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EVALUATING THE PRODUCTIVITY POTENTIAL OF CHICKPEA, LENTIL AND FABA BEAN UNDER SALINE WATER IRRIGATION SYSTEMS[†]

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ABSTRACT

The information on salinity threshold levels for food legumes when irrigating with saline water is limited and old. In a multi-year study at two sites in the Euphrates Basin, we aimed at (i) evaluating the potential of saline water irrigation for chickpea, faba bean and lentil production; and (ii) using the SALTMED model to determine threshold crop yields based on irrigation water salinity in equilibrium with ambient soil solution salinity. To evaluate 15 accessions each of lentil and chickpea, and 11 accessions of faba bean, three irrigation treatments were used with salinity levels of 0.87, 2.50 and 3.78 dS m^{-1} at Hassake and 0.70, 3.0 and 5.0 dS m^{-1} at Raqqa. Aggregated grain yields showed significant differences ($p < 0.05$) among crop accessions. Calibration and validation of the SALTMED model revealed a close relationship between actual grain yields from the field sites and those predicted by the model. The 50% yield reduction (π_{50} value) in chickpea, lentil, and faba bean occurred at salinity levels of 4.2, 4.4 and 5.2 dS m^{-1}, respectively. These results suggest that of the three food legume crops, faba bean can withstand relatively high levels of irrigation water salinity, followed by lentil and chickpea. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: Irrigation water salinity; food legumes; SALTMED model; crop salt tolerance; Mediterranean region

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RÉSUMÉ

Les informations sur les seuils de salinité pour les légumineuses alimentaires irriguées avec de l'eau saline sont limitées et anciennes. Dans une étude pluriannuelle sur deux sites dans le bassin de l'Euphrate, nous avons cherché à (i) évaluer le potentiel de l'irrigation de l'eau salée pour le pois chiche, la féverole, les lentilles; et à (ii), déterminer les rendements des cultures influencés par de l'eau saline en équilibre avec la solution du sol ambiante, en utilisant le modèle SALTMED. Nous avons évalué 15 rangées de lentilles et de pois chiches, et 11 de féves avec trois traitements d'irrigation de salinité de 0.87, 2.50 et 3.78 dS m^{-1} à Hassake, et de 0.70, 3.0 et 5.0 dS m^{-1} à Raqqa. Les rendements en grains ont montré des différences significatives ($p < 0.05$) dans les différents traitements. Le calibrage et la validation du modèle SALTMED ont révélé la relation étroite entre les rendements réels en grains et les prédictions du modèle. La réduction de rendement de 50% (valeur π50) pour les pois chiches, les lentilles et la féverole se produit à des niveaux de salinité de 4.2, 4.4 et 5.2 dS m^{-1}, respectivement. Ces résultats suggèrent que parmi les trois cultures de légumineuses alimentaires, la féve peut résister à des niveaux relativement élevés de salinité de l'eau d'irrigation, suivie par les lentilles et les pois chiches. Copyright © 2015 John Wiley & Sons, Ltd.

MOTS CLÉS: irrigation avec de l'eau saline; légumineuses alimentaires; modèle SALTMED; tolérance des cultures au sel; région méditerranéenne

INTRODUCTION

Irrigation has played an important role in crop production and agricultural development in dry areas of the Mediterranean region. Fresh water in the region is not only a scarce resource but is also unevenly distributed (Qadir *et al.*,

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2007; Food and Agriculture Organization of the United nations (FAO), 2013), as a result of which competition for fresh water among different water-use sectors is already increasing in the Mediterranean region (Guardiola-Claramonte *et al*., 2012). The consequence would be a gradual decrease in freshwater allocation to agriculture. Furthermore, there is the uncertain umbrella of global climate variability. Climate predictions anticipate not only an increase in temperatures, but a pronounced decrease in precipitation in most of the Mediterranean region (Intergovernmental Panel on Climate Change (IPCC), 2007; Giorgi and Lionello, 2008).

As supplies of good-quality irrigation water are expected to decrease in dry areas of the Mediterranean region, available water supplies need to be used more effectively and efficiently (Guardiola-Claramonte *et al*., 2012), and one of the approaches can be the reuse of marginal-quality water such as saline drainage water generated by irrigated agriculture or pumped from saline aquifers (Tanji and Kielen, 2002; Qadir and Oster, 2004). The same applies to salt-affected soils, which warrant attention for efficient, inexpensive and environmentally acceptable management to improve crop production. Beresford *et al*. (2001) and Munns (2002) reported that half of the irrigation schemes in the world have been subjected to varying levels of salinization.

A number of bioprocesses such as photosynthesis and respiration can be affected under saline water irrigation and saline soil conditions, in addition to the effect of salinity on the morphology of plants. Salinity may cause nutritional imbalance and affect the biochemical processes of the plant such as enzymes, nuclear acids and hormones. Based on the crop salt tolerance, there may be reduction in the effective green surface in photosynthesis and reduction in dry matter production, reflected negatively at the end in the decrease in economic yield (Munns, 1993).

