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SALINITY EFFECT ON CROP DEVELOPMENT AND YIELD, ANALYSIS OF SALT TOLERANCE ACCORDING TO SEVERAL CLASSIFICATION METHODS

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SUMMARY - The publication is a synthesis of previous publications on the results of a long-term lysimètre experiment. From 1989 to 1998, the experimental variables were soil salinity and soil type, from 1999 onwards, soil salinity and crop variety. The plant was studied during the whole growing period by measuring the saline stress and analyzing its effect on leaf area and dry matter development and on crop yield. Salinity affected the pre-dawn leaf water potential, stomatal conductance, evapotranspiration, leaf area and yield. The following criteria were used for crop salt tolerance classification: soil salinity, evapotranspiration deficit, water stress day index. The classification according to soil salinity distinguished the salt tolerant group of sugar beet and wheat, the moderately salt sensitive group comprising broadbean, maize, potato, soybean, sunflower and tomato, and the salt sensitive group of chickpea and lentil. The results for the salt tolerant and the moderately salt sensitive groups correspond with the classification of Maas and Hoffman, excepted for soybean. The evapotranspiration deficit criterion was used, because for certain crops the relation between yield and evapotranspiration remains the same in case of drought and salinity. This criterion, however, did not appear useful for salt tolerance classification. The water stress day index, based on the pre-dawn leaf water potential, distinguished a tolerant group, comprising sugar beet, wheat, maize, sunflower and potato, and a sensitive group, comprising tomato, soybean, broadbean, chickpea and lentil. The classification corresponds with a difference in water use efficiency. The tolerant crops show a more or less constant water use efficiency. The sensitive crops show a decrease of the water use efficiency with increasing salinity, as their yield decreases stronger than the evapotranspiration. No correlation could be found between osmotic adjustment, leaf area and yield reduction. As the flowering period is a sensitive period for grain and fruit formation and the sensitive crops are all of indeterminate flowering, their longer flowering period could be a cause of their greater sensitivity. The tolerant group according to water stress day index can be divided according to soil salinity in a salt tolerant group of sugar beet and wheat and a moderately sensitive group, comprising maize, sunflower and potato. The difference in classification can be attributed to the difference in evaporative demand during the growing period. The sensitive group according to water stress day index can be divided according to soil salinity in a moderately sensitive group, comprising tomato, soybean and broadbean, and a salt sensitive group of chickpea and lentil. The difference in classification can be attributed to the greater salt sensitivity of the symbiosis between rhizobia and grain legume in the case of chickpea and lentil.

Key words: Crop salt tolerance, osmotic adjustment, pre-dawn leaf water potential, soil salinity, water use efficiency

INTRODUCTION

Much research has been done to determine crop response to salinity by measuring crop yields at increasing salinity and relating yield reduction directly to soil salinity. This method permits to distinguish salt tolerant and salt sensitive crops and to choose a cropping pattern corresponding with the expected soil salinity. The method is simple and practical, but it does not, however, explain the behavior of crops under saline conditions, nor why crops differ in salt tolerance.

In 1989, the Mediterranean Agronomic Institute at Bari, southern Italy, started a longterm lysimeter experiment to initiate students in the study of plant growth under saline conditions. In this experiment, the plant was studied during its whole development by measuring the saline stress and analyzing its effect on the growth and yield of the plant to arrive at a better understanding of crop behavior under saline conditions.

The experimental set-up, the laboratory facilities and the manpower put certain restrictions. One crop per year was grown. During the period from 1989 to 1998, the first variable was the soil salinity, at three levels, and the second variable the soil type, loam and clay. From 1998 onwards, the second variable was the variety of the crop. All treatments were irrigated at the same time with surplus water for leaching. Soil dryness was not a variable in this experiment. Since the set-up consisted of lysimeters equipped with porous cups for soil water sampling, it was not possible to study root development. This was only done in a pot experiment with early seedlings. The lysimeter set-up allowed to establish the nitrogen balance of the grain legumes, but a laboratory study of the salinity effect on rhizobia was outside the scope of this experiment.

The results of the experiment have been published from 1992 onwards in Agricultural Water Management. This publication is a summary of previous publications. It starts with a description of the experimental procedure, after which examples are presented of the salinity effect on the water stress of the plant, followed by the effect on growth and yield to arrive finally at a comparison between the crops, their salt tolerance classification and some hypothesis about salt tolerance.

EXPERIMENTAL PROCEDURE

Set-up

The set-up consisted of 30 tanks of reinforced fiber 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 repacked 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 from 1989 to 1998. In summer 1998, the tanks were emptied and refilled with clay. Table 1 presents some properties of the soils after filling the lysimeters.

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 CaCl2 to fresh water. During the second year wheat was irrigated with waters containing 10 and 20 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. Table 2 presents the chemical composition of the irrigation waters. To eliminate the salinity effect on germination and emergence 10 l fresh water were applied after sowing.

Table 1. Soil properties

Soil	Particle size in percentage of mineral parts			$CaCO_3$ (%)	%Water (v/v)		Bulk density (kg/dm^3)
	< 2 µm	2-50 µm	> 50 µm		pF2.0	pF4.2	
Loam	19	49	32	25	36.3	20.4	1.45
Clay	47	37	16	05	42.0	24.0	1.45
Clay	49	22	29	11.4	38.5	21.9	1.41

Table 2. Composition of irrigation water (meq./l)

Treatment	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	EC (dS/m)	SAR
Fresh	6.2	3.1	2.3	0.4	3.7	7.3	0.6	1.0	1.1

15 meq. Cl/l	10.8	3.1	8.7	0.4	15.0	6.6	0.8		2.3	3.3
30 meq. Cl/l	16.7	3.4	16.2	0.4	30.0	6.5	0.7		3.6	5.1

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 50 mmduring the beginning of the growing season and 80–100 mm during the full growing season, the latter corresponding with an evapotranspiration of about 80 mm, half of the total amount of available water. The evapotranspiration during the irrigation interval was calculated for each tank as the difference between the amounts of irrigation and drainage water. Soil moisture sampling during the first experimental year showed almost the same moisture content after each irrigation, corresponding with field capacity. No infiltration or water logging problems were observed.

For determining the depth average 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, In EC ¼ 0:824 In Cl _ 1.42. This EC-value of soil water was divided by 2 for the conversion into ECe. 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. A previous publication (Van Hoorn *et al.*, 1997) presents detailed information on development of soil salinity.

Crops

Table 3 presents the crops grown during the past 11 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 broom rape.

Water stress of the plant

The parameters used to characterize the water stress of the plant were the pre-dawn leaf water potential, the stomatal conductance and the osmotic potential.

