Article (refereed) - postprint

Rameshwaran, Ponnambalam; Qadir, Manzoor; Ragab, Ragab; Arslan, Awadis; Majid, Ghalia Abdul; Abdallah, Khalaf. 2016. **Tolerance of faba bean, chickpea and lentil to salinity: accessions' salinity response functions**. *Irrigation and Drainage*, 65 (1). 49-60. 10.1002/ird.1922

TOLERANCE OF FABA BEAN, CHICKPEA AND LENTIL TO SALINITY: ACCESSIONS' SALINITY RESPONSE FUNCTIONS

PONNAMBALAM RAMESHWARAN [1], MANZOOR QADIR[2,3], RAGAB RAGAB[1], AWADIS ARSLAN[4], GHALIA ABDUL MAJID[4] AND KHALAF ABDALLAH[4]

[1]*Centre for Ecology & Hydrology, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, United Kingdom*

[2]*International Center for Agricultural Research in the Dry Areas (ICARDA), Khalid Abu Dalbouh Street, Abdoun, P.O. Box 950764, Amman, Jordan*

[3]*United Nation University, Institute for Water, Environment and Health, 175, Longwood Road South, Hamilton, L8P 0A1, Ontario, Canada*

[4]*General Commission for Scientific Agricultural Research (GCSAR), Ministry of Agriculture and Agrarian Reform, Damascus, Syria*

ABSTRACT

The productivity of crops irrigated with saline water or grown on salt-affected soils depends on the salt tolerance of the crops, their accessions, and various environmental and cultural conditions such as soil properties, climate and irrigation methods. The level and ability of plants to tolerate salt stress is the most critical information for the successful management of salt-affected agricultural lands and saline irrigation waters. In this paper, responses of three food legume crops (faba bean, chickpea and lentil) to salinity stress were analyzed using the threshold-slope linear response function and modified discount function. The response functions are calibrated using the 2009-2010 season's data and validated using the 2010-2011 season's data from faba bean, chickpea and lentil experiments conducted in Raqqa, Syria. The comparison was also made through SALTMED model predictions. The results of this study show that the salinity response functions and productivity of grain yield are highly variable within the accessions of the same crop. For optimum outcome, the practitioners need to consider the salinity response functions and also the productivity of different accessions and their response to salinity in relation to the soil and available irrigation water salinity levels.

KEY WORDS: food legume; crop productivity; saline water irrigation; salinity response function; crop salt tolerance.

INTRODUCTION

Salts in irrigation water or soil inhibit plant growth, affect crop yield and sometimes quality as salt reduces water uptake. Excessive salt in the root zone can cause further reductions in growth and yield because of specific toxic ion effects (Qadir and Oster, 2004). The inherent ability to tolerate or resist root zone salinity depends on crops and their varieties (e.g. Maas and Hoffman, 1977; Shannon and Grieve, 1999, Rameshwaran *et al.*, 2014). Traditionally, the crop response to salinity has been analyzed with response functions where yields generally tend to be constant with increasing soil salinity until a salinity threshold has been exceeded then they generally decrease with further increase in salinity until the yield reaching zero value (Maas and Hoffman, 1977).

Recent studies have looked into response functions beyond the application of the threshold-slope linear response function illustrated by Maas and Hoffman (1977). Steppuhn *et al*. (2005a) compared six forms of empirical response functions describing the yield of crops subject to increasing levels of root-zone salinity using the test data from a spring wheat cultivar Biggar. The experiment was conducted in Canada's Salt Tolerance Testing Facility. These six linear and nonlinear relationships are given in Table I as simple linear function, threshold-slope linear function, modified Weibull function, bi-exponential function, modified Gompertz function and modified discount function. Steppuhn *et al*. (2005a) concluded that of the six response functions, the modified-discount sigmoidal-shape response function gave the best fit and correlation for the data. Therefore, in this paper, the classical threshold-slope linear response function (Maas and Hoffman, 1977) and the modified-discount nonlinear response function (Steppuhn *et al*. 2005a) indices were calibrated for food legumes – faba bean, chickpea and lentil. The two-season (2009-2010 and 2010-2011) salinity experiment data from Raqqa, Syria are used. SALTMED modelling of the data was also performed and the predicted yields were compared with the response functions. The actual measured grain yields (kg ha^{-1}) for seasons 2009-2010 and 2010-2011 were also compared.

Table I: ABOUT HERE

CROP YIELD RESPONSE FUNCTIONS

The salt tolerance of a crop can be described by several forms of response functions where the yield is reduced with salinity of the irrigation water or soil, i.e. root-zone salinity (Maas and Hoffman, 1977, Maas, 1993; Shannon and Grieve 1999; Steppuhn *et al*., 2005a,b). These functions provide useful information for agronomic practices and management. In these functions, yields are standardised or scaled and expressed in terms of relative yield in order to compare the salt tolerance or resistance of crops, which is defined as:

$$Y_r = Y/Y_{max} \quad (1)$$

Where Y_r is the relative yield, Y is the absolute yield and Y_{max} is the maximum yield where salinity has minimal or no effect on yield.

Threshold-slope linear response function

The threshold-slope linear response function of Maas and Hoffman (1977) is characterized mathematically by a three-piece linear model for the salinity response – maximum yield until salinity threshold, rate of yield decline with increase in salinity beyond threshold, and zero yield beyond a particular value of salinity (van Genuchten, 1983):

$$\begin{aligned} Y_r &= 1 && 0 < C < C_t \\ Y_r &= 1 - \mathrm{b}(C - C_t) && C_t < C < C_0 \\ Y_r &= 0 && C > C_0 \end{aligned} \quad (2)$$

where C is the salinity during the growing season, C_t is the maximum threshold salinity without a yield reduction (Y_r = 1), C_0 is the salinity beyond which the yield is zero (Y_r = 0) and b is the absolute value of the declining slope in relative yield (Y_r). The parameters C_t and b are usually estimated by curve fitting (mathematically or visual inspection) or regression methods which depend on the amount of data available from the field experiment.

Modified-discount function

The modified-discount function of Steppuhn *et al.* (2005a, b) is a sigmoidal-shaped response function:

$$Y_r = 1 / [1 + (C/C_{50})^{\exp(sC_{50})}] \quad (3)$$

where C_{50} is the salinity at which yield is reduced by 50 percent and s represents the response curve steepness. In their paper, Steppuhn *et al.* (2005a) evaluated the steepness parameter s (= $\mathrm{d}Yr/\mathrm{d}C$) using experimental data between 0.3 and 0.7.

Initially, a form of the modified-discount function was suggested by van Genuchten (1983) in order to better represent the experimental data as:

$$Y_r = 1 / [1 + (C/C_{50})^p] \quad (4)$$

where p is the shape parameter. Using Maas and Hoffman (1977) salt tolerance database, van Genuchten and Gupta (1993) estimated the C_{50} and the p values as well as the range in fitted p values. They noticed that the log-normal frequency distribution fits the p values quite well with a mode of 2.55, a median of 3.05 and a mean of 3.34. They fixed the p at the very convenient value of 3, which was judged to be the average value without biophysical meaning.

Steppuhn *et al*. (2005a) used $\exp(sC_{50})$ as the exponent in equation (3) instead of the empirical constant p. They argue that the exponent component sC_{50} in equation (3) contributes to a symmetrical concave-convex (i.e. sigmoidal-shaped) yield response with inflection point at C_{50} which is corresponding to the bC_t of the threshold-slope linear response function equation (2). In both functions, the parameters s and b determine the rate of decrease in relative yield with increasing salinity. Steppuhn *et al*. (2005a) also argue that both functions have biophysical characteristics with meaningful parameters b, s and C_{50} compared to other functions evaluated in their study (Table I).