Food legumes—chickpea, lentil, and faba bean—are generally classified as sensitive to salinity. At the same level of root zone salinity, the yield of legumes tends to be more affected than that of cereals (Katerji *et al*., 2011). Information on their salinity threshold levels and slope of yield decline with salinity is extremely limited (Steppuhn *et al*., 2005) and old (Ayers and Eberhard, 1960). Growing food legumes and evaluating their growth and yield response in the Mediterranean region under saline conditions is important because of (i) scarcity of freshwater resources to grow food legume crops; (ii) increasing areas of irrigated land under salt-affected soils and/or irrigated with saline water in the semi-arid and arid areas; and (iii) increasing demand for food legumes due to increasing meat prices, the need to meet human requirements for protein from food legumes, and population growth.

In this study undertaken in the Euphrates Basin within Syria, we aimed at (i) evaluating the potential of saline water irrigation for food legume (chickpea, faba bean and lentil) production and characterizing them for salt tolerance; and (ii) using the SALTMED model to determine the salinity level for 50% yield threshold, π_{50} value, of chickpea, faba bean and lentil based on irrigation water salinity levels in equilibrium with ambient soil solution salinity levels.

MATERIALS AND METHODS

Based on the average annual rainfall, land resources in Syria are divided into the following agro-ecological zones: annual rainfall > 350 mm (Zone 1); annual rainfall > 600 mm (Zone 1a); annual rainfall 350–600 mm (Zone 1b); annual rainfall 250–350 mm (Zone 2); annual rainfall > 250 mm, and ≥ 250 mm during 1/2 of the years monitored (Zone 3); marginal land, annual rainfall 200–250 mm (Zone 4) and desert or steppe region (Zone 5).

The study sites were located in two agro-ecological zones in Syria, namely, Zone 3 where the study site was near Hassake city, and Zone 5 where the study site was close to Raqqa. In these areas, soils are formed over Neogene limestone, marl, gypsum and conglomerates.

Site characterization: Hassake

The Hassake study site is located 7 km north-west of Hassake city. The site is surrounded by a rainfed agricultural system where the main crop is wheat. For site characterization, representative soil samples from three randomly selected sites were collected from the experimental field before planting from 0–20, 20–40, 40–60, 60–80 and 80–100 cm depths (15 samples). These soil samples were processed and analysed by standard procedures for texture, calcite ($CaCO_3$), organic matter, cation exchange capacity, major nutrients, pH and electrical conductivity (EC) of the saturated extract, and major cations and anions.

The experimental soil is deep clay loam to clay, of slightly alkaline pH with a high percentage of calcium carbonate (approximately 32%) and slightly affected by salinity and moderate in nutrient availability status (Table I). There is a general decline in EC, organic matter and nutrient (N, P and K) concentrations in the soil with depth.

Soil surface laser levelling was performed prior to the start of the experiment to improve surface irrigation water application efficiency. EC of the groundwater was close to 4 dS m^{-1} while the sodium adsorption ratio (SAR) was less than 2 due to the presence of high concentrations of calcium, sulphate and magnesium. As the groundwater level at the experimental site was deep (30 m below the soil surface), there was no contribution of groundwater to crop evapotranspiration. Long-term average climatic data

Table I. Soil properties of the experimental site at Hassake before sowing of crops (pre-experiment soil before 2009–2010 cropping season)

Depth cm	pH	EC_e dS m^{-1}	OM %	$CaCO_3$ %	Total N %	P mg kg^{-1}	K mg kg^{-1}	Sand	Silt	Clay	Texture
									%		
0–20	7.7	3.32	1.22	32.2	0.093	12.4	405	30.0	36.7	33.3	Clay loam
20–40	7.7	3.38	0.82	31.6	0.077	3.42	274	28.7	26.0	45.3	Clay
40–60	7.8	3.22	0.31	32.2	0.060	2.80	140	26.7	24.7	48.7	Clay
60–80	7.7	2.86	0.25	33.4	0.050	2.89	126	24.0	24.7	51.3	Clay
80–100	7.7	2.54	0.13	31.9	0.050	2.91	126	23.3	23.3	53.3	Clay

(1995–2009) of the experimental station are presented in Table II.

Site characterization: Raqqa

The experimental site at Raqqa is located 16 km north-east of Raqqa city. It receives fresh water for irrigation from the Euphrates River through an open channel, 12 km from the experimental site. The experimental site is located in the stability zone 5 with an average rainfall of 218 mm during 1974–1994. The recent rainfall pattern reveals that the amount of rainfall has decreased, perceived to be a result of climate change. Climatic data (average of 20 years) of the experiment site at Raqqa are presented in Table III.