Table 3. Crop, variety, growth period and reference

Crop	Variety	Growth period	Reference
Broadbean (*Vicia faba*)	Superguadulce	8/12/1989–28/5/1990	Katerji *et al.* (1992)
Durum wheat (*Triticum durum*)	ISA	22/11/1990–26/6/1991	Van Hoorn *et al.* (1993)
Potato (*Solanum tuberosum*)	Spunta	3/2/1992–7/6/1992	Van Hoorn *et al.* (1993)
Maize (*Zea mays*)	Hybride Asgrow 88	27/7/1993–2/11/1993	Katerji *et al.* (1996)
Sunflower (*Helianthus annuus*)	Hybride ISA	22/4/1994–2/9/1994	Katerji *et al.* (1996)
Sugar beet (*Beta vulgaris*)	Suprema	25/11/1994–2/6/1995	Katerji *et al.* (1997)
Soybean (*Glycine max*)	Talon	18/7/1995–16/9/1995	Katerji *et al.* (1998a)
Tomato (*Lycopersicon esculentum*)	Elko 190	28/6/1996–10/9/1996	Katerji *et al.* (1998b)
Broadbean (*Vicia faba*)	Superguadulce	25/11/1997–20/5/1998	
Lentil (*Lens culinaris*)	Idlib I ICARDA 6796	29/12/1998–13/6/1999	Katerji *et al.* (2001a)
Chickpea (*Cicer arietinum*)	ILC 3279 Filip 87-59C	23/12/1999–24/6/2000	Katerji *et al.* (2001b)

The pre-dawn leaf water potential was determined with a pression chamber (Scholander *et al.*, 1965) on the upper leaf surface of 1 leaf per lysimeter (five leaves per treatment), taken from the upper part of the canopy to avoid senescent leaves. The stomatal conductance was measured with a diffusion porometer at midday on the lower leaf surface of two leaves per lysimeter (10 leaves per treatment). The osmotic potential was determined with the pressure volume curve, established from two replicates for all six treatments, following the procedure described in a previous publication (Katerji *et al.*, 1997). The measurements were made on five crops: sugar beet, tomato, broadbean, lentil and chickpea.

Growth and yield

The leaf area and the dry matter of leaf and stem were determined at the successive phenological stages on five plants, equally distributed over the five tanks per treatment, first the leaf area and afterwards the dry matter.

At harvest, the commercial yield, the number of fruits, ears and tubers and the average weight of grains, fruits and tubers were determined on each lysimeter.

Nitrogen balance

The nitrogen balance of the grain legumes was established to determine the salinity effect on the biological nitrogen contribution of the soil. The detailed procedure was described in a recent paper (Van Hoorn *et al.*, 2001). The biological nitrogen of the soil was calculated as the difference between the nitrogen absorbed by the plant on one hand and the nitrogen input from fertilizer and irrigation water minus the output from drainage water on the other hand.

WATER STRESS OF THE PLANT

Pre-dawn leaf water potential and stomatal conductance

Salinity affects the water stress of the plant through its effect on the osmotic potential of the soil water. With increasing salinity the osmotic potential decreases and so the water availability for the plant, resulting in increasing water stress which in turn affects stomatal conductance, leaf growth and photosynthesis (West *et al.*, 1986; Yeo *et al.*, 1985).

Several indicators for the water stress can be used. After the first year of experiment, during which the radiation temperature and the pre-dawn leaf water potential were compared, the latter was selected (Katerji *et al.*, 1992).

Fig. 1 presents the salinity effect on the pre-dawn leaf water potential of sugar beets, showing an increase after each irrigation and then a decrease during the irrigation interval. The stomatal conductance, presented in Fig. 2, also shows the effect of salinity and irrigation. The largest difference appears after irrigation, whereas the pre-dawn leaf water potential shows the largest difference before irrigation.

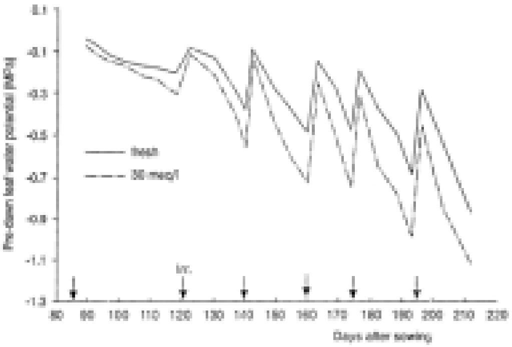

Fig. 1. Pre-dawn leaf water potential of sugar beet vs. days after sowing

The observations of the pre-dawn leaf water potential and the stomatal conductance show a perfect synchronization as the changes after each irrigation are simultaneous. The daily course of the leaf water potential and the stomatal conductance also shows a simultaneous change as presented in Fig. 3.

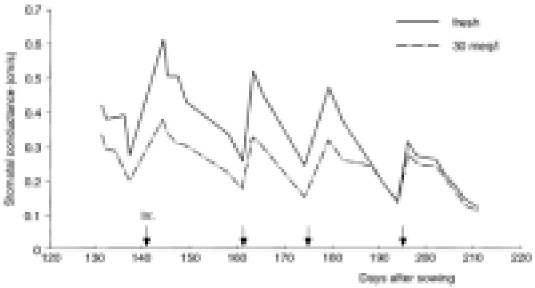

Fig. 2. Stomatal conductance of sugar beet vs. days after sowing

The Figs. 1 and 2, presenting the response of sugar beets, can be considered as general examples for all the crops grown during the experiment. Potatoes show a slight difference: the response of the pre-dawn leaf water potential on irrigation was immediate as for other crops, whereas the response of the stomatal conductance, in contrast to the other crops, showed a delay of 2–3 days before it attained the maximum value. This particular behavior was also observed by other authors (Epstein and Grant, 1973).

