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Salt tolerance classification of crops according to soil salinity and to water stress day index

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Abstract

The observations of a long-term experiment on the use of saline water were used to compare the crop tolerance to salinity. Salinity affected significantly yield, evapotranspiration, pre-dawn leaf water potential and stomatal conductance. The higher the salinity, the lower the yield, evapotranspiration, pre-dawn leaf water potential and stomatal resistance. The crop classification, based on soil salinity, corresponds with the classification of Maas and Hoffman: sugarbeet and durum wheat as salt tolerant, broadbean, maize, potato, sunflower and tomato as moderately salt sensitive. The difference with respect to soybean, classified as moderately salt sensitive instead of moderately salt tolerant can be ascribed to difference in variety. Weather conditions affected strongly the salt tolerance of broadbean. The water stress day index was also used for salt tolerance classification. According to this method, maize, sunflower and potato were included in the same salt tolerant group as sugarbeet and durum wheat. The previous classification of maize and sunflower as moderately sensitive is caused by the fact that these crops are grown during a period of higher evaporative demand than when sugarbeet and durum wheat are grown. The change of potato from moderately sensitive to salt tolerant may be ascribed to its shallow root system. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Crop salt tolerance; Soil salinity; Water stress day index; Broadbean; Durum wheat; Maize; Potato; Soybean; Sugarbeet; Sunflower; Tomato

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1. Introduction

Use of saline water for irrigation is a subject of increasing interest because of the increasing water requirements for irrigation and the competition between human, industrial and agricultural use and moreover because of the pressure for the disposal of drainage water through reuse.

In the Mediterranean area Tunisia is an example, where the fresh water resources for agricultural use are rather limited, and extension of irrigated agriculture is mainly possible by using saline water. For that reason extensive field research was already carried out in the 1960's, within the framework of a UNESCO project (UNESCO, 1970).

In 1989 the Mediterranean Agronomic Institute at Bari, southern Italy, started a long-term lysimeter experiment to initiate students in the study of plant growth under soil and salinity conditions as may be encountered in practice. Therefore two soils, loam and clay, were chosen and three water qualities, fresh water as a control and two saline waters in the range still considered suitable for irrigation.

A previous paper (Van Hoorn et al., 1997) describes the long-term salinity development from the start in 1989 till 1995, after which year no important changes occurred in salinity and adsorption complex. In this paper we present a comparison of the reaction of the crops.

2. Experimental procedure

2.1. Set-up

The set-up consisted of 30 tanks of reinforced fibre glass with a diameter of 1.20 m and a depth of 1.20 m. A layer of coarse sand and gravel, 0.10 m thick, was overlain by a re-packed soil profile of 1 m. At the bottom of the tank, a pipe serving as a drainage outlet connected the tank to a drainage reservoir. The set-up was covered at a height of 4 m by a sheet of transparent plastic to protect the assembly against precipitation.

One series of 15 tanks was filled with loam and a second series of 15 tanks with clay. Table 1 presents some properties of the soils.

The tanks were irrigated with water of three different qualities: the control treatment with fresh water containing 3.7 meq Cl/l and an electrical conductivity (EC) of 0.9 dS/m and two saline treatments, obtained by adding equivalent amounts of NaCl and $CaCl_2$ to fresh water. During the second year wheat was irrigated with waters containing 10 and 20

Table 1
Soil properties

Soil	Particle size in % of mineral parts			$CaCO_3$ (%)	% water (v/v)		Bulk density (Kg/dm^3)
	<2 μm	2–50 μm	>50 μm		pF 2.0	pF 4.2	
Loam	19	49	32	25	36.3	20.4	1.45
Clay	47	37	16	5	42.0	24.0	1.45

meq Cl/l; during the third year potatoes were irrigated with waters containing 15 and 30 meq Cl/l on loam and 15 and 20 meq Cl/l on clay; from the fourth year onwards the saline waters contained 15 and 30 meq Cl/l and an EC of 2.3 and 3.6 dS/m.

