% ETM; T35: irrigated at 35% ETM; T3: moderate salinity (3 g NaCl L^{-1}) at 100% ETM; T6: severe salinity (6 g NaCl L^{-1}) at 100% ETM.

Tab. 4 - Principali caratteristiche radicali alla raccolta (metodo del monolito: 0,2×0,2×0,2 m). Lettere: differenze statisticamente significative tra i trattamenti per ciascun parametro (Test Newman-Keuls, P≤0,05).
T100: apporto irriguo al 100% ETM; T70: apporto irriguo al 70% ETM; T35: apporto irriguo al 35% ETM; T3: salinità moderata (3 g NaCl L^{-1}) al 100% ETM; T6: salinità elevata (6 g NaCl L^{-1}) al 100% ETM.

Treatment	Thousand Kernel Weight (g DW)	Grain yield (t DW ha^{-1})	Ear length (mm)	Ear diameter (mm)	Kernel weight per ear (g DW)	Kernel number per ear
T100	268 (a)	3.55 (a)	131 (a)	46.7 (a)	39.5 (a)	149 (a)
T70	268 (a)	2.76(b)	124 (b)	39.8 (b)	33.1 (a)	124 (a)
T35	227 (b)	0.55 (c)	104 (b)	33.4 (c)	10.4 (b)	46 (b)
T3	269 (a)	2.66 (b)	137 (a)	46.3 (a)	30.7 (a)	115 (a)
T6	225 (b)	0.97 (c)	107 (b)	34.4 (b)	12.1 (b)	54 (b)

Tab. 5 - Main yield parameters. Letters: statistically significant differences between treatments within same parameter (Newman-Keuls test, $P \leq 0.05$).

T100: irrigated at 100% ETM; T70: irrigated at 70% ETM; T35: irrigated at 35% ETM; T3: moderate salinity (3 g NaCl L^{-1}) at 100% ETM; T6: severe salinity (6 g NaCl L^{-1}) at 100% ETM.

Tab. 5 - Principali parametri produttivi dell'ibrido di mais Naudi. Lettere: differenze statisticamente significative tra i trattamenti per ciascun parametro (Test Newman-Keuls, $P \leq 0,05$).

T100: apporto irriguo al 100% ETM; T70: apporto irriguo al 70% ETM; T35: apporto irriguo al 35% ETM; T3: salinità moderata (3 g NaCl L^{-1}) al 100% ETM; T6: salinità elevata (6 g NaCl L^{-1}) al 100% ETM.

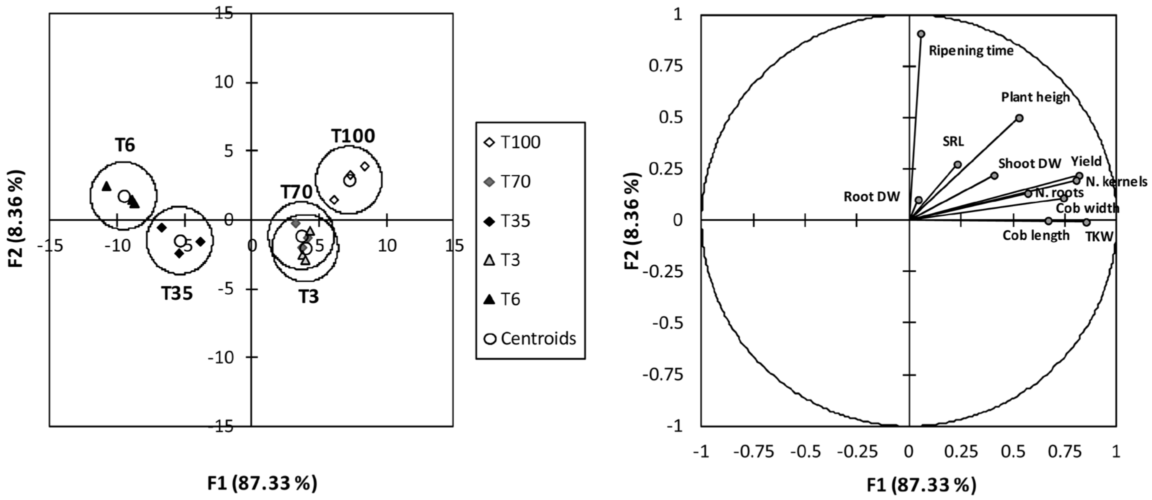
growing regions of roots of this crop (Pritchard, 1994).