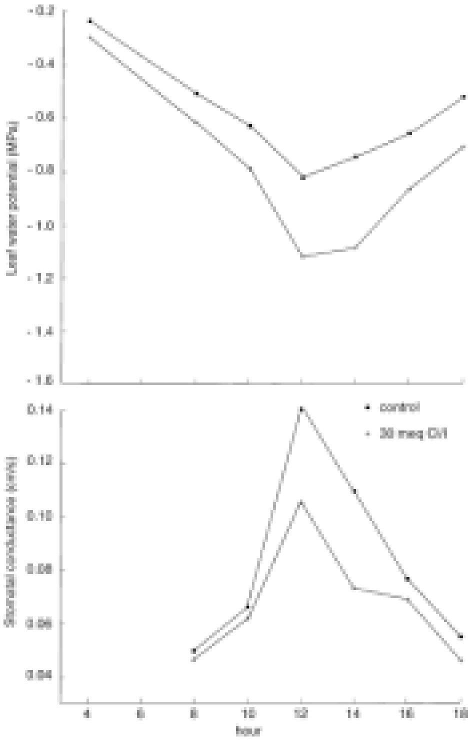

Fig. 3. Daily course of leaf water potential and stomatal conductance of maize

The pre-dawn leaf water potential and the stomatal conductance are also affected by the climatic conditions. According to the Figs. 1 and 2, the maximum values observed after irrigation decrease with time, which means with increasing temperature. This decrease is less pronounced for the pre-dawn leaf water potential, because the temperature and the relative humidity at dawn change less with time than at noon, when the stomatal conductance is measured (Ferreira and Katerji, 1992).

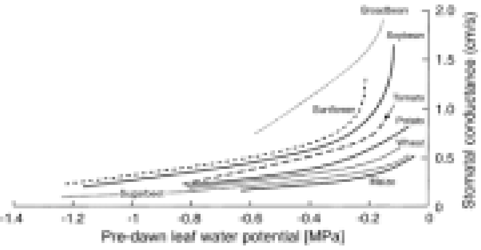

Fig. 4. Stomatal conductance vs. pre-dawn leaf water potential

Since the pre-dawn leaf water potential and the stomatal conductance are changing simultaneously, the relationship between both parameters is presented in Fig. 4 (the stomatal conductance of potato immediately after irrigation was left out). Sunflower, soybean and particularly broadbean are able to maintain the stomatal conductance at a rather high level at decreasing pre-dawn leaf water potential, that means under saline conditions, in comparison with the other crops.

Osmotic adjustment

Crops, when exposed during a long period to water stress caused by salinity or drought, are able to make an osmotic adjustment. This phenomenon consists of decreasing the leaf osmotic potential by accumulation of solutes and in that way increasing the turgor potential to maintain stomatal conductance and leaf growth under saline conditions (Beeg and Turner, 1976). A detailed description of the relationship between osmotic and turgor potential was given in a previous paper (Katerji *et al.*, 1997).

Table 4 presents the maximum osmotic potential at three growth stages of sugar beets and shows that:

- the maximum osmotic potential of the control treatments (fresh) decreases with time, which means an osmotic adjustment to the phenological stage;
- the maximum osmotic potential decreases with increasing salinity, indicating an osmotic adjustment to salinity;
- the osmotic adjustment to salinity increases with the time of exposure to salinity, shown by comparing for t + 118, t + 172 and t + 211 the differences between the control and the saline treatments;
- soil texture does not show a clear effect on the maximum osmotic potential.

Table 4. Maximum osmotic potential at three growth stages of sugar beet (MPa)

Time	Loam			Clay		
	Fresh	15 meq./l	30 meq./l	Fresh	15 meq./l	30 meq./l
t + 118	-0.84	-0.89	-1.11	-0.88	-0.91	-1.09
t + 172	-1.13	-1.32	-1.50	-1.03	-1.15	-1.35
t + 211	-1.27	-1.45	-1.67	-1.36	-1.50	-1.73

Tomato, broadbean, lentil and chickpea showed a similar behavior, but the crops differed in the degree of osmotic adjustment. Table 5 presents the osmotic adjustment, expressed as the difference between the osmotic leaf potentials of the most saline treatment and the control treatment, also mentioning soil salinity and days after sowing, since the osmotic adjustment increases with the time of exposure. For detailed information on the osmotic adjustment, the reader is referred to the publications on the crops, mentioned in Table 3.

To analyze the effect of the osmotic adjustment on the stomatal conductance, the relationship between pre-dawn leaf water potential and stomatal conductance was calculated for sugar beet, tomato and broadbean. Owing to the small size of the lentil and chickpea leaves it was not possible to make reliable measurements of their stomatal conductance. Fig. 5 shows that the relationship for sugar beet and tomato can be approximated by straight lines. The higher the salinity, less steep the slope. Osmotic adjustment does not mean maintaining stomatal conductance at a high level, but it contributes to maintaining a low stomatal conductance under saline conditions (low pre-dawn leaf water potential). Broadbean, presented in Fig. 6, did not show an effect of the osmotic adjustment on the relationship between pre-dawn leaf water potential and stomatal conductance. For this crop no reliable difference in the relationship could be distinguished between different salinity levels. Varieties of broadbean, differing in salt tolerance, showed the same relationship between pre-dawn leaf water potential and stomatal conductance, almost similar to the curve for the variety Superaguadulce in Fig. 6.

Table 5. Leaf osmotic adjustment of the most saline treatment in MPa and in percentage of the control treatment at the end of the growing season

Crop	EC_e (dS/m)	Days after sowing	Leaf osmotic adjustment	
			MPa	Percentage of control
Sugar beet	6.1	211	0.39	29
Tomato	5.9	080	0.21	15
Broadbean	6.1	157	0.20	16
Chickpea	3.8	133	0.13	10
Lentil	3.1	146	0.36	28

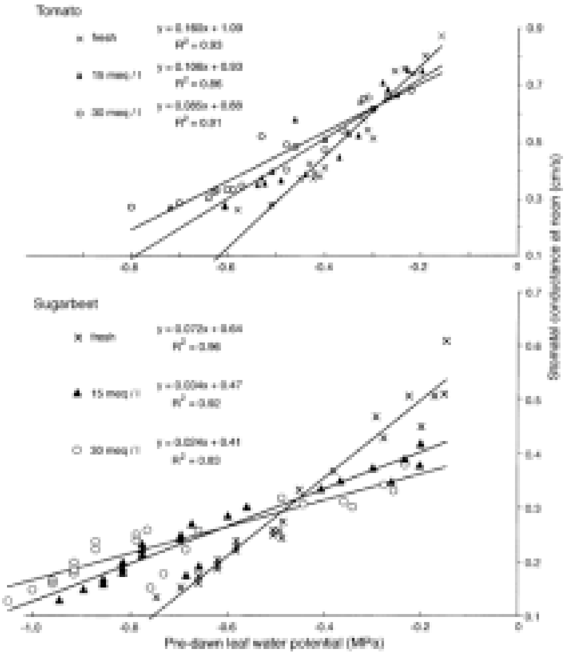

Fig. 5. Stomatal conductance vs. pre-dawn leaf water potential for tomato and sugar beet

Growth and yield

Crop establishment consists of three parts: germination, emergence and early seedling growth. When seeds are put in the soil, germination can only be observed as emergence, which may be affected by the water content and structure of the soil.