SALTMED model yield response function

SALTMED model is a physically based model using water and solute transport, evapotranspiration and water uptake equations (Ragab, 2002, 2010). In the model, the relative yield Y_r is expressed in following relationship (van Genuchten, 1987):

$$Y_r = S/S_{max} \quad (5)$$

where S is the actual plant water uptake and S_{max} is the maximum potential plant water uptake (under no water and salinity stress conditions).

The assumption van Genuchten (1987) made was that the actual water uptake can be calculated by combining equations (4) and (5) and converting salinity to osmotic pressure π as:

$$Y_r = S/S_{max} = 1 / [1 + (\pi / \pi_{50})^p] \quad (6)$$

where π_{50} is the osmotic pressure at which yield reduced by 50 percent. The further assumption van Genuchten (1987) made was that plant response to metric pressure can be included similarly where matric and salinity effects are both present, a combined equation can be written as:

$$Y_r = S/S_{max} = 1 / \{1 + [(ah + \pi) / \pi_{50}]^p\} \quad (7)$$

where h is the soil water pressure, a is a weighing coefficient that accounts for the differential response of a crop to matric and osmatic pressure and is equal to π_{50}/h_{50} where h_{50} is the matric pressure at which S_{max} is reduced to 50 percent.

The SALTMED model predicts the relative yield Y_r using equation (7) with empirical constant p equal to 3 (van Genuchten and Gupta 1993; Cardon and Letey, 1992). More details of the model approach and equations can be found in Ragab (2002 and 2010).

SALINITY TOLERANCE INDEX

Traditionally, the C_{50} value is used as salinity tolerance index (*ST Index*) for crops simply derived from the threshold-slope linear response function or from experimental data. In management practice, these values are used to access the relative tolerance among agricultural crops. With their modified-discount function, equation (3), Steppuhn *et al*. (2005a) defined the salinity tolerance index (*ST Index*) as:

$$ST\ Index = C_{50} + s\ C_{50} \quad (8)$$

Steppuhn *et al*. (2005a) argue that, in equation (8), C_{50} is enhanced by the shape of the yield response curve approaching C_{50} (i.e. curve steepness *s*).

The *ST Index* indicates a salinity value equal to the 50% reduction in crop yield from that of the non-saline irrigation yield plus the tendency to maintain some product yield in increasing salinity levels due to the shape (i.e. curve steepness *s*) of the yield response curve approaching C_{50} (Steppuhn *et al.*, 2005a). The *ST Index* is an indicator of the inherent salinity tolerance or resistance of crops to root-zone salinity.

MATERIALS AND METHODS

The site of this study is located in an agro-ecological zone 16 km northeast of Raqqa city, in Syria; namely Zone 5 (Figure 1) with an average (1989-1999) rainfall of 136 mm (FAO, 2003). In this area, the soil is formed over Neogene limestone, marl, gypsum, and conglomerates. Soil properties of the experimental site at Raqqa are given in Table II. Experiments were performed for 2009-2010 and 2010-2011 seasons.

Figure 1: ABOUT HERE
Table II: ABOUT HERE

The Raqqa experimental site receives water for irrigation from the Euphrates River through an open channel, 12 km from the site. Three irrigation treatments were used which represented river water, mixing river water with the pumped saline groundwater at the ratio about 1:1 and pumped saline groundwater. These three water quality treatments had average electrolyte conductivities of 0.7, 3.0 and 5.0 dS m^{-1}. Mixing in the case of preparing water for 3.0 dS m^{-1} case was done in a large tank to store water for irrigation of three food legume crops.

The experiment was laid out using split plot design with water quality in the main plots and food legume accessions in the sub-plots. Basin irrigation method was used after laser levelling of the land. This is the dominant method of irrigation in the area. The treatments were replicated three times. The amount of applied irrigation water was calculated from the water balance equation. In other words, the irrigation consumptive water use needed to satisfy crop water demand was calculated using potential crop evapotranspiration, effective precipitation and change in soil moisture. The threshold soil water content to initiate irrigation was when the soil water potential drops down to about 4 bars. The amount of water calculated and applied was to raise soil moisture to about 95% field capacity of the upper 100 cm depth of soil as the root zone depth for food legumes (faba bean, chickpea and lentil) is about 60 cm (Allen et al., 1998). The total amounts of irrigation water of 300 mm and 586 mm were provided over 5 and 11 scheduled days for 2009-2010 and 2010-2011 seasons, respectively. The rainfall amounted to 81.2 mm in 36 days and 59.4 mm in 29 days during the 2009-2010 and 2010-2011 seasons, respectively. The field site was setup with a horizontal drainage system with the drains installed between 1.6 to 1.9 m depth. Therefore, there was no contribution of groundwater to crop evapotranspiration. Fertilizers were applied to crops before seeding as: N at 10 kg ha^{-1}, P_2O_5 at 50 kg ha^{-1} and K_2O at 20 kg ha^{-1}.

Eleven accessions of faba bean and fifteen accessions each of chickpea and lentil were used in the experiments. The details of these accessions are provided in Table III. Eleven accessions of faba bean were planted in rows with 50 cm row spacing and 25 cm apart while fifteen accessions of chickpea were planted in rows with 35 cm row spacing and 7 cm apart and fifteen accessions of lentil were planted in rows with 35 cm row spacing and 4 cm apart. During the 2009-2010 season, sowing was carried out on 3rd of December 2009 and harvest took place in May 2010. In the 2010-2011 season the crops were sown about a month later than in the 2009-2010 season, with sowing date of 5th of January 2011 and harvested in June 2011. The dry grains were harvested at maturity and the total grain yields were measured at harvest for each accession and treatment separately.

Table III: ABOUT HERE

ELECTRICAL CONDUCTIVITY

Average root zone soil salinity, EC_e, is normally measured and expressed on the basis of the electrical conductivity of the saturated soil paste extracts of the soil. Twelve replicates of soil samples from the layers 0-20 cm, 20-40 cm and 40-60 cm of the root zone were collected in all treatment plots (0.7, 3.0 and 5.0 dS m^{-1}) and analyzed for EC_e at mid cropping season which is assumed to be the mean reflection of the soil salinity in overall cropping season. The root depth for these food legumes was found to be about 60 cm (Allen *et al*., 1998). The measured EC_e data for each salinity treatment are shown in Figure 2 for layers 0-20 cm, 20-40 cm and 40-60 cm along with the mean values for root zone 0-60 cm which is calculated from averaging layers 0-20 cm, 20-40 cm and 40-60 cm. Mean and median values of EC_e from replicates for these layers are given in Table IV.

Figure 2: ABOUT HERE
Table IV: ABOUT HERE

Figure 2 and Table IV show that the measured soil salinity EC_e is generally increasing with increasing irrigation water salinity EC_{iw} and decreasing with root zone depth as expected. They also show that the rate of increase in soil salinity EC_e between lower irrigation treatment (0.7 dS m^{-1}) and higher irrigation treatment (5.0 dS m^{-1}) is more in the top two layers compared to bottom layer. In fact in 40 -60 cm layer, the measured soil salinity EC_e is almost similar for all three treatments (0.7, 3.0 and 5.0 dS m^{-1}). Although the salinity of the irrigated water EC_{iw} of the first treatment is 0.7 dS m^{-1}, the measured EC_e values are much higher. This is because the soil before sowing of crops (Table II) had already affected slightly by salinity with mean EC_e value of 2.45 dS m^{-1} for the root zone layer 0–60 cm. It also shows that the mean and median values of the root zone (0– 60 cm) layer are nearly the same.