As expected, both water and salinity stress caused significant yield reductions, particularly with severe water deficit (-84%) and at the highest salinity (-73%). The effects of moderate water stress T70 on yield were similar to those of moderate salinity T3, causing reductions of 22% and 25% ($P \leq 0.05$), respectively (Tab. 5). Marked yield losses were mainly related to diminished cob fertility and reduced TDK, reflected in reduced cob size (both length and diameter; Tab. 5). Many studies have confirmed the great negative impact of water deficit on a variety of cultivated plants (Hussain *et al.*, 2009 and 2013; Anjum *et al.*, 2011; Zafar-al-Hye *et al.*, 2014; Farnia and Khodabandehloo, 2015). According to a previous study by Guelloubi *et al.* (2005), drought stress is thought to affect maize productivity mainly at three critical stages, tassel differentiation (5-6-leaf stage), flowering, and mid-to-late grain filling. Our study suggests that, with limited water resources, moderately saline water can be supplied to the crop with estimated yield losses comparable to those of moderate drought stress. However, attention should be paid to salt accumulation in the soil over time. Highly saline and sodic water can cause problems for soil quality, depending on the type and amount of salts present, soil type, and the amount of water able to percolate. Although many salts can improve soil structure, sodium has the opposite effect, and its accumulation causes soil dispersion, clay platelets and aggregate swelling.

Our results confirm the results of Blanco *et al.* (2008) who noted that, up to 4.6 mS cm^{-1} of EC, a value close to our moderate salinity level, yield was almost unaffected, whereas a 20% decrease should be expected for each unit increase in salinity above that threshold. Yield losses of maize under salinity have been widely reported (Yokoi *et al.*, 2002; Pitman and Läuchli, 2002; Munns and Tester, 2008), generally due to reduced grain weight and number (Kaya *et al.*, 2013).

PCA of all investigated parameters identified two dummy variables, accounting for a high rate of variability (95.69%), F1 representing the major part (87.33%; Fig. 3). F1 was described by several significant (loading > |0.5|) variables, and yield correlated well with number of kernels per ear and TKW. Although significant, the duration of ripening time only explained a small fraction of variability, being associated with F2. Among root parameters, the number of main roots was the most important (loading: 0.53), indicating that maize plants probably cope better with stressful conditions with a high number of roots, exploited to search for soil water resources or to escape salinity. According to the centroid positions and overlap among clusters (circles), four homogeneous groups were identified: controls (T100), moderate drought (T70) together with moderate salinity (T3), and the worst situations, i.e., severe water stress (T35) and severe salinity (T6).

This study, although focusing only on one hybrid, confirms the great sensitivity of maize to abiotic stresses such as drought and salinity, when they



	F1	F2
Shoot DW	0.407	0.219
Thousand Kernel Weight (TKW)	0.851	-0.008
Yield	0.816	0.219
Cob length	0.668	-0.001
Cob width	0.742	0.109
Root DW	0.042	0.101
Specific root length (SRL)	0.230	0.273
Plant height	0.527	0.499
Ripening time	0.054	0.908
N. kernels per ear	0.803	0.195
N. roots	0.570	0.132

Fig. 3 - PCA with parameter loadings (highlighted values > |0.5|) for two main components F1 and F2 and DA for treatment classification, using yield components, shoot and root growth parameters and ripening time.
T100: irrigated at 100% ETM; T70: irrigated at 70% ETM; T35: irrigated at 35% ETM; T3: moderate salinity (3 g NaCl L^{-1}) at 100% ETM; T6: severe salinity (6 g NaCl L^{-1}) at 100% ETM.

Fig. 3 - PCA e valori dei pesi (in grassetto > |0.5|) dei parametri per le variabili fittizie F1 e F2, e DA per la classificazione dei trattamenti, utilizzando le componenti della resa, i parametri radicali e la durata del periodo di riempimento della granella.
T100: apporto irriguo al 100% ETM; T70: apporto irriguo al 70% ETM; T35: apporto irriguo al 35% ETM; T3: salinità moderata (3 g NaCl L^{-1}) al 100% ETM; T6: salinità elevata (6 g NaCl L^{-1}) al 100% ETM.

occur throughout the crop cycle. The effects of drought and salinity are similar, in that they both give rise to anticipated flowering and maturity, and reduction in both shoot height and productivity. The yield potential of the hybrid Naudi was poor even with optimal water supply (3.55 tons per hectare). Compared with higher latitudes and more temperate climates, in the sub-tropical climate of Tunisia the yield potential of maize hybrids with similar precocity is expected to be lower, mainly due to higher temperatures and lower soil fertility.