As fresh water was applied on the lysimeters after sowing to obtain a good stand, emergence and early seedling growth were studied in a greenhouse experiment, using pots filled with two soils, sandy loam and sandy clay, and two crops, maize and sunflower (Katerji *et al.*, 1994).

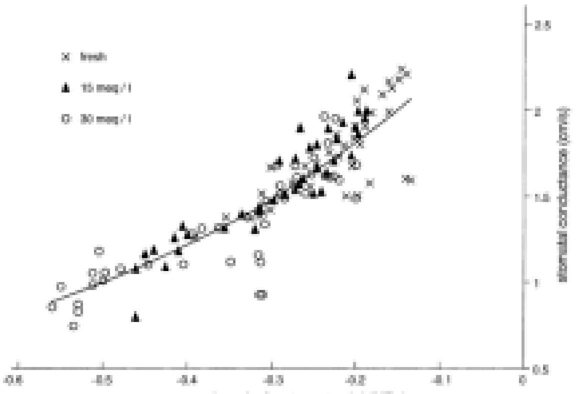

Fig. 6. Stomatal conductance vs. pre-dawn leaf water potential for broadbean

Table 6 presents the development as average values of both soils: at the start a delay with increasing salinity and at the end a lower emergence percentage. The difference between the crops was due to a difference in temperature. In practice, the delay in germination may lead to a failure in emergence and crop establishment, if a hard soil crust is formed under favorable weather conditions. Due to the evaporation of soil water during germination and emergence the salinity increases strongly in the top layer of the soil and seeds are exposed to a higher salinity than during later growth stages (Van Hoorn, 1991). Therefore it is doubtful whether plants during germination and emergence are more sensitive than later on.

A few days after emergence salinity already affected the pre-dawn leaf water potential of both crops. Fig. 7 shows that the dry matter production, calculated as average for both soils about 1 month after sowing, was affected in almost similar way for leaf, stem and root. The growth reduction of 20–30% at an ECe of 4 dS/m is in the same order as the yield reduction at harvest time.

The decrease in root development under saline conditions means that a smaller soil volume is available for crop water uptake. So, the moisture availability is not only reduced by less available water per unit of volume due to the osmotic potential, but also by the available soil volume.

Table 6. Development of emergence of maize and sunflower after sowing

Crop	Time (days)	Cl^- concentration of irrigation water (meq./l)				
		3.7	15	30	45	60
Maize	3	62	64	49	46	41
	4	81	78	67	65	60
	6	95	94	88	86	82
Sunflower	4	60	58	54	51	40
	7	77	74	71	67	61
	10	94	91	86	80	75

The slight difference in dry matter production between maize and sunflower during early seedling growth becomes more pronounced during the later growing period. Fig. 8 presents the leaf area development of both crops. The leaf area of maize is only slightly affected, a reduction of about 10%, whereas the leaf area of sunflower shows a stronger salinity effect. Tomato and soybean showed a similar, moderate effect on leaf area as maize, but the leaf area of the other crops was strongly affected, showing a reduction of 20–50%.

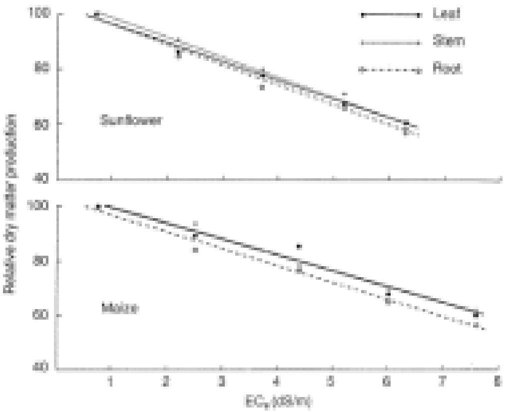

Fig. 7. Relative dry matter production of leaf, stem and root vs. soil salinity

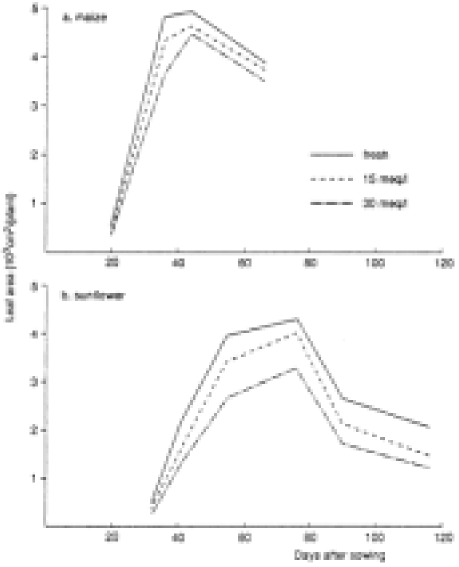

Fig. 8. Leaf area of maize and sunflower vs. days after sowing

Table 7 presents the commercial crop yields and the corresponding evapotranspiration and soil salinity. Table 8 presents the result of the statistical analysis of the salinity and texture effects on yield, evapotranspiration, pre-dawn leaf water potential, stomatal conductance and leaf area.

Salinity always affected yield, evapotranspiration, pre-dawn leaf water potential, stomatal conductance and leaf area. Salinity causes a yield reduction by affecting the number and weight of grains, tubers and fruits.

The yield of all crops, excepted broadbean, was lower on clay than on loam. 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 on loam is higher than on clay, permitting probably a better root development and water supply. The statistical analysis did not show an interaction between salinity and texture.

Broadbean, as the only exception among the crops, showed a higher grain yield on clay, but a lower aerial biomass. The crop was harvested shortly after ripening on clay. At that moment broadbean on loam, on which the vegetative growth had continued longer, was still flowering and probably, if harvested later, would have shown an equal or even higher yield.