The mean values of the root zone electrical conductivity of the saturated soil paste extract of the soil EC_e which are referred to as the soil salinity are selected and used to develop relative salt tolerance ratings of the three food legume crops faba bean, chickpea and lentil. In other words, in equations (2) to (4), the salinity C represents the soil salinity EC_e.

RESULTS AND DISCUSSION

Using the 2009-2010 season's relative yield data, the parameter b, C_t, s and C_{50} crop yield response function equations (2) and (3) were calibrated. The fitted threshold-slope linear function and modified-discount function for minimum, average and maximum of the data points (after outliers removed) of all accessions are shown in Figure 3 for faba bean, chickpea and lentil, respectively, along with SALTMED predictions for these crops. Table V shows the calibrated threshold-slope linear response function parameters b and C_t; modified-discount function parameters s and C_{50} and salinity tolerance index (*ST Index*) for faba bean, chickpea and lentil.

Figure 3: ABOUT HERE
Table V: ABOUT HERE

The SALTMED model was first calibrated on minimum, average and maximum of the yield data points before performing prediction for series of salinity concentrations. The model calibration was carried out using measured crop and soil parameters along with crop coefficients K_c and K_{cb} values from FAO-56 (Rameshwaran *et al.*, 2014). The calibrated osmotic pressure (i.e. salinity stress parameter) π_{50} mid-season growth stage is given in Table VI.

Table VI: ABOUT HERE

The 2010-2011 season relative yield data were used to validate the calibrated response function parameters and the SALTMED model simulation results. Figure 4 shows the calibrated region between maximum and minimum curves with 2010-2011 season's relative yield data. It can be seen from the figure that only few data points fall outside the region which gives confidence in calibrated threshold-slope linear and modified-discount functions and SALTMED model predictions.

Figure 4: ABOUT HERE

In literature, the salt tolerance of a crop is often described as single linear or non-linear function regardless of accession response (e.g. Maas and Hoffman, 1977; Maas and Grattan, 1999; Shannon and Grieve, 1999; Munns *et al*., 2006; Ashraf and Foolad, 2013). The current study shows that there is a wide range in relative yield variation with accessions of the same crop as shown in Figures 3 and 4. These figures also show that variation range in relative yield is less for lentil compared to faba bean and chickpea and, on other hand, faba bean and chickpea have a similar variation range which is also reflected in the salinity tolerance index (*ST Index*) listed in Table V. For all three crops, the modified-discount function fit the data reasonably well.

The published values from literature for threshold-slope linear response function parameters for faba bean are b = 0.096 and Ct = 1.6 dS m^{-1} (Ayers and Eberhard, 1960; Maas and Hoffman, 1977) and from Lysimeter experiments b = 0.144 and Ct = 2.8 dS m^{-1} (Katerji *et al.*, 2004). The values from Lysimeter experiments for chickpea are b = 0.370 and Ct = 1.9 dS m^{-1} and for lentil are b = 0.620 and Ct = 1.7 dS m^{-1} (Katerji *et al.*, 2004). The published values are within the range or similar order of the parameter values obtained in the Raqqa experiment listed Table V. The main different between the Raqqa experiment and Katerji *et al.* (2004) experiment is that Katerji *et al.* (2004) was performed in Lysimeter with one variety. For example, several studies (Abel and Mackenzie, 1964; Velagaleti and Schweitzer, 1993, Katerji *et al*., 2004) already mentioned the large differences in the threshold-slope linear response function parameters in the case of soybean crop and they attributed the possibility of main source differences to crop variety. This study also showed that the accessions (i.e. variety) of food legume crops - faba bean, chickpea and lentil play a major part in determine salinity response functions.

Figure 3(c) also shows that the SALTMED model predicts minimum, average and maximum response functions for the Raqqa 2010-2011 season data reasonably well. In comparison with the modified-discount function, the model predicted a slightly wider region. In SALTMED model, the response function empirical constant p is assumed to be 3 for all crops which may not be the case for these food legume crops. In their paper, van Genuchten and Gupta (1993) showed that the empirical constant p can be variable between 1.99 and 5.07 for thirteen different vegetable crops they listed and mentioned that the only average empirical constant *p* value is close to 3. The calibrated osmotic pressure π_{50} values from SALTMED model in Table VI also show wide variation between maximum and minimum values compared to C_{50} variation of the modified-discount function given in Table V. Comparing average values of C_{50} and *ST Index* in Table V and π_{50} in Table VI which show that faba bean is the most salinity tolerant among the three food legume crops, followed by lentil and chickpea.

Figure 5 shows the actual measured yield (kg ha^{-1}) for faba bean, chickpea and lentil, respectively, for both seasons which are also listed in Table III. It can be seen from the figure that there is variation in yield between seasons for the same accession which may mainly be due to variation in climate, sowing date, soil conditions and quality, rainfall frequency (facilitate leaching), irrigation water amount and possibly minor plant pests and diseases between seasons and any other experimental measurement errors. In general, it shows that the better performing accessions seem to perform well regardless of seasons with some degree of variation in measured yields between seasons. In almost in all accessions, the measured yields in both seasons are displaying decreasing trend with salinity with few exceptions where the higher salinity treatment cases perform slightly better than the lower treatment cases and there is also a crop failure in lentil accession 7201 in 2009-2010 season. On other hand, among the accessions there are considerable variations in actual measured yield and rate of decrease in yield with increasing salinity. Analysis of variance of grain yield for faba bean, chickpea and lentil in Table III revealed that there was a significant difference ($p<0.05$) among the grain yield values of the three levels of salinity treatment and accessions.

Figure 5: ABOUT HERE

In order to compare the overall accessions response regardless of seasons, the combined actual measured yield (kg ha^{-1}) of both seasons 2009-2010 and 2010-2011 was presented by plotting the minimum yield of the two seasons with the variation between seasons for each accession along with the average yield curves between seasons for faba bean, chickpea and lentil in Figure 6. The average yield curves in Figure 6 show that most accessions display decreasing yield with increasing salinity except faba bean accessions DT/B7/9043/2005/06, DT/B7/9005/2005/06 and DT/B7/9009/2005/06, chickpea accessions FLIP87-8C and ILC10722 and lentil accession 10072. The variable distance between the average yield curves with accessions represent the rate of yield response to salinity. Figure 6 shows that in a range salinity treatment, faba bean accessions ILB1814 (Syrian local) and ILB1266 (Aguadolce), chickpea accessions ILC3182, FLIP03-145C, FLIP03-46C, ILC216, FLIP04-19C, ILC3279 and ILC1302 and lentil accessions 7947, 6994, 7670 and 10707 performed above average of all accessions (last panel in the graphs) of each crop in all three treatments (marked in red solid dots in Figure 6 and highlighted in Table III).

Figure 6: ABOUT HERE

For best agronomic practices and management, this study showed that it is essential not only to consider the salinity response functions and their variation range but also the productivity of different accessions and their response to salinity.