The soil at the experimental site is clay loam to clay, slightly alkaline with a pH around 7.7. The soil contains a large percentage of calcium carbonate (approximately 32%) and the surface soil is slightly affected by salinity and moderate in fertility (Table IV). Except for soil texture, which is loam to clay loam at Raqqa, other properties of the study site are similar to those at the Hassake site, where soil texture is clay loam to clay, i.e. soil texture is relatively finer at Hassake than at Raqqa. Soil surface laser levelling was performed prior to the start of the experiment to improve surface irrigation water application efficiency. The site was provided with a horizontal drainage system with the drains installed at 1.6–1.9 m depth. As the site was equipped with a drainage system, there was no contribution of groundwater to crop evapotranspiration.

Irrigation treatments

Three irrigation treatments were used at each site. At Hassake, the irrigation water had average electrolyte concentrations of 0.87, 2.50 and 3.78 dS m^{-1}. The treatment referred to as Irrig-1 had different levels of EC ranging from 0.52 to 1.19 dS m^{-1} with an overall average of 0.87 dS m^{-1} (good quality water). The treatment denoted as Irrig-3

Table II. Average climatic data of the experiment site at Hassake (the letters J to D stand for January through December in order)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Total or mean
Rainfall (mm)	53	39	41	47	20	1	0	0	1	10	17	43	272
Temperature (°C)	8.6	9.2	13	18	26	31	32	34	28	22	15	11	20.7
Humidity (%)	78	64	70	67	56	45	48	53	55	50	62	70	60
Evaporation (mm)	28	36	78	105	160	297	324	289	195	114	60	28	1710
Wind speed (m s^{-1})	2	2	2.2	2.5	2.5	2.5	2.7	2.6	2.9	1.9	2.1	1.7	2.2
Sunshine (h)	5.1	6.4	7	8.7	11	13	13	13	10	9.1	6.9	5.6	9.1

Table III. Average climatic data of the experiment site at Raqqa (the letters J to D stand for January through December in order)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Total or mean
Rainfall (mm)	35	39	36	17	15	4	0	0	3	22	18	29	218
Temperature (°C)	6.5	8.8	12.5	17.4	23.8	28.2	30.1	29.5	25.6	19.9	12.8	8.0	18.6
Humidity (%)	79	72	63	55	44	34	38	41	44	52	65	79	55.5
Evaporation (mm)	34	50	109	153	233	327	366	295	207	121	60	34	1990
Wind speed (m s^{-1})	2.6	2.8	3.3	3.6	3.6	4.8	5.4	4.4	2.8	2.0	1.7	2.3	3.3
Sunshine (h)	4.6	5.9	6.9	8.0	10.4	12.0	12.2	11.5	10.5	8.4	7.0	4.9	8.5

Table IV. Soil properties of the experimental site at Raqqa before sowing of crops (pre-experiment soil before 2009–2010 cropping season)

Depth cm	pH	EC_e dS m^{-1}	OM %	$CaCO_3$ %	Total N %	P mg kg^{-1}	K mg kg^{-1}	Sand	Silt	Clay	Texture
								%			
0–20	7.6	3.48	1.73	23.8	0.1	14.1	436	42.7	32.0	25.3	Loam
20–40	7.9	1.78	0.66	29.2	0.1	4.3	233	36.7	29.3	34.0	Clay loam
40–60	7.9	2.09	0.38	28.3	0.1	4.2	169	37.3	26.0	36.7	Clay loam
60–80	7.8	2.47	0.07	33.2	0.0	5.1	113	36.0	26.7	37.3	Clay loam

consisted of pumped groundwater with EC levels ranging from 2.96 to 4.62 dS m^{-1} at different pumping times and having an average EC value of 3.78 dS m^{-1}. The treatment referred to as Irrig-2 was based on a mix of good quality water and groundwater from treatments Irrig-1 and Irrig-3 at the ratio of 1: 1.

The EC levels in this blended treatment were also variable depending upon the water EC variability in the Irrig-1 and Irrig-3 treatments. The average EC in treatment Irrig-2 was 2.50 dS m^{-1}. Blending in the case of preparing water for treatment Irrig-2 was done in a large tank to store water for irrigation of three food legume crops.

At the Raqqa site, the irrigation treatments had more stable EC values than at Hassake. The treatments (Irrig-1, Irrig-2 and Irrig-3) had average electrolyte concentrations of 0.70, 3.0 and 5.0 dS m^{-1}. Blending in the case of treatment Irrig-2 was undertaken in a way similar to that followed at the Hassake site.

Experimental and statistical procedures

Experimental design and layout and field management practices used at both sites were the same. The plot size of 14.0 × 12.5 m (175 m^2) was used for the experimental layout using a split-plot design with water quality in the main plots in three complete blocks and food legume accessions in the sub-plots. There were three separate split-plot experiments, one for each of the food legumes with a layout in nearby fields. Lentil accessions were planted in rows 35 cm long and 4 cm apart while chickpea accessions were planted in rows at 35 cm row spacing and 7 cm apart. In the case of faba bean, the accessions were planted in rows at 50 cm row spacing and 25 cm apart. In each treatment, there were 15 rows each of lentil and chickpea, and 11 rows of faba bean. The basin irrigation method, a prevalent method of irrigation in the area, was used after laser levelling. At the time of each irrigation application, samples of the irrigation water were collected and analysed for pH, EC, major cations and anions, in addition to boron and mineral nitrogen.