At each irrigation surplus water was added to provide a leaching fraction of about 0.2. Irrigation water was applied when the evaporation of the class A pan had attained about 80 mm. The evapotranspiration during the irrigation interval was calculated for each tank as the difference between the amounts of irrigation and drainage water.

For determining soil salinity, the average chloride concentration of soil water was calculated from the salt balance of irrigation and drainage water and converted into EC of soil water by the equation, established after the first 3 years, 1989–1992, $\ln EC = 0.824 \ln Cl - 1.42$. This EC-value of soil water was divided by 2 for the conversion into EC_e. Owing to leaching at each water application, soil salinity remained almost constant from the start till the end of the growing period. According to measurements with soil water samplers, soil salinity slightly increased with depth. The paper mentioned above (Van Hoorn et al., 1997) presents detailed information on composition of irrigation water and soil salinity.

2.2. Crops

Table 2 presents the crops grown during the past 9 years, their variety and the reference publication with detailed information concerning crop density, fertilization, water stress, growth and yield.

Broadbeans, grown during the first year, only succeeded on clay, since the loam was infected with broomrape.

2.3. Water stress of the plant

The parameters used to characterize the water stress of the plant were the pre-dawn leaf water potential and the stomatal conductance, measured on the upper leaves of the plant.The pre-dawn water potential was measured with a pressure chamber (Scholander et al., 1965). Each value corresponded with the average of five measurements per treatment (one leaf per lysimeter). Measurements were made two to three times per week,

Table 2
Crop, variety, growth period and reference

Crop	Variety	Growth period	Reference
Broadbean (Vicia faba)	Superaguadulce	08.12.89–28.05.90	Katerji et al., 1992
Durum wheat (Triticum durum)	ISA	22.11.90–26.06.91	Van Hoorn et al., 1993
Potato (Solanum tuberosum)	Spunta	03.02.92–07.06.92	it
Maize (Zea mays)	Hybride Asgrow 88	27.07.93–02.11.93	Katerji et al., 1996
Sunflower (Helianthus annuus)	Hybride ISA	22.04.94–02.09.94	it
Sugarbeet (Beta vulgaris)	Suprema	25.11.94–02.06.95	Katerji et al., 1997
Soybean (Glycine max)	Talon	18.07.95–16.09.95	Katerji et al., 1998a,b
Tomato (Lycopersicon esculentum)	Elko 190	28.06.96–10.09.96	Katerji et al., 1998a,b
Broadbean (Vicia faba)	Superaguadulce	25.11.97–20.05.98	

and started between 10 days (maize) and 80 days (sugarbeet) after emergence, as soon as the leaves attained a sufficient size to allow measurements with the pressure chamber. Moreover hourly measurements of the leaf water potential were made between sunrise and sundown at several growth stages.

The stomatal conductance was measured with a diffusion porometer. Each value corresponded with the average of 10 measurements per treatment (two leaves per lysimeter). Measurements were made at the same rhythm as the pre-dawn leaf water potential.

3. Results and discussion

3.1. Crop classification according to soil salinity

Table 3 presents the yield and the corresponding soil salinity of the crops grown during the lysimeter experiment. Table 4 presents the result of the statistical analysis of the

Table 3
Yield (kg/m^2) and EC_e (dS/m) of the crops grown during the lysimeter experiment