Table 7. Yield (kg/m^2), ET (mm) and EC$_e$ (dS/m) of the crops growing during the lysimeter experiment

	Loam	Clay
Broadbean, 1990		

	Loam			Clay		
Yield, grain	–	–	–	000.246	000.179	000.175
ET	–	–	–	802	763	750
EC_e	–	–	–	000.8	001.2	001.75
Durum wheat, 1991						
Yield, grain	000.90	000.82	000.80	000.78	000.78	000.64
ET	883	800	721	733	648	563
EC_e	000.8	002.9	006.0	000.8	001.7	003.1
Potato, 1992						
Yield, grain	008.62	006.54	005.40	005.80	005.00	004.84
ET	415	382	328	363	327	304
EC_e	000.8	002.6	005.9	000.8	002.5	003.4
Maize, 1993						
Yield, grain	000.678	000.674	000.533	000.548	000.486	000.414
ET	607	578	494	644	552	505
EC_e	000.8	001.8	003.0	000.8	001.9	003.7
Sunflower, 1994						
Yield, grain	0000.351	0000.291	0000.263	0000.216	0000.193	000.154
ET	1450	1310	1157	1215	1040	994
EC_e	0000.8	0002.7	0003.8	0000.8	0002.0	003.9
Sugar beet, 1995						
Yield, grain	006.56	005.84	005.53	004.47	003.57	003.68
ET	836	753	734	731	642	657
EC_e	000.8	003.5	006.3	000.8	003.4	005.8
Soybean, 1995						
Yield, grain	000.334	000.294	000.180	000.311	000.221	000.106
ET	410	376	306	430	361	300
EC_e	000.8	004.2	007.0	000.8	003.8	006.3
Tomato, 1996						
Yield, grain	006.12	004.46	002.42	005.31	003.85	002.29
ET	708	631	540	667	628	522
EC_e	000.8	004.5	006.4	000.8	004.0	005.4
Broadbean, 1998						
Yield, grain	000.468	000.339	000.236	000.706	000.572	000.337
ET	409	354	322	448	398	345
EC_e	000.8	004.9	006.6	000.8	004.3	005.6
Lentil, 1999		Variety Idlib I			Variety 6796	
Yield, grain	000.683	000.517	000.082	000.411	000.353	000
ET	272	254	225	248	230	198
EC_e	000.7	002.0	003.1	000.7	002.0	003.3
Chickpea, 2000		Variety ILC 3279			Variety 87-59C	
Yield, grain	000.474	000.460	000.134	000.420	000.240	000.130
ET	613	467	290	516	328	239
EC_e	000.8	002.5	003.8	000.8	002.4	003.8

Table 8. Effect of salinity and texture on yield, evapotranspiration, pre-dawn leaf water potential and stomatal resistance

Crop	Yield		Evapotranspiration		Pre-dawn leaf water potential		Stomatal resistance	
	Salinity	Texture	Salinity	Texture	Salinity	Texture	Salinity	Texture
Broadbean 1990	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
Sugar beet	s	s	s	s	s	ns	s	s
Soubean	s	s	s	ns	s	ns	s	ns
Tomato	s	s	s	ns	s	ns	s	ns

Braodbean 1998	s	s	s	s	s	ns	s	ns
Chickpea	s	–	s	–	s	–	s	–
Lentil	s	–	s	–	s	–	s	–

s: significant; ns: non-significant

The evapotranspiration of durum wheat, potato, sunflower and sugar beet also was lower on clay than on loam, corresponding with the texture effect on pre-dawn leaf water potential, stomatal conductance and leaf area. Maize, soybean and tomato did not show a significant difference in evapotranspiration between both soils, also corresponding with the observations on pre-dawn leaf water potential, stomatal conductance and leaf area, that did not show significant difference or, for maize, only a slight difference. The evapotranspiration of broadbean was higher on clay than on loam, but as mentioned above, the crop on loam was harvested before full maturity.

SALT TOLERANCE CLASSIFICATION

Crop classification according to soil salinity

The method consists of determining the relationship between soil salinity and relative yield, the latter being the ratio between the yields under saline and non-saline conditions, the other growth conditions remaining the same. Maas and Hoffman (1977) proposed the following equation to express the relationship between soil salinity and relative yield:

$$y = 100 - b(EC_e - a) \tag{1}$$

where y is the relative yield, ECe the electrical conductivity of the saturated paste (dS/m), a the threshold value of ECe (dS/m), and b is the slope, expressing percentage yield depression per dS/m.

The result of the linear regression analysis of the relationship between relative yield and salinity for the crops grown during the experiment is presented in Fig. 9 and Table 9, the latter also presenting the values published by Ayers andWestcot (1985) according to Maas and Hoffman (1977) and the values obtained from the water quality test at the Cherfech experimental station in Tunesia (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 ECe 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 sugar beet 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. 10 shows 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. The spring of 1998 was cold and the evapotranspiration during April and May attained 3–5 mm per day, whereas the spring of 1990 was exceptionally warm and the evapotranspiration in April and May attained 10–11 mm per day. Apparently in a period of high

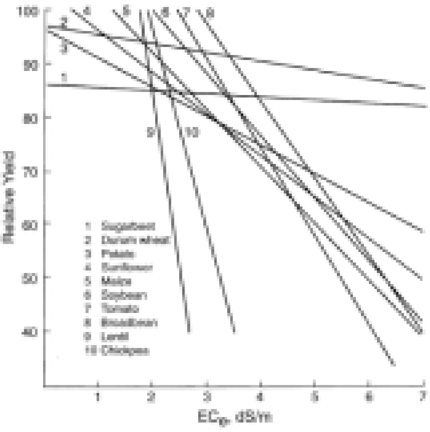

Fig. 9. Relative yield vs. soil salinity

Table 9. Threshold EC_e (dS/m) and slope (percentage yield reduction per dS/m) according to the regression analysis of the saline treatments, the corresponding values published by Mass and Hoffman and those obtained from a water quality test in Tunisia temperature a crop is more sensitive to salinity due to the high evaporative demand. The relationships obtained by Maas and Hoffman and Tunisia correspond more or less with the one obtained in 1998.

Crop	Lysimeter experiment		Mass and Hoffman		Water quality test	
	EC_e	b	EC_e	b	EC_e	b
Sugar beet	0.0	00.4	7.0	05.9	>6.5	–
Durum wheat	0.0	01.9	5.7	03.8	–	–
Potato	0.0	05.6	1.7	12.0	–	–
Sunflower	0.5	08.7	–	–	–	–
Maize	1.3	10.5	1.7	12.0	01.8	11.9
Soybean	2.0	11.4	5.0	20.0	01.7	11.2–23.5
Tomato	2.4	16.4	2.5	09.9	01.8	12.7
Broadbean, 1998	2.8	14.4	1.6	09.6	02.5	08.9
Chickpea	1.9	37	–	–	–	–
Lentil	1.7	62	–	–	–	–

A statistical analysis of the regression lines of the crops grown during the lysimeter experiment distinguished three groups:

- the salt tolerant group: sugar beet, wheat;
- the moderately salt sensitive group: potato, sunflower, maize, soybean, tomato, broadbean;
- the salt sensitive group: chickpea, lentil.