Soil samples from the 5 depths, 0–20, 20–40, 40–60, 60–80, 80–100 cm, and each of the 9 main plots were collected (45 samples) mid-season and after crop harvest and analysed for major nutrients (N, P and K), pH and EC of saturated extract, major cations and anions in addition to percentage moisture. The amount of applied irrigation water was calculated from the water balance equation including rainfall. Fertilizers were applied before seeding as: N at 10 kg ha^{-1}, P_2O_5 at 50 kg ha,$^{-1}$ K_2O at 20 kg ha^{-1}.

Fifteen accessions each of lentil and chickpea and 11 accessions of faba bean were used in the experiments at the Hassake and Raqqa sites. These food legume accessions were provided by the International Centre for Agricultural Research in Dry Areas (ICARDA). During the 2009–2010 crop season sowing at Hassake and Raqqa was done on 2 and 3 December 2009, respectively. In the 2010–2011 season, the crops were sown about a month later than the 2009–2010 season, with respective sowing dates for the Hassake and Raqqa sites being 4 and 5 January 2011.

Statistical analysis, for each crop, was performed at each site (Hassake and Raqqa) and combined over the sites using the split-plot design on the grain yield where the same accessions and experimental layout and similar field management practices were used. The combined analysis of variance of data over the sites and years was carried out to evaluate the interaction of salinity levels, accessions and salinity × accession interaction with site and years within the site using the blocking structure for the split-plot design. The multiple comparison test based on Bonferroni adjustment was used to compare the accessions for their mean productivity values.

SALTMED model for crop threshold levels for salinity

The SALTMED model was used to calibrate the relative yield of the food legume crops obtained from the field with the model-predicted values. This was followed by validating the model calibration. The model calibration was undertaken from the data generated from the field site in Raqqa in 2009–2010. It was validated from the data generated from the same site in 2010–2011. The model was run in the predictive mode with the anticipated yield loss of food legume crops when exposed to an incremental increase in irrigation water salinity beyond the irrigation water salinity used in the experiment. The model was run to predict yields of the crops exposed to irrigation water salinity as high as 19 dS m^{-1}.

As initially developed, the SALTMED model included the following key processes: evapotranspiration, plant water uptake, water and solute transport under different irrigation systems, drainage and the relationship between crop yield and water use, and relationship between salinity and crop yield and yield components (Ragab, 2002; Ragab *et al.*, 2005a, 2005b; Ragab, 2015). Later improvements in the model have added several important features as reported in Hirich *et al.* (2012) and Silva *et al.* (2013).The model can be used for a variety of irrigation systems, soil types, soil stratifications, crops and trees, water management strategies (blending or cyclic), leaching requirements, and water quality. The model is based on established water and solute transport, evapotranspiration and crop water uptake equations (Oster *et al.*, 2012).

RESULTS AND DISCUSSION

Response of food legumes to irrigation water quality

Lentil. Analysis of variance of lentil grain yield for the experimental sites, Raqqa and Hassake, for 2009–2011 and three irrigation water salinity levels revealed significant differences ($p < 0.05$) among lentil accessions (Table V). There was no significant ($p > 0.05$) interaction between accessions and salinity levels, nor were any higher-order interactions significant. Averaged over all the salinity levels, lentil accession 10712 produced the highest grain yield (1680 kg ha^{-1}), closely followed by accession 7947 (1670 kg ha^{-1}), accession 10707 (1670 kg ha^{-1}) and accession 10 691(1650 kg ha^{-1}). These accessions remained statistically at par using a multiple comparison test (Table V). Accession 10712's performance was significantly superior to that of accession 6037 (1220 kg ha^{-1}). Among the lentil accessions, accession 10707 had the highest average grain yield (2050 kg ha^{-1}) when irrigated with good quality water under Irrig-1 treatment where irrigation water salinity was less than 1 dS m^{-1} at both experimental sites. This accession was followed by accession 10712, which yielded lentil grain at 1880 kg ha^{-1}. In the case of the treatment with blended water (Irrig-2), the same accession (10707) performed better for grain yield (1840 kg ha^{-1}) than other accessions. At the highest irrigation water salinity (Irrig-3), accession 10712 took over with grain yield of 1500 kg ha^{-1}. It is interesting to note that most accessions followed the same pattern as was found in the drought-tolerance studies undertaken at ICARDA's research station near Aleppo. This may be due to the effect of water stress in the first phase of salt stress, which has also been documented by several studies evaluating crops and their same accessions for salt and drought tolerance (Fortmeier and Schubert, 1995).