	Loam			Clay		
Broadbean, 1990						
Yield, grain	–	–	–	0.246	0.179	0.175
EC_e	–	–	–	0.8	1.2	1.75
Durum wheat, 1991						
Yield, grain	0.90	0.82	0.80	0.78	0.78	0.64
EC_e	0.8	2.9	6.0	0.8	1.7	3.1
Potato, 1992						
Yield, tuber	8.62	6.54	5.40	5.80	5.00	4.84
EC_e	0.8	2.6	5.9	0.8	2.5	3.4
Maize, 1993						
Yield, grain	0.678	0.674	0.533	0.548	0.486	0.414
EC_e	0.8	1.8	3.0	0.8	1.9	3.7
Sunflower, 1994						
Yield, grain	0.351	0.291	0.263	0.216	0.193	0.154
EC_e	0.8	2.7	3.8	0.8	2.0	3.9
Sugarbeet, 1995						
Yield, beet	6.56	5.84	5.53	4.47	3.57	3.68
EC_e	0.8	3.5	6.3	0.8	3.4	5.8
Soybean, 1995						
Yield, grain	0.334	0.294	0.180	0.311	0.221	0.106
EC_e	0.8	4.2	7.0	0.8	3.8	6.3
Tomato, 1996						
Yield, fruit	6.12	4.46	2.42	5.31	3.85	2.29
EC_e	0.8	4.5	6.4	0.8	4.0	5.4
Broadbean, 1998						
Yield, grain	0.468	0.339	0.236	0.706	0.572	0.337
EC_e	0.8	4.9	6.6	0.8	4.3	5.6

Table 4
Effect of salinity and texture on yield, evapotranspiration, pre-dawn leaf water potential and stomatal resistance

Crop	Yield		Evapotransp.		Pr.d. l.w. pot.		Stom. rest.	
	Sal.	Text.	Sal.	Text.	Sal.	Text.	Sal.	Text.
Broadbean ’90	s	–	s	–	s	–	s	–
Durum wheat	s	s	s	s	s	s	s	s
Potato	s	s	s	s	s	s	s	s
Maize	s	s	s	ns	s	s	s	s
Sunflower	s	s	s	s	s	s	s	s
Sugarbeet	s	s	s	s	s	ns	s	s
Soybean	s	s	s	ns	s	ns	s	ns
Tomato	s	s	s	ns	s	ns	s	ns
Broadbean ’98	s	s	s	s	s	ns	s	ns

s: significant; ns: non-significant.

salinity and texture effects on yield, evapotranspiration, pre-dawn leaf water potential and stomatal conductance.

Salinity always affected yield, evapotranspiration, pre-dawn leaf water potential and stomatal conductance. The higher the soil salinity, the lower the yield, the evapotranspiration, the pre-dawn leaf water potential and the stomatal conductance.

Texture always affected yield, but its effect on evapotranspiration, pre-dawn leaf water potential and stomatal conductance was less pronounced. Unlike all other crops, broadbeans showed a higher yield and evapotranspiration on clay than on loam, perhaps due to a still remaining effect of broomrape notwithstanding disinfection of the soil. According to Table 1 the total available moisture content between field capacity and wilting point is almost the same for both soils, but the air content of loam is higher than that of clay, permitting probably a better root development and water supply. The analysis did not reveal an interaction between salinity and texture.

The result of the linear regression analysis of the relationship between relative yield and salinity is presented in Fig. 1 and Table 5, the latter also presenting the values published

Table 5
Threshold EC_e (dS m^{-1}) and slope (% yield reduction/dS m^{-1}) according to the regression analysis of the saline treatments, the corresponding values published by Maas and Hoffman and those obtained from a water quality test in Tunesia

Crop	Lysimeter experiment		Maas and Hoffman		Water quality test	
	EC_e	*b*	EC_e	*b*	EC_e	*b*
Sugarbeet	0.0	0.4	7.0	5.9	>6.5	–
Durum wheat	0.0	1.9	5.7	3.8	–	–
Potato	0.0	5.6	1.7	12.0	–	–
Sunflower	0.5	8.7	–	–	–	–
Maize	1.3	10.5	1.7	12.0	1.8	11.9
Soybean	2.0	11.4	5.0	20.0	1.7	11.2–23.5
Tomato	2.4	16.4	2.5	9.9	1.8	12.7
Broadbean ’98	2.8	14.4	1.6	9.6	2.5	8.9