4. CONCLUSIONS

Both extreme salinity and drought have dramatic effects on maize yield, seriously threatening the sustainability of cultivation of this crop. In this study, we describe the importance of preserving ear fertility and kernel nutrition to maintain acceptable yield levels through correct management of irrigation volumes and water quality. We also highlight the important role of the root system in improving the tolerance of maize to abiotic stresses, suggesting that thorough screening of hybrids may be one way of improving water use efficiency and tolerance to extreme salinity conditions. Management of limited water resources in semi-arid areas indicates that moderate water stress or, alternatively, full irrigation with moderate salinity values, may limit yield losses to 20-30%. This also leads to early flowering, which allows irrigation to be managed properly at farm level during the most sensitive phases of maize growth.

4. ACKNOWLEDGEMENTS

The authors would like to thank Prof. Sifi Bouaziz (head, Laboratory of Agronomic Sciences and Technical, INRAT-Ariana, Tunisia) for help in managing this field trial, and Dr. Giuseppe Barion (DAFNAE, University of Padova, Legnaro, Italy) for help in statistical analysis. The authors also wish to thank Gabriel Walton for revision of the English text.

REFERENCES

Abendroth L.J., Elmore R.W, Boyer M.J., Marlay S.K., 2011. Corn growth and development. Iowa State Univ. Extension Publication. PMR-1009. https://store.extension.iastate.edu/Product/Corn-Growth-andDevelopment

Acevedo E., Silva P., Silva H., 2002. Wheat growth and physiology. In: Bread wheat improvement and production. Curtis BC, Rajaram S and Gómez Macpherson H (eds.). FAO, Rome, Italy, pp. 39-70.

Ashraf M., McNeilly T., 2004. Salinity tolerance in *Brassica* oilseeds. Cr Rev Plant Sci 23: 157–174.

Argentel L., López R., Fonseca I., Girón R., González L.M., 2008. Efecto de la salinidad sobre la fenología, los componentes del rendimiento y su relación con la tolerancia varietal a la salinidad en trigo (*Triticum aestivum* y *T. durum*). Cultrop 29 : 53-57.

Anjum S.A.,Wang L.C., Farooq M., Hussain M., Xue L.L., Zou C.M., 2011. Brassinolide application improves the drought tolerance in maize through modulation of enzymatic antioxidants and leaf gas exchange. J Agron Crop Sci 197: 177-185.

Aydinsakir K., Erdal S., Buyuktas D., Bastug R., Toker R., 2013. The influence of regular deficit irrigation applications on water use, yield, and quality components of two corn (*Zea mays* L.) genotypes. Agr Water Manage 128: 65-71.

Azizian A., Sepaskhah A.R., 2014. Maize response to water, salinity and nitrogen levels: physiological growth parameters and gas exchange. Int J Plant Prod 8: 131-162.

Bernstein N., Laüchli A., Silk W.K., 1993. Kinematics and dynamics of sorghum (*Sorghum bicolor* L.) leaf development at various Na/Ca salinities. I. Elongation growth. Plant Physiol 103: 1107-1114.

Blanco F.F., Folegati M.V., Ghegi H.R., Fernandez P.D., 2008. Growth and yield of corn irrigated with saline water. Sci Agric 65: 574-580.

Bybordi A., 2010. Effects of salinity on yield and component characters in canola (*Brassica napus* L.) cultivars. Not Sci Biol 2 : 81-83.

Carpici E.B., Celik N., Bayram G., Asik B.B., 2010. The effects of salt stress on the growth, biochemical parameter and mineral element content of some maize (*Zea mays* L.) cultivars. Afr J Biotechnol 9: 6937-6942.

Chaum S., Kirdmanee C., 2009. Effect of salt stress on proline accumulation, photosynthetic ability and growth characters in two maize cultivars. Pak J Bot 41: 87-98.

Cheeseman J.M., 1988. Mechanisms of salinity tolerance in plants. A review. Plant Physiol 87: 547-550.