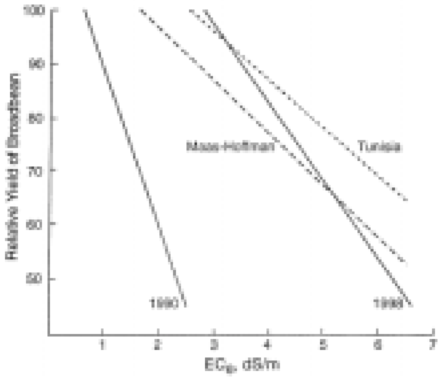

Fig. 10. Relative yield of broadbean vs. soil salinity

The analysis confirms the classification of Maas and Hoffman, excepted for soybean, classified as moderately tolerant, and the not mentioned crops chickpea and lentil.

Crop classification according to evapotranspiration deficit

Stewart *et al.* (1977) showed that the relation between yield and evapotranspiration of maize is the same in case of drought and salinity. Shalhevet (1994) appears to generalize this result for other crops, assuming a common relationship between yield and evapotranspiration, independent of whether changes in the two variables are caused by drought or salinity, but no information on other crops was available to check this hypothesis.

According to the theory of De Wit (1958) crop yield is a linear function of crop transpiration. The equation mostly used for yield prediction from evapotranspiration is the one proposed by Stewart and Hagan (1973):

$$y_a = y_m - y_m K_y \frac{ET_m - ET_a}{ET_m} \qquad (2)$$

where ya is the actual crop yield, ym the maximum crop yield under the same growing conditions, Ky the crop coefficient, ETa the actual evapotranspiration, and ETm the maximum evapotranspiration.

Using as crop coefficients for maize, sunflower, potato and soybean, respectively 1.25, 0.95, 1.1 and 0.85, as determined by Doorenbos and Kassam (1979), the yields of the saline treatments of the lysimeter experiment were calculated from the measured yield of the control treatment and the observed evapotranspiration of the control and the saline treatments. Fig. 11a and b shows the comparison between the calculated and measured yields. The statistical analysis (Katerji *et al.*, 1998a) showed a good correspondence between the predicted and measured yields for maize, sunflower and potato, but the accuracy of the yield prediction for soybean was not satisfactory. The particular behavior of soybean could be ascribed to:

- the large difference in salt tolerance between soybean varieties, already mentioned in Section 5.1;
- the salinity effect on the nitrogen supply from rhizobium bacteria (Bernstein and Ogata, 1966; Tu, 1981).

The results obtained on maize confirm the conclusions of Stewart *et al.* (1977) and Shalhevet (1994) who admit a common relationship between yield and evapotranspiration, independent of whether changes in the two variables are caused by drought or salinity. The results obtained on soya contradict the results of Shalhevet and Hsiao (1986) on cotton and pepper, who observed that plants under saline conditions present at the same soil water potential a better growth than plants under drought. They attributed this difference to osmotic adjustment.

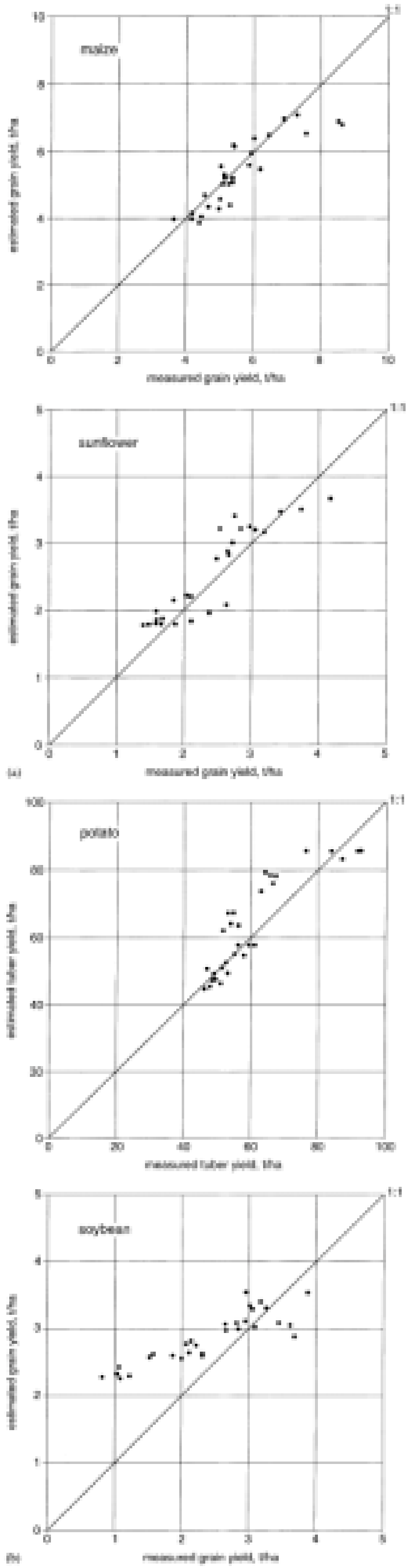

Fig. 11. Measured yield vs. yield estimated with Eq. (2)

Eq. (2) can also be used for crop classification according to evapotranspiration deficit, when written as relation between relative yield decrease and relative evapotranspiration deficit, proposed by Stewart *et al.* (1977):

$$1-\frac{y_a}{y_m}=b\left(1-\frac{ET_a}{ET_m}\right) \qquad (3)$$

According to Eq. (3), the higher the slope coefficient b, the stronger the drought effect, the relative yield decrease at equal evapotranspiration deficit. Doorenbos and Kassam (1979) classified in this way crops in four groups from drought tolerant to drought sensitive. Fig. 12 shows the result of the linear regression analysis for the crops of the lysimeter experiment. For lentil, the average values of both varieties were used, whereas for chickpea only the variety FLIP 87-59 was used, the other variety showing a particular behavior (Katerji *et al.*, 2001b). Four groups with a different slope can be distinguished:

- durum wheat (slope 0.6);
- maize, chickpea, sunflower, sugar beet, potato (slope 1.3);
- soybean, broadbean, tomato (slope 2.3);
- lentil (slope 4.2).