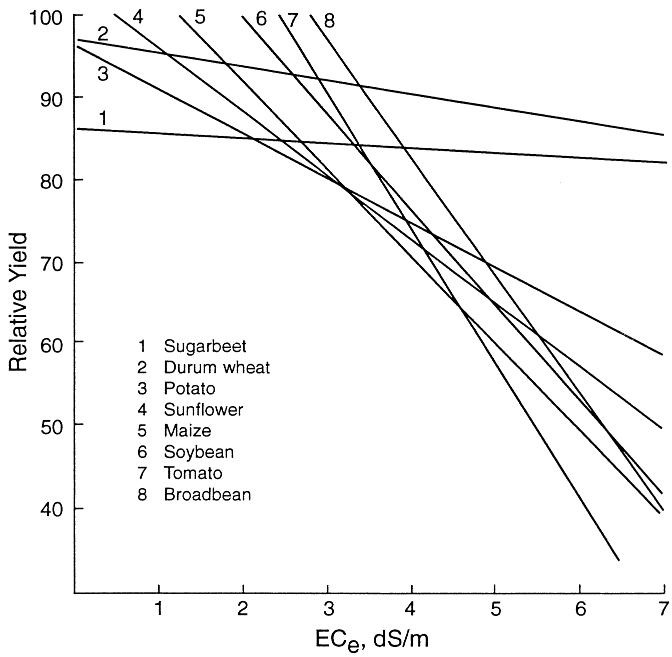

Fig. 1. Relative yield vs. soil salinity.

by Ayers and Westcot (1985) according to Maas and Hoffman (1977) and the values obtained from the water quality test at the Cherfech experimental station in Tunisia (UNESCO, 1970). The regression analysis is based on the four observations of the saline treatments and did not include the relative yields of 100 with the corresponding EC_e of 0.8 dS/m in order to avoid the effect of the non-saline treatments on the threshold value and the slope.

Differences between the three sources can be attributed to variety and weather conditions. Letey and Dinar (1986) mentioned a personal communication of Maas that in more recent studies lower values for the threshold and the slope of sugarbeet were found. The large differences in the case of soybean are due to differences in variety. Four varieties were grown on the water quality test, two of which (Flora, Violetta) were moderately salt sensitive and two (Amsoy, Chipewa) sensitive. Several authors (Abel and Mackenzie, 1964; Velagaleti and Schweitzer, 1993) already mentioned the large differences in salt tolerance of soybean.

Fig. 2 presents an example of the effect of weather conditions on the threshold value by comparing the relationship between the yield of broadbean and soil salinity, obtained in 1998 and the one obtained in 1990, based on only three observations including the control on clay. The evapotranspiration during both growth periods (Table 6) differed considerably due to a difference in temperature, the spring of 1990 being exceptionally warm and the spring of 1998 being exceptionally cold. The threshold values obtained by Maas and Hoffman and in Tunisia show an intermediate position.

In view of the effect of variety and weather conditions on the relationship between relative yield and soil salinity, the question arose whether the differences between the

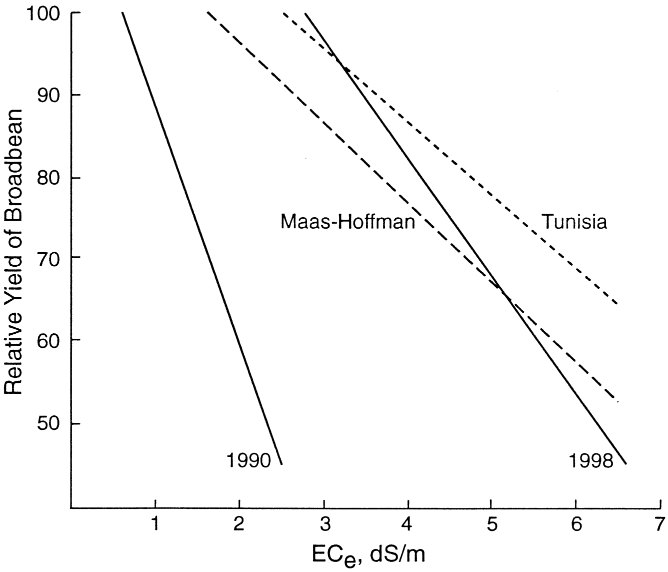

Fig. 2. Relative yield of broadbean vs. soil salinity.

regression lines of the crops grown during the lysimeter experiment are significant. A statistical analysis showed no significant difference between sugarbeet and durum wheat and no difference between the other crops, but a significant difference between sugarbeet and durum wheat on the one hand (threshold 0, slope −2.1) and the six other crops on the other hand (threshold 1.1 and slope −9.7). The analysis confirms the classification of Maas and Hoffman: sugarbeet and durum wheat as salt tolerant, the other crops as moderately sensitive, with the exception of soybean, classified as moderately tolerant by Maas and Hoffman.