CONCLUSIONS

In this study, responses of three food legume crops (faba bean, chickpea and lentil) to salinity stress were analyzed and indices for the threshold-slope linear response function and modified discount function were calibrated and validated using 2009-2010 and 2010-2011 seasons' salinity experimental data from Raqqa, Syria. The study showed that the response functions are highly variable with accession and can only be represented by a range for each crop. Faba bean and chickpea have a similar variation range in relative yield and lentil has a small variation range compared to faba bean and chickpea. The indices for response functions calibrated from the overall average of accessions show that faba bean is the most salinity tolerant crop followed by lentil and chickpea.

In terms of productivity, the study shows that there are considerable variations among the accessions and their rate of decrease in productivity with the increase in salinity stress. In both growth seasons, the accessions largely performed in a similar manner, even with differences in experimental and environmental conditions between seasons. This study demonstrated that for best management practices for crops irrigated with saline water or grown on salt-affected soils, the practitioners need to take into account both the salinity response functions and the productivity of different accessions and their response to salinity to get optimum results in the field.

REFERENCES

Abel, G.H. and Mackenzie, A.J. (1964). Salt tolerance of soybean varieties (*Glycine max* L. Merrill) during germination and later growth. *Crop Science*, **4**, 157–161.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop evapotranspiration - Guidelines for computing crop water requirements, *FAO Irrigation and Drain Paper No. 56*, Rome, Italy, 300pp

Ashraf, M. and Foolad, M.R. (2013) Crop breeding for salt tolerance in the era of molecular markers and marker-assisted selection. *Plant Breeding* **132**, 10–20.

Ayers, A.D. and Eberhard, D.L. (1960) Response of edible broadbean to several levels of salinity. *Agronomy Journal*, **52**, 110–111.

Cardon, G.E. and Letey, J. (1992) Plant water uptake terms evaluated for soil water and solute movement models. *Soil Science Society of America Journal*, **32**, 1876-1880.

FAO (2003) *Fertilizer use by crop in the Syrian Arab Republic*, Published by Food and Agriculture Organization of the United Nations, Rome, 33pp.

Katerji N., van Hoorn J.W., Hamdy A and Mastrorilli M. (2004) Salinity effect on crop development and yield, analysis of salt tolerance according to several classification methods. In: Hamdy, A. (Ed.), Non-Conventional Water Resources: Salinity and Saline Irrigation Practices and Management, Bari, Italy, 159–189.

Maas, E.V. (1993) Testing crops for salinity tolerance. In: Maranville, J.W., BaIigar, B.V., Duncan, R.R., Yohe, J.M. (Eds.), *Proceedings of a Workshop on Adaptation of Plants to Soil Stresses,* l–4 August 1993. INTSORMIL Publication No. 94-2. Univ. of Nebraska, Lincoln, NE, 234-247.

Maas, E.V. and Hoffman, G.J. (1977) Crop salt tolerance - current assessment. *Journal of Irrigation and Drainage Division*, ASCE, **103**, 115-134.

Maas, E.V. and Grattan, S.R. (1999) Crop yields as affected by salinity. In: Skaggs RW, van Schilfgaarde J (eds), *Agricultural Drainage*. ASA-CSSA-SSSA, Madison, Wisconsin, 55-108.

Ministry of Agriculture and Agrarian Reform (MAAR) (1999). *The annual agricultural statistical abstract*. Damascus, Syrian Arab Republic: MAAR.

Munns, R., James, R. A. and Lauchli, A. (2006) Approaches to increasing the salt tolerance of wheat and other cereals. *Journal of Experimental Botany* **57**, 1025–1043.

Qadir, M. and Oster, J.D. (2004) Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. *Science of the Total Environment* **323**, 1-19.

Ragab, R. (2002) A holistic generic integrated approach for irrigation, crop and field management: the SALTMED model. *Environmental Modelling & Software*, **17**, 345–361.

Ragab R (2010) SALTMED model as an integrated management tool for water, crop, soil and fertilizers. In: Gheyi HR, Dias NS, de Lacerda CF (eds), *Manejo da salinidade na* *agricultura: Estudos básicos e aplicados*. Instituto Nacional de Ciência e Tecnologia em Salinidade, Fortaleza, Brazil, 320–336.

Rameshwaran P., Tepe A., Yazar A. and Ragab R. (2015) The effect of saline irrigation water on the yield of pepper: experimental and modelling study, *Irrigation and Drainage*, **64**, 41-49.

Shannon, M.C. and Grieve, C.M. (1999) Tolerance of vegetable crops to salinity. *Scientia Horticulturae*, **78**, 5-38.

Steppuhn, H., van Genuchten, M.T. and Grieve, C.M. (2005a). Root-zone salinity: I. Selecting a product-yield index and response function for crop tolerance. *Crop Science*, **45**, 209-220.

Steppuhn, H., van Genuchten, M.T. and Grieve, C.M. (2005b). Root-zone salinity: II. Indices for tolerance in agricultural crops. *Crop Science*, **45**, 221-232.

van Genuchten, M.Th. (1983) Analyzing crop salt tolerance data: Model description and user's manual. US Department of Agriculture, Agricultural research service, US Salinity Laboratory. *Research Report No. 120*, USDA-ARS, California, Riverside, 50p.

van Genuchten, M. Th., (1987). A numerical model for water and solute movement in and below the root zone. US Department of Agriculture, Agricultural research service, US Salinity Laboratory. *Research Report No. 121*, USDA-ARS, California, Riverside, 61p.

van Genuchten, M. Th. and Gupta, S. K. (1993) A reassessment of the crop tolerance response function. *Journal of the Indian Society of Soil Science*, **41**, 730-737.

Velagaleti, R. and Schweitzer, S.M. (1993). General effects of salt stress on growth and symbiotic nitrogen fixation in soybean. In: Pessarakli, M. (Ed.), *Plant and Crop Stress*, Marcel Dekker, Inc. New York, 461–471.

Table I. Salinity response functions (Steppuhn *et al*., 2005a)

Number	Function	Equation
1	Simple Linear	$Y_r = a - b(C)$
2	Threshold-slope	$Y_r = 1 - \mathrm{b}(C - C_t)$
3	Weibull	$Y_r = \exp[a(C^b)]$
4	Bi-Exponential	$Y_r = \exp[aC - b(C^2)]$
5	Gompertz	$Y_r = \exp[a \exp(bC)]$
6	Discount	$Y_r = 1 / [1 + (C/C_{50})^{\exp(sC_{50})}]$

a and *b* are the coefficients.

Table II. Soil properties of the experimental site at Raqqa before sowing of crops in the 2009-2010 growth seasons

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	pH	EC_e
0 – 20	42.7	32.0	25.3	Loam	7.6	3.48
20 – 40	36.7	29.3	34.0	Clay loam	7.9	1.78
40 – 60	37.3	26.0	36.7	Clay loam	7.9	2.09
60 – 80	36.0	26.7	37.3	Clay loam	7.8	2.47

Table III. The food legume (faba bean, chickpea and lentil) accessions used in the experiment and the grain yield for Raqqa 2009-2010 and 2010-2011 seasons.