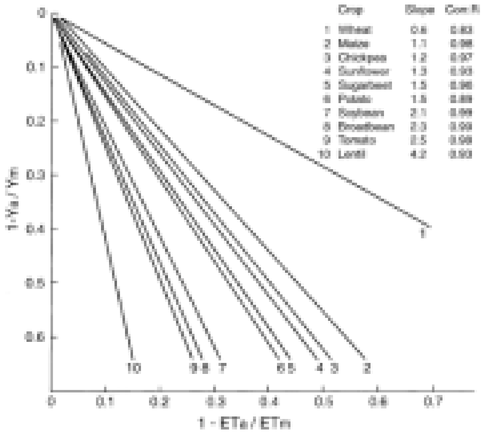

Fig. 12. Relative yield decrease vs. relative evapotranspiration deficit

The slope coefficients of crops of the same group do not differ significantly, but show a significant difference with the slope coefficients of the other crops. In contrast with the classification according to soil salinity, that indicates durum wheat and sugar beet both as salt tolerant and chickpea and lentil as salt sensitive, the classification according to the evapotranspiration deficit puts sugar beet and chickpea together with maize, sunflower and potato, still making a distinction with soybean, broadbean and tomato and indicating lentil as sensitive. Apparently the evapotranspiration deficit does not give a satisfactory classification for salt tolerance. Stegman (1985) mentioned that the slope coefficient is sensitive to climate conditions, e.g. an increase with decreasing air humidity, and the slope coefficient is also sensitive to the leaf area index (Katerji *et al.*, 1991).

Crop classification according to water stress day index

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.

To compare crop salt tolerance, the crop water stress is determined 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:

$$Y = a - b \times WSDI \qquad (4)$$

with

$$WSDI = \sum_{1}^{n} \frac{\psi_c - \psi_s}{n} \qquad (5)$$

in which cc is the daily value of the pre-dawn leaf water potential of the control treatment, irrigated with fresh water, from the start of leaf growth until the start of senescence, cs the equivalent of the saline treatment, n the number of days from the start of leaf growth until the start of senescence, b the yield loss in percentage per unit increase of WSDI, and a the value of the ordinate, which should be around 100. Because c is negative, WSDI positive.

The WSDI, as defined above, only translates a salinity effect and no drought effect, because it is based on a difference in pre-dawn leaf water potential between non-saline and saline treatments under equal environmental conditions of evaporative demand and irrigation regime.

Fig. 13 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 sugar beet, of which the slopes do not differ significantly but show a significant or highly significant difference with the second group comprising broadbean, soybean, tomato lentil and chickpea.

In comparison with the classification based on soil salinity, the classification according to the water stress day index also includes maize, sunflower and potato in the tolerant group and does not distinguish between broadbean, soybean and tomato on one hand and chickpea and lentil on the other hand in the sensitive group. So, the first question is why durum wheat and sugar beet are classified in the same group as maize, sunflower and potato. Wheat and sugar beet 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 sugar beet, 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.

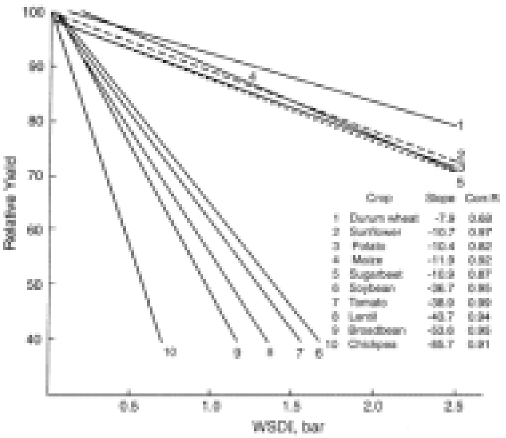

Fig. 13. Relative yield decrease vs. water stress day index

Potato is grown during the same period as sugar beet, but, unlike wheat and sugar beet, it is a shallow rooting crop. The limited capacity of potato to exploit the water-holding capacity of the soil could explain its salt sensitivity.

The second question regards the sensitive group. Broadbean, chickpea and lentil are winter crops, soybean and tomato are summer crops. Their sensitivity does not seem to be linked with the season of the year. All crops of the sensitive group are crops of indeterminate flowering. The flowering period lasts longer in comparison with crops having a determinate flowering. Several studies (Salter and Goode, 1967, Mouhouche *et al.*, 1998) indicate a maximum sensitivity during flowering. The effect of water stress during this period can be attributed to several causes.

- The reduction of the number of flowers, caused by a decrease of dry matter growth (Meynard and Sebillotte, 1994) or by a disturbance of the nitrogen uptake (Jeuffroy and Sebillotte, 1997), observed during water stress.
- The disturbance of pollination and fecundation. According to several authors (Sioni and Kramer, 1977; Westgate and Boyer, 1985) the fecundation is particularly affected by water stress.

So, the longer flowering period, a common characteristic of the five crops, could be a cause of their greater sensitivity to water stress.

Water use efficiency, osmotic adjustment and leaf area

Table 10 presents the soil salinity, expressed as ECe, the relative yield, the relative evapotranspiration and the water use efficiency of the crops. For the eight crops grown from 1989 to 1998, the values are the averages obtained on loam and clay, for lentil the average of both varieties, whereas for chickpea only the variety FLIP 87-59 was used. Two groups can be distinguished, corresponding with the classification according to the water stress day index:

- the group of which the water use efficiency is not affected by salinity and remains more or less constant: durum wheat, potato, maize, sunflower, sugar beets;
- the group of which the water use efficiency clearly decreases with increasing salinity: tomato, soybean, broadbean, chickpea and lentil.

Table 10 shows that the decrease of the water use efficiency results from the yield decrease being stronger than the decrease of evapotranspiration. Apparently, the grain and fruit formation of the second group is stronger affected than the evapotranspiration, indicating that the factors affecting the transpiration (stomatal conductance and adaptation by osmotic adjustment, leaf area) are not determining salt tolerance.

Table 10. ECe relatively yield, relative evapotranspiration and water use effeciency of crops grown during the lysimeter experiment

Crop	EC_e (dS/m)	Yield (%)	ET (%)	WUE (kg/m)	WUE (%)
Durum wheat	0.8	100	100	1.04	100
	2.3	095	090	1.10	106
	4.6	086	080	1.12	107
Potato	0.8	100	100	18.5	100
	2.6	081	091	16.3	088
	4.7	073	081	16.2	088
Maize	0.8	100	100	0.98	100
	1.9	094	090	1.03	105
	3.4	077	080	0.95	097
Sunflower	0.8	100	100	0.21	100
	2.4	086	088	0.20	097
	3.9	073	081	0.19	091
Sugar beet	0.8	100	100	7.0	100
	3.5	085	089	6.7	096
	6.1	083	089	6.6	094
Tomato	0.8	100	100	8.3	100
	4.3	073	091	6.6	080
	5.9	041	077	4.4	053
Soybean	0.8	100	100	0.77	100
	4.0	080	088	0.70	091
	6.7	044	072	0.47	061
Broadbean	0.8	100	100	1.37	100
	4.6	077	088	1.21	088
	6.1	049	078	0.86	063
Lentil	0.7	100	100	2.09	100
	2.0	081	091	1.78	085
	3.2	06	081	0.36	17
Chickpea	0.8	100	100	0.81	100
Variety 87-59C	2.4	057	064	0.73	090
	3.8	031	046	0.54	067

In Section 3.2, several examples of osmotic adjustment were presented that showed a different behavior in adjustment to salinity and its effect on stomatal conductance. The osmotic adjustment of sugar beet and lentil are the same (Table 5), whereas chickpea, classified in the same, sensitive group as lentil, shows a much lower value. Tomato and broadbean show the same osmotic adjustment but behave differently with respect to its effect on stomatal conductance, as shown in Figs. 5 and 6. At least for these five crops, it is not possible to use the osmotic adjustment as a criterion for explaining differences in salt tolerance.