The overall lentil response to irrigation treatment revealed a yield-decreasing trend with increasing salinity levels in the irrigation water. The average yield for all lentil accessions was in the order: 1590 kg ha^{-1} (Irrig-1) $>$ 1550 kg ha^{-1} (Irrig-2) $>$ 1250 kg ha^{-1} (Irrig-3). The average soil profile (1 m deep) salinity for the three irrigation levels at the Hassake site cultivated with lentil accessions was 3.84 dS m^{-1}. It was 2.28 dS m^{-1} at the Raqqa site for the same soil depth. The lower salinity level at the Raqqa site was due

Table V. Mean grain yields (kg ha^{-1}) of 15 accessions of lentil, 15 accessions of chickpea, and 11 accessions of faba bean under three irrigation water quality treatments applied at the experimental sites in Hassake and Raqqa, 2009–2011

Lentil		Chickpea		Faba bean	
Accession	Yield	Accession	Yield	Accession	Yield
590	1460 abcd	ILC3182	1870 defg	DT/B7/9028/2005/06	2160 ab
6002	1420 abcd	FLIP03-145C	2020 g	DT/B7/9013/2005/06	2670 bc
6037	1220 abc	CPI 060546	836 a	DT/B7/9043/2005/06	2480 ab
7947	1670 cd	ILC 5948	1710 bcdefg	DT/B7/9035/2005/06	2390 ab
6994	1640 bcd	FLIP03-2C	1130 ab	DT/B7/9005/2005/06	2660 bc
7201	1140 a	FLIP03-46C	1780 cdefg	DT/B7/9020/2005/06	2490 ab
7537	1310 abcd	FLIP87-59C	1420 abcdef	DT/B7/9008/2005/06	2040 a
7670	1650 bcd	ILC216	1330 abcd	ILB1270 Reina Blanca	2450 ab
7979	1210 ab	FLIP87-8C	1300 abcd	DT/B7/9009/2005/06	1990 a
8068	1500 abcd	ILC588	2160 g	ILB1814 (Syrian local)	3190 c
10072	1280 abcd	ILC 1283	1270 abc	ILB1266 (Aguadolce)	3230 c
10135	1460 abcd	FLIP04-19C	1380 abcde		
10691	1650 bcd	ILC3279	1730 cdefg		
10707	1670 bcd	ILC1302	1200 fg		
10712	1680 d	ILC10722	1950 efg		
SE	±82	SE	±106	SE	±107

Means with different letters under the columns yield for each food legume crop are statistically different at 5% level of significance.

to the leaching of soluble salts from the soil profile and their subsequent removal through the drainage system installed at the site.

Chickpea. Significant ($p < 0.05$) accession differences were found for chickpea yield. The average values for chickpea grain yield suggest chickpea accession ICL588 as the most promising accession with the ability to withstand high levels of salts in the irrigation water. This accession produced highest average grain yield (2159 kg ha^{-1}), closely followed by accession FLIP03-145C (2020 kg ha^{-1}); both accessions remained statistically at par (Table V). Accession ICL588 also produced the highest average grain yield (2440 kg ha^{-1}) when irrigated with good quality water under Irrig-1 treatment, where irrigation water salinity was less than 1 dS m^{-1} at both experimental sites. The same accession produced the highest yield in Irrig-2 treatment (2260 kg ha^{-1}). In the case of Irrig-3 treatment, this accession was again among the highest grain-yield-producing chickpea accessions. ICL588 also emerged as one of the top accessions in the case of drought tolerance by producing significantly higher grain yield under water-stressed conditions, again demonstrating the crucial effect of water stress in the first phase of salt stress.

The overall chickpea response to irrigation treatment revealed a yield-decreasing trend with increasing salinity levels in the irrigation water. The average yield for all chickpea accessions was in the order: 1750 kg ha^{-1} (Irrig-1) $>$ 1600 kg ha^{-1} (Irrig-2) $>$ 1430 kg ha^{-1} (Irrig-3). Based on the three irrigation levels, the average salinity of the 1 m soil depth at the Hassake site under chickpea accessions was 3.86 dS m^{-1}. However, the average salinity for the same soil depth at the Raqqa site (2.34 dS m^{-1}) was lower than at the Hassake site. The effective leaching of soluble salts from the soil profile and removal through the drainage system at the Raqqa site contributed to lower levels of soil profile salinity.