No.	Accessions	2009-2010 Irrigated water salinity EC_{iw}			2010-2011 Irrigated water salinity EC_{iw}		
		0.7 dS m^{-1}	3.0 dS m^{-1}	5.0 dS m^{-1}	0.7 dS m^{-1}	3.0 dS m^{-1}	5.0 dS m^{-1}
	Faba bean	(kg ha^{-1})					
1	DT/B7/9028/2005/06	1991	1114	906	515	954	847
2	DT/B7/9013/2005/06	2638	1407	1079	1297	1578	1141
3	DT/B7/9043/2005/06	2139	1117	1168	1108	1062	1415
4	DT/B7/9035/2005/06	2161	1659	1139	1025	1500	678
5	DT/B7/9005/2005/06	1615	1946	1417	1345	1758	965
6	DT/B7/9020/2005/06	1561	1248	1363	2039	1520	1305
7	DT/B7/9008/2005/06	2315	1879	1118	1834	1317	894
8	ILB1270 Reina Blanca	1968	1933	1501	1202	962	863
9	DT/B7/9009/2005/06	1419	1124	822	1148	1591	1277
10	ILB1814 (Syrian local)	3083	2404	1162	1848	2181	1708
11	ILB1266 (Aguadolce)	3750	2339	1501	2377	1712	1338
	Average	**2240**	**1652**	**1198**	**1431**	**1467**	**1130**
	Standard deviation (*n*=11)	**695**	**483**	**226**	**536**	**373**	**308**
	Chickpea	(kg ha^{-1})					
1	ILC3182	1593	1293	1035	1569	1595	840
2	FLIP03-145C	1246	1114	827	2053	1621	819
3	CPI060546	275	532	94	945	699	140
4	ILC5948	646	178	541	1570	1163	563
5	FLIP03-2C	1356	732	293	1129	808	886
6	FLIP03-46C	2324	1129	874	2020	1371	1129
7	FLIP87-59C	1642	755	379	1293	769	646
8	ILC216	1502	1420	695	1674	1178	1059
9	FLIP87-8C	556	1128	601	1254	1507	1061
10	ILC588	1821	1132	522	2083	1487	719
11	ILC1283	1116	439	355	1952	756	699
12	FLIP04-19C	2146	926	865	1291	1220	754
13	ILC3279	1670	1289	1379	1701	1073	890
14	ILC1302	1791	425	218	1743	2059	1351
15	ILC10722	1383	278	777	1906	1047	748
	Average	**1404**	**851**	**630**	**1612**	**1224**	**820**
	Standard deviation (*n*=15)	**571**	**403**	**342**	**361**	**387**	**280**
	Lentil	(kg ha^{-1})					
1	590	1369	898	583	677	594	386
2	6002	1456	1260	451	845	1042	195
3	6037	1426	666	591	918	573	511
4	7947	1573	1353	615	1593	953	312
5	6994	1296	1051	1219	1186	1186	357
6	7201	493	20	0	902	1196	410
7	7537	1454	1079	399	812	670	321
8	7670	1595	1127	658	963	1345	535
9	7979	1432	928	506	874	618	139
10	8068	1547	982	415	1582	1304	179
11	10072	1330	1145	507	336	584	189
12	10135	1094	823	606	642	709	178
13	10691	1262	1184	907	900	1004	189
14	10707	1493	1114	698	1323	1003	209
15	10712	1426	877	284	1319	724	311
	Average	**1350**	**967**	**563**	**991**	**900**	**295**
	Standard deviation (*n*=15)	**270**	**317**	**273**	**349**	**277**	**126**

Highlights indicate the better performing accessions in a range of irrigated water salinity EC_{iw} (i.e. Accession yield average from both seasons is higher than the combined total average of accessions in both seasons).

Table IV. Mean and Median values of electrical conductivity of the saturated soil paste extracts (EC_e) at mid cropping season for soil layers 0 – 20 cm, 20 – 40 cm and 40 - 60 cm with mean and median values for the whole 0 - 60 cm layer.

Layer	Irrigated water salinity (EC_{iw})	Mean EC_e (*n*=12)	Median EC_e (*n*=12)
0 – 20 cm	0.7 dS m^{-1}	2.29	2.10
	3.0 dS m^{-1}	2.69	2.81
	5.0 dS m^{-1}	5.12	4.78
20 – 40 cm	0.7 dS m^{-1}	1.86	1.64
	3.0 dS m^{-1}	2.48	2.42
	5.0 dS m^{-1}	3.57	3.50
40 - 60 cm	0.7 dS m^{-1}	2.24	1.95
	3.0 dS m^{-1}	2.09	2.20
	5.0 dS m^{-1}	2.72	2.45
Mean 0 - 60 cm	0.7 dS m^{-1}	2.13	2.07
	3.0 dS m^{-1}	2.42	2.34
	5.0 dS m^{-1}	3.80	3.88

n - number of replications.

Table V. The calibrated threshold-slope linear response function parameters *b* and C_t; modified-discount function parameters *s* and C_{50} and salinity tolerance index (*ST Index*).

Crop	Functions	Threshold-slope linear function			Discount function			
		b	C_t (dS m^{-1})	R^2	*s*	C_{50} (dS m^{-1})	R^2	*ST Index*
Faba bean	Minimum	0.28	0.70	0.62	0.11	2.50	0.67	2.77
	Average	0.19	1.27	0.82	0.11	3.89	0.84	4.31
	Maximum	0.07	2.15	0.99	0.11	8.90	0.99	9.88
Chickpea	Minimum	0.46	0.70	0.61	0.13	0.75	0.57	0.85
	Average	0.22	1.13	0.72	0.13	3.37	0.71	3.81
	Maximum	0.09	1.99	0.97	0.13	7.46	0.96	8.43
Lentil	Minimum	0.26	0.60	0.73	0.18	1.30	0.79	1.53
	Average	0.23	1.29	0.84	0.18	3.45	0.87	4.07
	Maximum	0.17	2.09	0.99	0.18	5.80	0.99	6.84

Table VI. The calibrated osmotic pressure (i.e. salinity stress parameter) π_{50} values for mid-season growth stage from SALTMED model.

Crop	Functions	π_{50} (dS m^{-1})
Faba bean	Minimum	5.00
	Average	8.00
	Maximum	17.00
Chickpea	Minimum	2.75
	Average	6.50
	Maximum	12.50
Lentil	Minimum	4.50
	Average	6.75
	Maximum	11.00

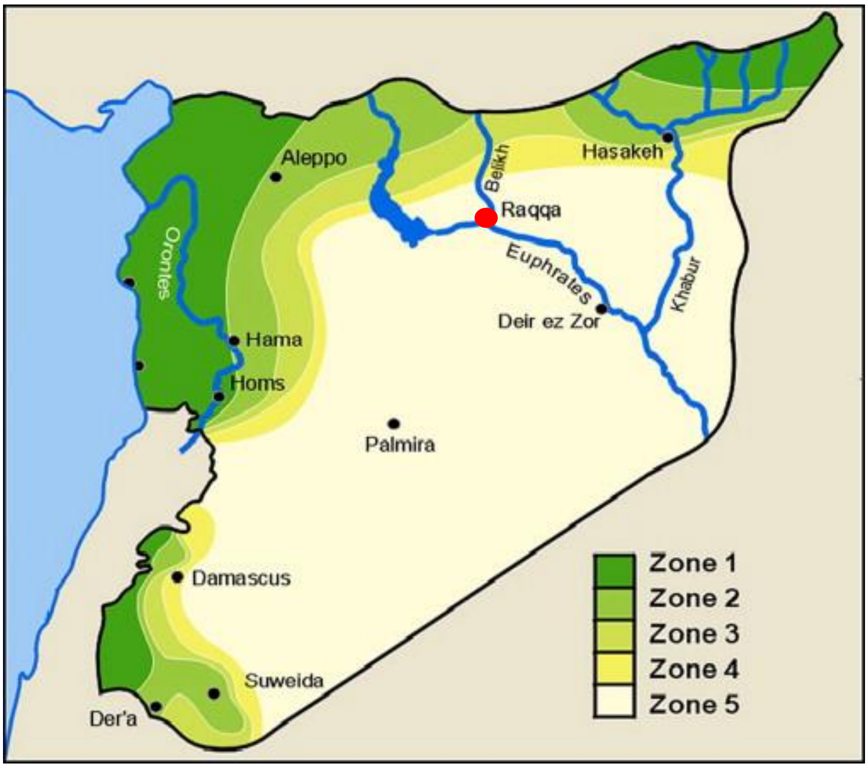


Figure 1. Map of agricultural stability zones of Syria based on the average annual rainfall and with the experimental site Raqqa marked with a red dot (Ministry of Agriculture and Agrarian Reform (MAAR), 1999).