Plants show a different salinity effect on leaf area. As already mentioned before, maize, soybean and tomato showed a leaf area reduction of about 10%, whereas the reduction was 20–50% for the other crops. The salinity effect on leaf area does not appear to be correlated with the plant's aptitude for osmotic adjustment. The leaf areas of sugar beet and broadbean, differing considerably in osmotic adjustment, are both strongly affected, whereas this is not the case for tomato. The leaf areas of chickpea and lentil are both strongly affected, whereas the crops differ strongly in their osmotic adjustment. Table 11 compares the salinity effect on leaf area and the crop classifications according to soil salinity and water stress day index. No relation appears between the salinity effects on leaf area and yield. Observations of leaf area of salt affected crops are not reliable for yield prediction.

Salt tolerance of grain legumes

If crops are classified according to the water stress day index, tomato, soybean, broadbean, lentil and chickpea belong to the same, sensitive group. Still these crops show considerable difference among themselves if classified according to soil salinity. Soybean is classified by Maas and Hoffman (1977) as moderately salt tolerant, but did not differ significantly in the lysimeter experiment from broadbean, classified as moderately sensitive by the same authors. This may be attributed to a difference in variety. Both crops, however, differ significantly from chickpea and lentil, as shown in Fig. 9.

Table 11. Salinity effect on leaf area and crop classification according to soil salinity and water stress day index (WSDI)

Crop	Leaf area		Crop classification				
	Slight	Strong	Soil salinity			WSDI	
			Tolerant	Moderate	Sensitive	Tolerant	Sensitive
Durum wheat		x	x			x	
Sugar beet		x	x			x	
Potato		x		x		x	
Maize	x			x		x	
Sunflower		x		x		x	
Tomato	x			x			x
Soybean	x			x			x
Broadbean		x		x			x
Lentil		x			x		x
Chickpea		x			x		x

To determine the salinity effect on the nitrogen uptake of the four grain legumes, the nitrogen concentration of the aerial parts was analyzed and the nitrogen uptake of the crop was calculated. The difference between the nitrogen uptake and the input from fertilizer and irrigation minus drainage water yielded the biological nitrogen contribution of the soil, comprising together the nitrogen fixation and the transformation of organic matter.

Table 12. Effect of soil salinity on relative biological nitrogen contribution of the soil

Soybean		Broadbean		Chickpea		Lentil	
EC_e (dS/m)	N (%)	EC_e (dS/m)	N (%)	EC_e (dS/m)	N (%)	EC_e (dS/m)	N (%)
0.8	100	0.8	100	0.8	100	0.7	100
4.0	077	4.6	056	2.4	045	2.0	045
6.7	028	6.1	015	3.8	024	3.2	000

Salinity did not affect the nitrogen concentration of the shoots and pods of soybean and chickpea, but the shoots and pods of broadbean and lentil showed a decrease of the nitrogen concentration at increasing salinity. Not only the total nitrogen uptake of the crop decreased at increasing salinity—not astonishing in view of the yield decrease—but also the biological nitrogen contribution of the soil. Table 12 shows this decrease and that it already starts at a lower salinity level for chickpea and lentil. At an ECe between 3 and 4 dS/m chickpea and lentil present much lower values for the nitrogen contribution than soybean and broadbean. Apparently, the difference in salt tolerance between the grain legumes is caused by a difference in nitrogen fixation and the symbiosis between rhizobia and plant is more salt sensitive in the case of chickpea and lentil.

APPLICATION IN MODELING CROP RESPONSE TO SALINITY

For simulating the effect of water deficit on plant growth, crop response models generally use stress coefficients that depend on the soil water status and are calculated from the soil water balance. Salinity affects the availability of soil water due to its osmotic potential component. Simply adding the osmotic potential and the soil matrix potential does not give an accurate expression of the water availability for the plant. Since the predawn leaf water potential is a reliable indicator of the plant water status, this parameter can be used for expressing the water stress instead of a soil water based stress coefficient.

This principle was applied in the modification of the CERES- Maize model (Castrignano *et al.*, 1998). The pre-dawn leaf water potential was introduced for the calculation of the stress coefficient and the modified model was tested with data obtained from the maize crop grown during the lysimeter experiment. Reasonable agreement was found between model predictions and measured data of evapotranspiration, leaf area index, biomass and grain yield.

Conclusions

The pre-dawn leaf water potential is a useful parameter for indicating plant water stress caused by salinity. Crops show a lower pre-dawn leaf water potential at increasing salinity. When used for salt tolerance classification of crops, the pre-dawn leaf water potential, expressed as water stress day index during the growing period, distinguishes a tolerant group, comprising durum wheat, sugar beet, maize, sunflower and potato, and a sensitive group, comprising tomato, soybean, broadbean, chickpea and lentil. The tolerant crops show a more or less constant water use efficiency at increasing salinity. The sensitive crops show a decrease of the water use efficiency, as their yield decreases stronger than the evapotranspiration. This indicates that the factors affecting the transpiration are not determining salt tolerance. Indeed no correlation could be found between osmotic adjustment, leaf area and yield reduction. As the flowering period is a sensitive period for grain and fruit formation and the sensitive crops are all of indeterminate flowering, their longer flowering period could be a cause of their greater sensitivity.

The tolerant group, when classified according to soil salinity, can still be divided in a salt tolerant group, comprising wheat and sugar beet, and a moderately sensitive group, comprising maize, sunflower and potato. The difference in classification can be attributed to the difference in evaporative demand during the growing period.

The sensitive group, when classified according to soil salinity, can be divided in a moderately sensitive group, comprising tomato, soybean and broadbean, and a salt sensitive group, comprising chickpea and lentil. The difference in classification can be attributed to the salinity effect on the biological nitrogen contribution of the soil, reflecting the greater sensitivity of the symbiosis between rhizobia and grain legume in the case of chickpea and lentil.

The combination of both classifications leads to better understanding of the salinity effect on crops. The salt tolerance classification according to soil salinity is necessary for practical purposes.

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