Faba bean. For faba bean too, the accession differences were statistically significant ($p < 0.05$). On average, faba bean accessions produced more grain than chickpea and lentil accessions. Of the faba bean accessions, accession ILB1266 Aguadolce had the highest average grain yield (3790 kg ha^{-1}) when irrigated with good quality water under Irrig-1 treatment where irrigation water salinity was less than 1 dS m^{-1} at both experimental sites. This accession was followed by accession ILB 1814 Syrian local, which yielded faba bean grain at 3570 kg ha^{-1}. In the case of treatment with blended water (Irrig-2), the same accession (ILB 1814 Syrian local) performed better for grain yield (3420 kg ha^{-1}), closely followed by accession ILB1266 Aguadolce, which produced grain at 3180 kg ha^{-1}. Both accessions performed better than other faba bean accessions at the highest irrigation water salinity (Irrig-3) treatment where accessions ILB1266 Aguadolce and ILB 1814 Syrian local produced grain yield at 2730 and 2580 kg ha^{-1}, respectively. In terms of aggregated grain yield from both sites and three irrigation salinity levels, faba bean accession ILB1266 Aguadolce produced the highest grain yield (3230 kg ha^{-1}) followed by ILB1814 Syrian local (3190 kg ha^{-1}); both remained statistically at par using the multiple comparison test based on Bonferroni adjustment (Table V).

The overall faba bean response to irrigation treatment revealed a yield-decreasing trend with increasing salinity levels in the irrigation water. The average yield for all faba bean accessions was in the order: 2700 kg ha^{-1} (Irrig-1) $>$ 2560 kg ha^{-1} (Irrig-2) $>$ 2300 kg ha^{-1} (Irrig-3). The average soil profile (1 m depth) salinity for the three irrigation levels at the Hassake site under faba bean accessions was 3.62 dS m^{-1}, while it was 2.94 dS m^{-1} at the Raqqa site for the same soil depth. The lower salinity level at the Raqqa site was due to the leaching of soluble salts from the 1 m soil depth and subsequent removal of the leached salts through the horizontal drainage system with the drains installed 1.6–1.9 m below the soil surface.

Estimation of crop threshold levels using SALTMED

Using the SALTMED model, $\pi 50$ values for three food legumes (faba bean, chickpea and lentil) were calibrated and validated using field data from the 2009–2010 and 2010–2011 seasons, respectively. For the model calibration, the values of $\pi 50$ used for the food legume crops at three growth stages (initial, middle and late) are given in Table VI.

Lentil. Based on the average of 15 accessions for the 2009–2010 data from the Raqqa site, yields of lentil from the field data for Irrig-2 and Irrig-3 relative to that of Irrig-1 were 0.717 and 0.417, respectively. As predicted by the SALTMED model during the model calibration process, the corresponding relative yields for Irrig-2 and Irrig-3 treatments were very close, i.e. 0.695 and 0.438, respectively. The difference between the average measured results from the field site and model-calibrated results for Irrig-2 and Irrig-3 treatments was 2.99 and −4.99%, respectively (Table VII). Based on the measured average relative yield

Table VI. Calibrated $\pi 50$ values (dS m^{-1}) for three food legume crops (lentil, chickpea and faba bean) for the 2009–2010 crop season

Crop stage	Lentil	Chickpea	Faba bean
Initial	5.75	5.50	7.00
Mid	6.75	6.50	8.00
Late	7.75	7.50	9.00

Table VII. Percentage of error between the average measured results from the field site and model calibrated results

Water salinity dS m^{-1}	Lentil %	Chickpea %	Faba bean %
0.7	0.00	0.0	0.00
3.0	2.99	−11.0	−5.84
5.0	−4.99	8.79	1.61

Table VIII. As predicted and validated by the SALTMED model, yield potential (%) of food legume crops at specified levels of irrigation water salinity expressed as dS m^{-1}

	Yield potential (%) at specified salinity (dS m^{-1})			
Crop	25%	50%	75%	100%
Lentil	7.7	4.4	2.7	0.8
Chickpea	7.2	4.2	2.6	0.7
Faba bean	9.7	5.2	3.2	0.9

of lentil accessions and model-calibrated results for lentil for the 2009–2010 season data, the linear regression equation for field-obtained relative yield and model-predicted relative yield was $y = 0.963x + 0.0259$ ($R^2 = 0.996$).

During the model validation process for the field data for the next season (2010–2011) from the same site using calibrated π50, the relative yields of lentil from the field data for Irrig-2 and Irrig-3 treatments were 0.834 and 0.262, respectively. The corresponding relative yields for Irrig-2 and Irrig-3 treatments as predicted by the SALTMED model were 0.622 and 0.323, respectively. In terms of using the SALTMED model to determine the 50% threshold yield of lentil (π_{50} value) based on salinity levels in irrigation water in equilibrium with ambient soil solution salinity levels, the 50% yield reduction occurred at salinity of 4.4 dS m^{-1} during the model validation process based on 2010–2011 data for lentil (Fig. 1).

As predicted and validated by the SALTMED model, yield potential of lentil increased with decreasing levels of irrigation water salinity. For example, yield potential of lentil was 100% at irrigation water salinity of 0.8 dS m^{-1}, 75% at 2.7 dS m^{-1} and 25% at 7.7 dS m^{-1} (Table VIII).