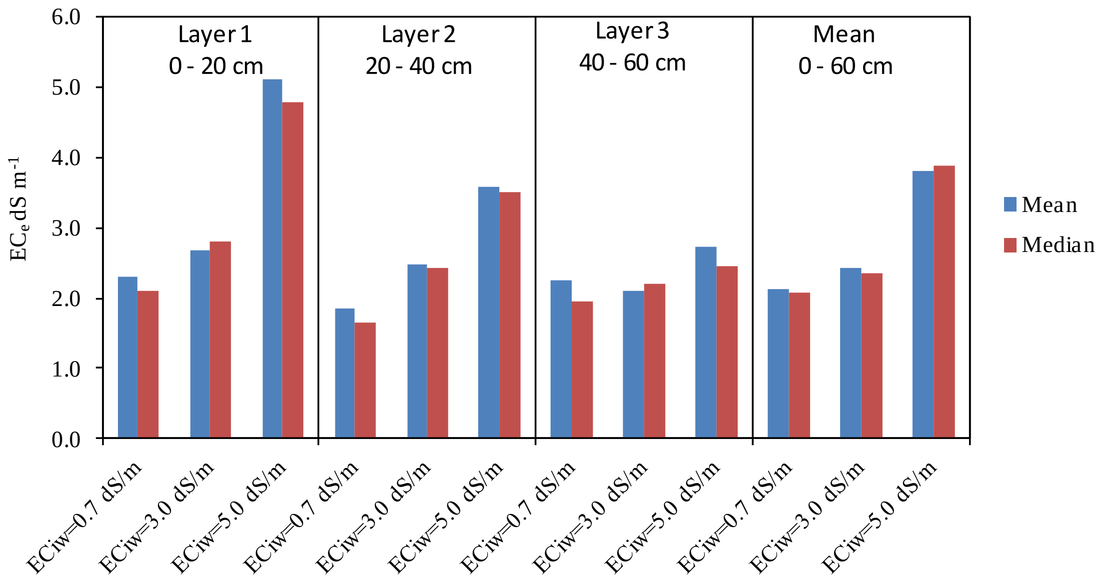
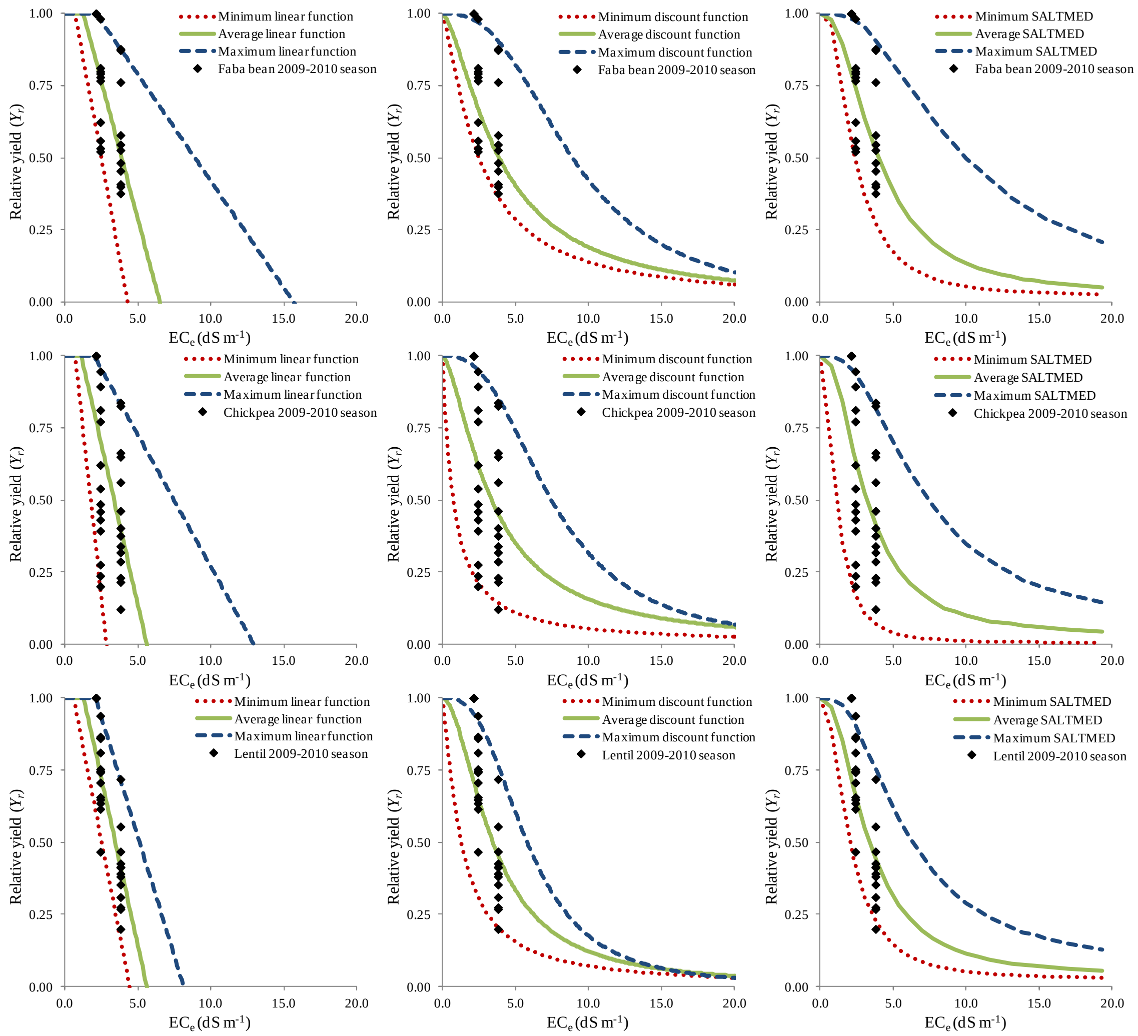
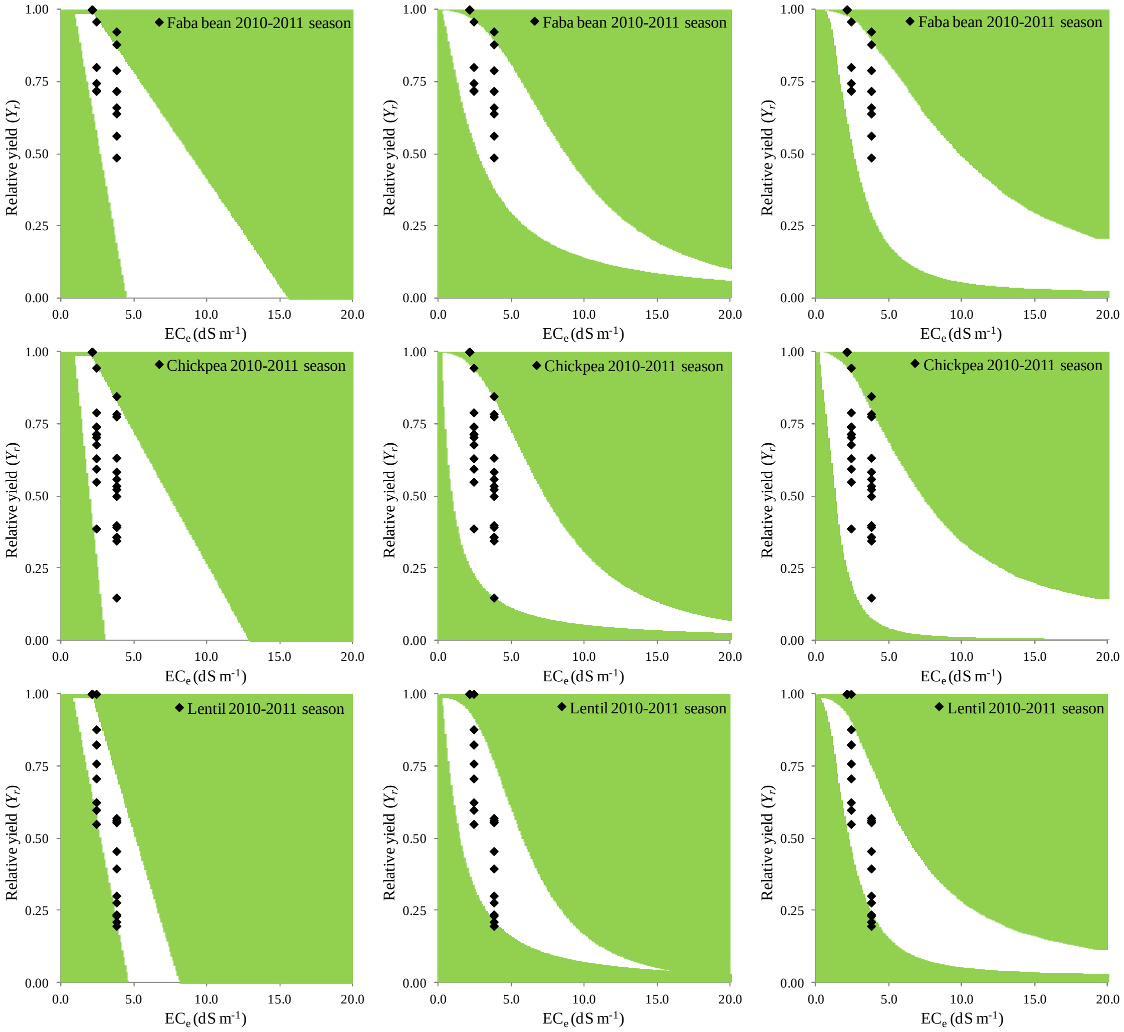