A pot experiment was carried out for studying the effect of soil salinity on maize and sunflower during the early seedling stage (Katerji et al., 1994). The effect of salinity already appeared after about 10 days: the higher the salinity, the lower the pre-dawn leaf water potential and the stomatal conductance. The growth was determined about 30 days after sowing by weighing leaves, stems and roots, which showed the same relative decrease with increasing salinity. The results of the regression analysis were a threshold value of 0.8 and slopes of −6.1 and −7.5 respectively for maize and sunflower. These values did not differ significantly from those obtained for the grain yield at harvest time.

Table 6
Evapotranspiration of broadbeans, irrigated with fresh water (mm/day)

1989–90	26.12–19.2	19.2–9.3	9.3–11.4	11.4–8.5	8.5–28.5
	1.0	3.7	5.7	9.8	11.3
1997–98	21.12–13.2	13.2–18.3	18.3–10.4	10.4–6.5	6.5–21.5
	1.2	2.3	2.4	3.2	5.3

3.2. Crop classification according to water stress day index

Weather conditions exert a considerable effect on the relationship between yield and soil salinity, as was shown in the previous paragraph by the example of broadbeans grown during two growth periods. Shalhevet (1994) mentioned several examples of the effect of climate on the salt sensitivity of several crops and concluded that "Under harsh environmental conditions of high temperature and low humidity, the salinity response function may change so that the threshold salinity decreases and the slope increases, rendering the crop greater sensitivity."

Salinity affects the plant through the reduced water availability and increased water stress, which is reflected by the leaf water potential. The concept of the water stress day index (WSDI) provides a quantitative method for determining the stress imposed on a crop during its growing season (Hiler and Clark, 1971). The use of this concept in irrigation scheduling was discussed in detail by Hiler and Howell (1983). Hiler et al. (1974) and Katerji (1997) reviewed the methods characterizing the water stress of the plant and their accuracy. In practice the use of the WSDI concept remains limited, the main reason being the lack of a simple and sufficiently sensitive method to characterize crop water stress.

The WSDI concept will be used to compare crop salt tolerance. The difficulty to determine crop water stress will be tackled by measuring simultaneously the pre-dawn leaf water potential of the plant on the saline and non-saline treatments. This choice is justified for the following reasons:

The pre-dawn leaf water potential expresses the equilibrium between soil water potential and leaf water potential of the plant, when the plant has covered its need for water after the moisture loss of the previous day (Katerji and Hallaire, 1984).

This parameter is measured at dawn and is not affected by the change in meteorological conditions during the day (radiation etc.) which affect other parameters such as the stomatal conductance and the leaf temperature (Katerji et al., 1997).

The pre-dawn leaf water potential is significantly affected by soil salinity, as was shown in Table 4.

The difference in pre-dawn leaf water potential, used to calculate WSDI, only depends on soil salinity, excluding the evaporative demand of the environment and the irrigation regime, which are the same for all treatments.