Chickpea. The relative yields of chickpea from the field data for Irrig-2 and Irrig-3 treatments were 0.606 and 0.449, respectively. These relative yields were based on the average of 15 accessions for the 2009–2010 data from the Raqqa site. As predicted by the SALTMED model during the model calibration process, the corresponding relative yields for Irrig-2 and Irrig-3 treatments were very close, i.e. 0.673 and 0.409, respectively. The percentage of error between the average measured results from the field site and model-calibrated results for Irrig-2 and Irrig-3 treatments was −10.96 and 8.79, respectively (Table VI). Based on the measured average relative yield of chickpea accessions and model-calibrated results for chickpea for the 2009–2010 season data, the linear regression equation for field-obtained relative yield and model-predicted relative yield was $y = 1.03x - 0.0083$ ($R^2 = 0.968$).

During the model validation process for the field data for the next season (2010–2011) from the same site, the relative yields of chickpea from the field data for Irrig-2 and Irrig-3 treatments were 0.650 and 0.465, respectively. The corresponding relative yields for Irrig-2 and Irrig-3 treatments as predicted by the SALTMED model were 0.728 and 0.425, respectively. In terms of using the SALTMED model to determine the 50% threshold yield of chickpea (π_{50} value) based on salinity levels in irrigation water in equilibrium with ambient soil solution salinity levels, the 50% yield

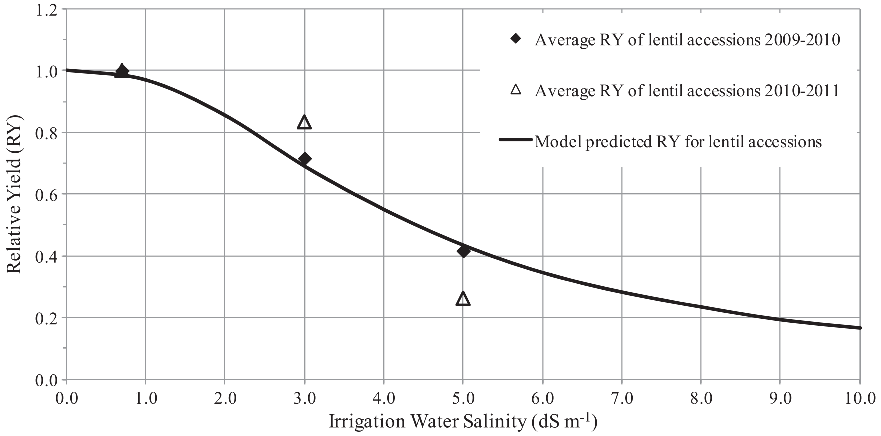

Figure 1. As predicted and validated by the SALTMED model, decrease in relative grain yield of lentil as affected by the incremental increase in irrigation water salinity up to 10 dS m^{-1}

reduction occurred at salinity of 4.2 dS m^{-1} during the model validation process (Fig. 2). As predicted and validated by the SALTMED model, 100% yield potential of chickpea was at irrigation water salinity of 0.7 dS m^{-1}, 75% at 2.6 dS m^{-1} and 25% at 7.2 dS m^{-1} (Table VIII).

Faba bean. The relative yields of faba bean from the field data for Irrig-2 and Irrig-3 treatments were 0.737 and 0.535, respectively. These relative yields were based on the average of 11 accessions for the 2009–2010 data from Raqqa. As predicted by the SALTMED model during the model calibration process, the corresponding relative yields for Irrig-2 and Irrig-3 treatments were very close, i.e. 0.781 and 0.526, respectively. The percentage of error between the average measured results from the field site and model-calibrated results for Irrig-2 and Irrig-3 treatments was −5.84 and 1.61, respectively (Table VI). Based on the measured average relative yield of faba bean accessions and model-calibrated results for faba bean for the 2009–2010 season data, the linear regression equation for field-obtained relative yield and model-predicted relative yield was $y = 1.01x + 0.0041$ ($R^2 = 0.986$).

During the model validation process for the field data for the next season (2010–2011) from the same site, the relative yields of faba bean from the field data for Irrig-2 and Irrig-3 treatments were 0.740 and 0.590, respectively. The corresponding relative yields for Irrig-2 and Irrig-3 treatments as predicted by the SALTMED model were 0.801 and 0.546, respectively. In the process of determining the 50% threshold yield of faba bean (π_{50} value) based on salinity levels in irrigation water in equilibrium with ambient soil solution salinity levels, the 50% yield reduction as predicted by the SALTMED model occurred at a salinity of 5.2 dS m^{-1} during the model validation process (Fig. 3). As predicted and validated by the SALTMED model, 100% yield