Farnia A., Khodabandehloo S., 2015. Changes in yield and its components of maize (*Zea mays* L.) to foliar application of zinc nutrient and mycorrhiza under water stress condition. Int J Life Sci 9: 75-80.

Farooq M., Hussain M., Wakeel A., Siddique K.H.M., 2015. Salt stress in maize: effects, resistance mechanisms and management. A review. Agron Sustain Dev 35 (3): 461-481.

Farré I., Faci J.M., 2009. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. Agr Water Manage 96: 383-394.

Francois L.E., Maas E.V., Donovan T.J., Youngs V.L., 1986. Effect of salinity on grain yield and quality, vegetative growth, and germination of semi-dwarf and durum wheat. Agron J 78: 1053-1058.

Ghobadi M., Bakhshandeh M., Fathi G., Gharineh M.H., Alamisaeed K., Naderi A., Ghobadi V., 2006. Short and long periods of water stress during different growth stages of canola (*Brassica napus* L.). Effect on yield, yield components, seed oil and protein contents. Agron J 5: 336-341.

Golabadi M., Arzani A., Tabatabaie B., Mohamadi

A., 2008. Identification of SSR markers linked with genes controlling phenological characteristics of durum wheat under moisture stress and non-stress. In: Proceedings of the Tenth Congress of Genetics, May 21-23, Tehran, Iran.

Grieve C.M., Francois L.E., Maas E.V., 1994. Salinity affects the timing of phasic development in spring wheat. Crop Sci 34: 1544–1549.

Guelloubi R., Hamdy A., Sardo V., 2005. Maize production under two water saving techniques. In: Hamdy A. (ed.), El Gamal F. (ed.), Lamaddalen a N. (ed.), Bogliotti C. (ed.), Guelloubi R. (ed.). *Non-conventional water use: WASAMED project.* Bari: CIHEAM / EU DG Research. 2005 (Options Méditerranéennes : Série B. Etudes et Recherches, n. 53), pp. 77 -91.

Hasanuzzaman M., Nahar K., Fujita M., 2013. Ecophysiology and responses of plants under salt stress. In P Ahmad, MM Azooz, MNV Prasad (eds.). Springer, New York, pp. 25-87.

Henry C.W., Bledsoe S.A., Griffiths C., Kollman A., Paul M., Sakr S., Larigrimini L.M., 2015. Differential role for trehalose metabolism in salt-stressed maize. Plant Physiol 169: 1072-1089.

Hussain M., Malik M.A., Farooq M., Khan M.B., Akram M., Saleem M.F., 2009. Exogenous glycinebetaine and salicylic acid application improves water relations, allometry and quality of hybrid sunflower under water deficit conditions. J Agron Crop Sci 195: 98-109.

Hussain M., Park H.W., Farooq M., Jabran K., Lee D.J., 2013. Morphological and physiological basis of salt resistance in different rice genotypes. Int J Agric Biol 15: 113-118.

IPCC - Intergovernmental Panel on Climate Change, 2007. Climate Change. The Physical Science Basis: Summary for Policymakers. Geneva, Switzerland: IPCC Secretariat.

Jamil M., Lee C.C., Rehman S., Lee D.B., Ashraf M., Rha E.S., 2005. Salinity (NaCl) tolerance of *Brassica* species at germination and early seedling growth. Electronic J Environ Agric Food Chem 4: 970-976.

Jamil M., Shafiq Rehman S.H., Rha E.S., 2007. Salinity effect on plant growth, PSII photochemistry and chlorophyll content in sugar beet (*Beta vulgaris* L.) and cabbage (*Brassica oleracea capitata* L.). Pak J Bot, 39: 753-760.

Kafi M., 2001. Apex development of three wheat cultivars in the presence of salinity. J Agric Sci Technol 3: 1-8.

Kaya C., Ashraf M., Dikilitas M., Tuna A.L., 2013. Alleviation of salt stress induced adverse effects on maize plants by exogenous application of indole acetic acid (IAA) and inorganic nutrients. A field trial. Aust J Crop Sci 7: 249-254.

Moriondo M., Bindi M., 2008. Impact of climate change on the phenology of typical Mediterranean crops. Ital J Agrometeorol 3: 5-12.