Figure 2. Mean and Median values of electrical conductivity of the saturated soil paste extracts (EC_e) at mid cropping season for soil layers 0 – 20 cm, 20 – 40 cm and 40 - 60 cm with mean and median values for the whole 0 - 60 cm layer.



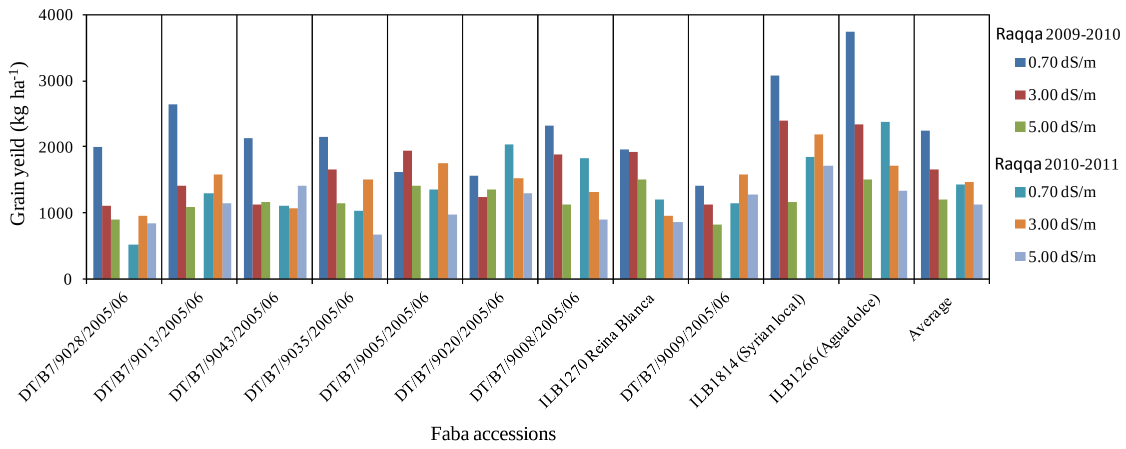
(a) Threshold-slope linear function (b) Modified-discount function (c) SALTMED model function

Figure 3 Calibrated minimum, average and maximum response functions for faba bean, chickpea and lentil for Raqqa 2009-2010 growth season data (a) Threshold-slope linear function, (b) Modified-discount function and (c) SALTMED model function (calibration).

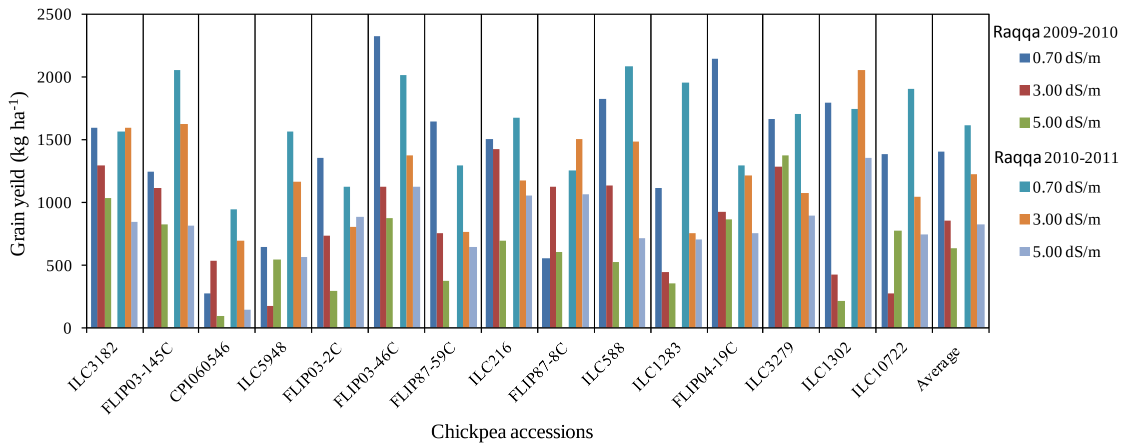


(a) Threshold-slope linear function (b) Modified-discount function (c) SALTMED model function