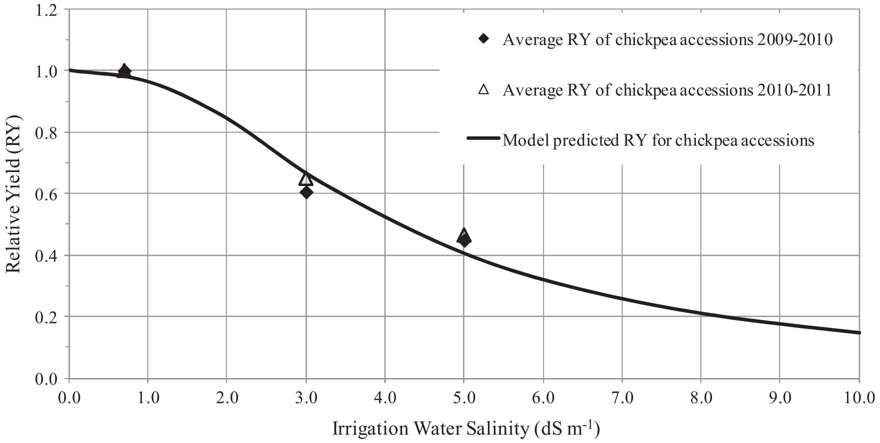

Figure 2. As predicted and validated by the SALTMED model, decrease in relative grain yield of chickpea as affected by the incremental increase in irrigation water salinity up to 10 dS m^{-1}

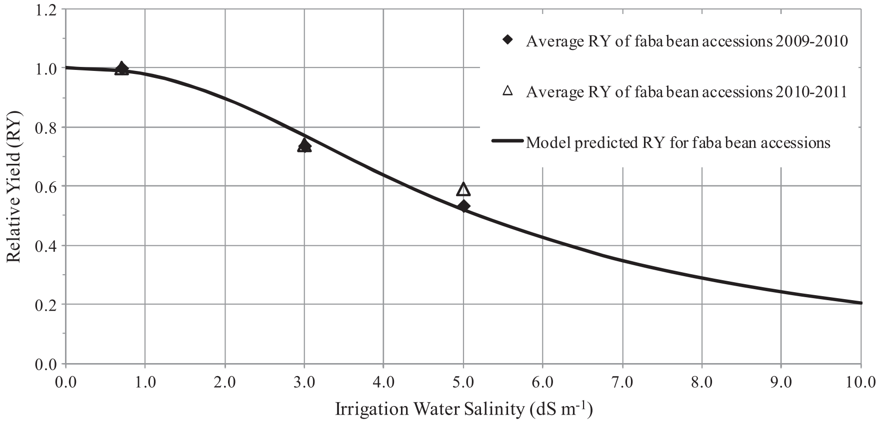

Figure 3. As predicted and validated by the SALTMED model, decrease in relative grain yield of faba bean as affected by the incremental increase in irrigation water salinity up to 10 dS m^{-1}

potential of faba bean was at irrigation water salinity of 0.9 dS m^{-1}, 75% at 3.2 dS m^{-1} and 25% at 9.7 dS m^{-1} (Table VII). These results are in line with those of Katerji *et al.* (2011) who reported that soil salinity levels equal to or higher than 6.5 dS m^{-1} affected faba bean growth, reduced number of grains and grain yield.

CONCLUSIONS

Combined analysis of grain yields for both experimental sites and three irrigation water salinity levels revealed significant differences among accessions of each food legume crop. There was no significant interaction with the salinity over its experimented range at any of the locations. This genetic diversity provides the opportunity to select a specific food legume accession that can withstand ambient level of salts in irrigation water. Genetic diversity among food legume crops has also been reported in earlier studies (Ayers and Eberhard, 1960; Maas and Grattan, 1999; Katerji *et al*., 2005). In addition, most accessions followed the same pattern for grain yield production as was found in the drought-tolerance studies concurrently undertaken during these years at ICARDA's research station near Aleppo. This may be due to the effect of water stress in the first phase of salt stress, which has also been documented by several other studies evaluating crops and their accessions for salt and drought tolerance (Fortmeier and Schubert, 1995; Katerji *et al*., 2011).

Calibration and validation of the SALTMED model revealed a close relationship between actual grain yields from the field sites and those predicted by the model. Based on salinity levels in irrigation waters, yield potential of lentil was 100% at irrigation water salinity of 0.8 dS m^{-1}, 75% at 2.7 dS m^{-1}, 50% at 4.4 dS m^{-1} and 25% at 7.7 dS m^{-1}. As predicted and validated by the model, 100% yield potential of chickpea was at irrigation water salinity of 0.7 dS m^{-1}, 75% at 2.6 dS m^{-1}, 50% at 4.2 dS m^{-1} and 25% at 7.2 dS m^{-1}. For faba bean, 100% yield potential was at irrigation water salinity of 0.9 dS m^{-1}, 75% at 3.2 dS m^{-1}, 50% at 5.2 dS m^{-1} and 25% at 9.7 dS m^{-1}. The yield potential of food legume crops as predicted by the SALTMED model reveals that faba bean can withstand relatively high levels of irrigation water salinity. These results are expected to help extension workers and farmers in making informed decisions in selecting appropriate food legume crop and crop accessions based on the salinity level of the water available as an irrigation source.

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