Munns R., James R.A., Läuchli A., 2006. Approaches to increasing the salt tolerance of wheat and other cereals. J Exp Bot 57: 1025-1043

Munns R., Tester M., 2008. Mechanisms of salinity tolerance. Annu Rev Plant Biol 59 : 651-681.

Neumann P.M., 1995. Inhibition of root growth by salinity stress: toxicity or adaptive biophysical response? In: Baluska, F, Ciamporova, M., Gasparikova, O, Barlow, PW, (eds.), Structure and Function of Roots: Developments in Plant and Soil Sciences. The Netherlands: Kluwer, pp. 299-304.

Ouda S.A.E., Mohamed S.G., Khalil F.A., 2008. Modeling the effect of different stress conditions on maize productivity using yield-stress model. Int J Nat Eng Sci 2 : 57–62.

Passioura J.B., 2007. The drought environment: physical, biological and agricultural perspectives. J Exp Bot, 58 : 113–117.

Pitman M.G., Läuchli A., 2002. Global impact of salinity and agricultural ecosystems. In: Läuchli A., Luttge U. (eds.) Salinity: environment – plants – molecules, Kluwer, pp. 3-20.

Poss R., Saragoni H., Imbernon J., 1988. Bilan hydrique simulé du maïs au Togo méridional. Agr Trop 43 : 18-29.

Pritchard J., 1994. The control of cell expansion in roots. New Phytol 127: 3-26.

Radhouane L., 2008. Caractéristiques hydriques du mil (*Pennisetum glaucum (L.R.Br.)* en présence de contraintes hydriques. Comptes Rendus Biologies 331: 206-214.

Rios-Gonzalez K., Erdei L., Lips S.H., 2002. The activity of antioxidant enzymes in maize and sunflower seedlings as affected by salinity and different nitrogen sources. Plant Sci 162: 923-930.

Sarr B., Diouf O., Diouf M., Roy-Macauley H., Ndjendole S., 1999. Suivi de l'état hydrique du sol et de la température du couvert de maïs au

Sénégal. Science et changements planétaires. Sécheresse, 10: 129-35.

Sarr B., Kafando L., Atta S., 2011. Identification des risques climatiques de la culture du maïs au Burkina Faso. Int J Biol Chem Sci 5: 1659-1675.

Shannon M.C., Grieve C.M., Francois L.E., 1994. Whole plant response to salinity. In: Wilkinson R.E. (ed) Plant-environment interactions. Dekker, New York, pp 199-244.

Stanton M.L., Roy B.A., Thiede D.A., 2000. Evolution in stressful environments. I. Phenotypic variability, phenotypic selection, and response to selection in five distinct environmental stresses. Evo 54: 93-111.

Tas B., Basar H., 2009. Effects of various salt compounds and their combinations on growth and stress indicators in maize (*Zea mays* L.). Afr J Agric Res 4: 156-161.

Turan M.A., Elkarim A.H.A., Taban N., Taban S., 2010. Effect of salt stress on growth and ion distribution and accumulation in shoot and root of maize plant. Afr J Agric Res 5: 584-588.

Valiollah R., Mahyar G., 2015. Soil salinity effects on phenological traits, plant height and seed yield in rapeseed genotypes. Soil Sci Ann 66: 17-20.

Vamerali T., Guarise M., Ganis A., Bona S., Mosca G., 2003. Analysis of root images from auger sampling with a fast procedure: a case of application to sugar beet. Plant Soil 255: 387-397.

Vamerali T., Guarise M., Ganis A., Mosca G., 2009. Effects of water and nitrogen management on fibrous root distribution and turnover in sugar beet. Eur J Agron 31: 69-76.

Volkmar K.M., Hu Y., Steppuhn H., 1998. Physiological responses of plants to salinity. A review. Can J Plant Sci 78: 19-27.

Yamaguchi M., Sharp R.E., 2010. Complexity and coordination of root growth at low water potentials: recent advances from transcriptomic and proteomic analyses. Plant Cell Environ 33: 590-603.

Yokoi S., Bressan R.A., Hasegawa P.M., 2002. Salt stress tolerance of plants. JIRCAS Working Report. pp. 25-33.

Zafar-ul-Hye M., Ahmad M., Shahzad S.M., 2014. Synergistic effect of rhizobia and plant growth promoting rhizobacteria on the growth and nodulation of lentil seedlings under axenic conditions. Soil Environ 32: 79-86.