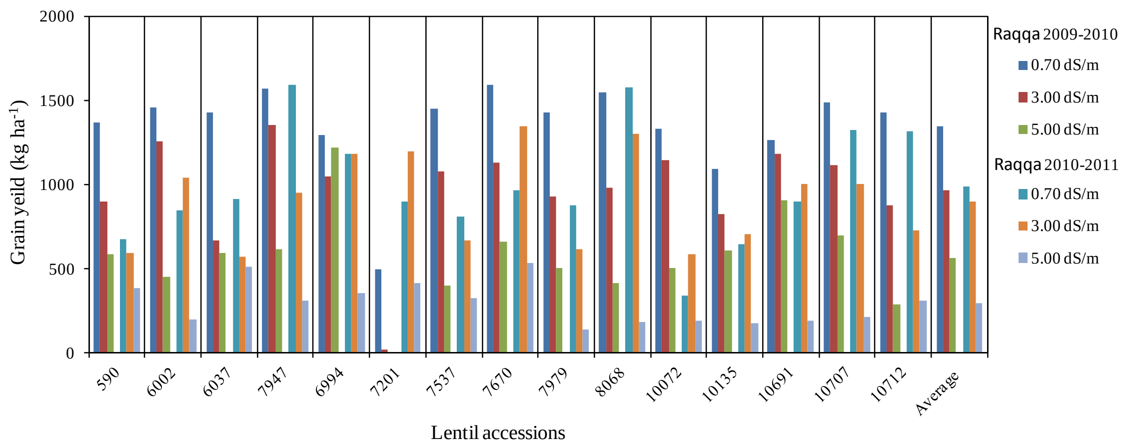
Figure 4 Calibrated response function regions (i.e. minimum and maximum curves) for faba bean, chickpea and lentil with Raqqa 2010-2011 season data (a) Threshold-slope linear function, (b) Modified-discount function and (c) SALTMED model function (validation).



(a) Faba bean accessions

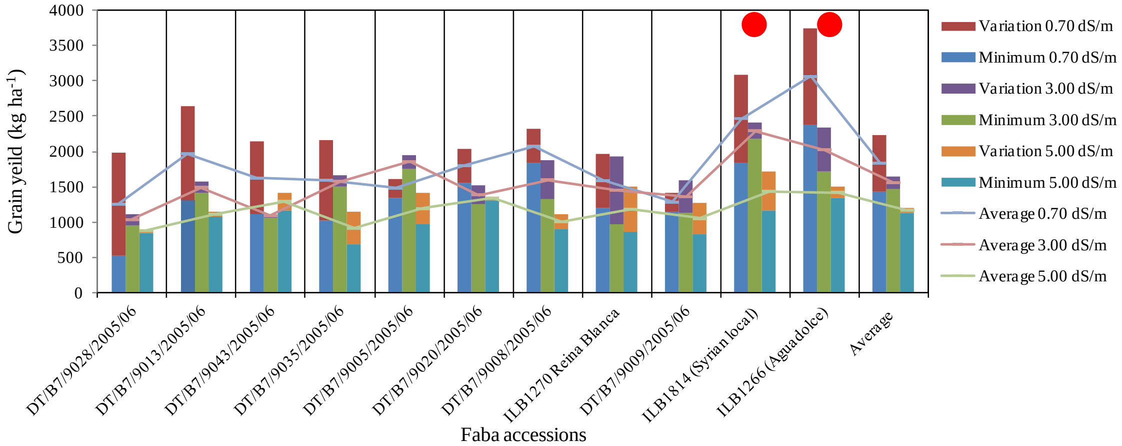


(b) Chickpea accessions

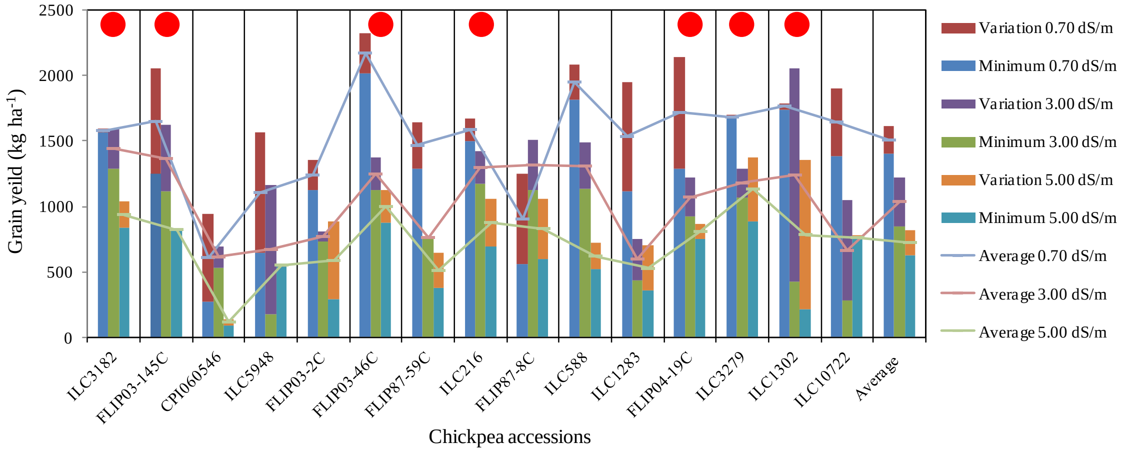


(c) Lentil accessions

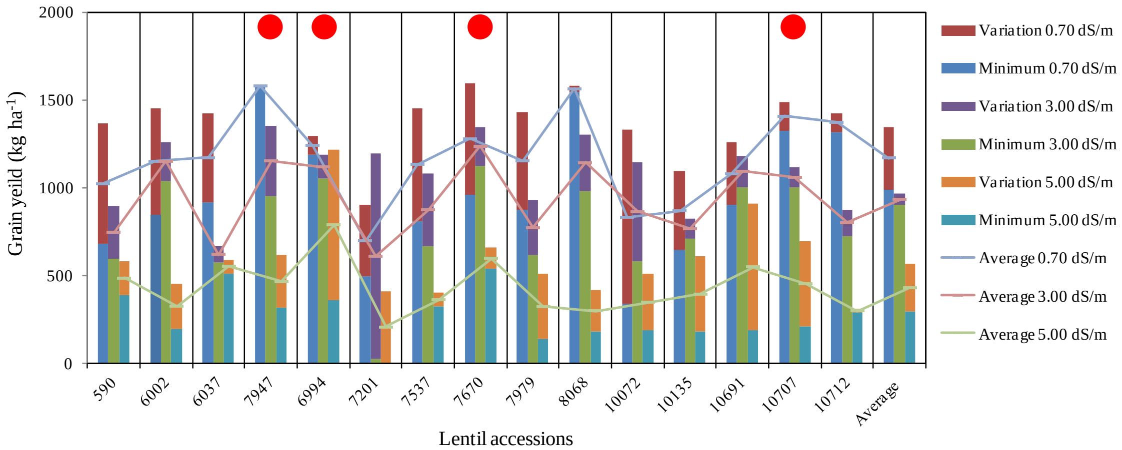
Figure 5 Measured grain yield (kg ha^{-1}) for Raqqa 2009-2010 and 2010-2011 growth seasons (a) Faba bean accessions, (b) Chickpea accessions and (c) Lentil accessions for different irrigation water salinities.



(a) Faba bean accessions



(b) Chickpea accessions



(c) Lentil accessions

Figure 6 Minimum grain yield (kg ha^{-1}) among the Raqqa 2009-2010 and 2010-2011 growth seasons with the variation between both seasons (Red dots indicate the better performing accessions in a range of irrigation water salinity EC_{iw}). (a) Faba bean accessions, (b) Chickpea accessions and (c) Lentil accessions.