The method is based on the hypothesis that crop salt tolerance is experimentally determined as the fractional yield reduction resulting from water deficit imposed on a crop during its growing season. The relationship between relative yield and water stress is expressed in the following way:

$$Y = a - b \times \mathrm{WSDI} \tag{1}$$

with

$$\mathrm{WSDI} = \sum_{1}^{n} \frac{\psi_c - \psi_s}{n} \tag{2}$$

in which ψ_c = daily value of the pre-dawn leaf water potential of the control treatment,

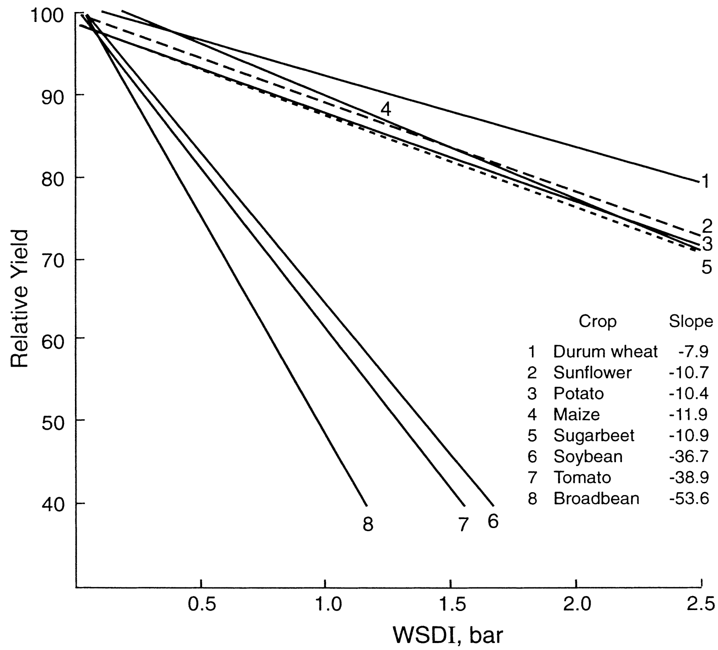

Fig. 3. Relative yield vs. water stress day index.

irrigated with fresh water, from the start of leaf growth until the start of senescence; ψ_s = the equivalent of the saline treatment; n = number of days from the start of leaf growth until the start of senescence; b = yield loss in % per unit increase of WSDI; a = value of the ordinate, which should be around 100. Because ψ is negative, WSDI positive.

Fig. 3 presents the relationship between relative yield and water stress day index. According to the linear regression analysis two groups can be distinguished: the first group comprising durum wheat, maize, potato, sunflower and sugarbeet, of which the slopes do not differ significantly but show a significant or highly significant difference with the second group comprising broadbean, soybean and tomato.

In comparison with the classification based on soil salinity, the classification based on the water stress day index includes in the salt tolerant group also maize, sunflower and potato and reduces the moderately sensitive group to broadbean, soybean and tomato. The classification based on soil salinity, indicating maize and sunflower as moderately sensitive, is a consequence of the season during which these crops are grown and not of the crop itself. Wheat and sugarbeet are grown during a cooler period of the year, when the evaporative demand is lower than during the warmer period when maize and sunflower are grown. The classification based on the water stress day index, indicating maize and sunflower just as salt tolerant as wheat and sugarbeet, excludes the effect of the evaporative demand and means that, if these crops could be grown during the same season, they would show the same salt tolerance. The classification based on soil salinity, indicating maize and sunflower as moderately sensitive, includes the reality that these crops are grown during a period of high evaporative demand and are for that reason more salt sensitive.

Potato is grown during the same period as sugarbeet, but, unlike wheat and sugarbeet, it is a shallow rooting crop. Even under Dutch temperate weather conditions potato is sprinkled on soils of good water-holding capacity for optimum production. The limited capacity of potato to exploit the water-holding capacity of the soil could explain its salt sensitivity.

4. Conclusion

The salt tolerance classification, based on soil salinity, of the eight crops grown during the lysimeter experiment corresponds well with the classification of Maas and Hoffman, except soybean, which can be ascribed to a difference in variety. Weather conditions exert a considerable effect on the salt tolerance.

The salt tolerance classification, based on the water stress day index, includes maize, sunflower and potato in the same, salt tolerant group as sugarbeet and durum wheat. The previous classification of maize and sunflower as moderately sensitive is caused by the fact that these crops are grown during a period of higher evaporative demand than when sugarbeet and durum wheat are grown. The change of potato from moderately sensitive to salt tolerant may be ascribed to its shallow rooting system.

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