Productivity analysis of crops grown in saline environment: presentation of the major research lines

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Productivity analysis of crops grown in saline environment: presentation of the major research lines

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Abstract

In this contribution, the various approaches mentioned in the literature are investigated to characterize crop responses to saline stress. In each case, the steps undertaken are presented and examples of the results obtained underlined. In addition, the presentation is accompanied by a critical analysis showing the advantages and limitations of each approach. In conclusion, we evoke arguments pleading for an eco-physiological approach associating a description of plant water behaviour in a saline environment with yield related to observations.

Introduction

In the Mediterranean region, the transition from rainfed agriculture to intensive irrigated agriculture has favoured the increase in soil salinity (Hamdy and Lacirignola, 1992). To maintain prosperous agriculture, the impact of this phenomena on the environment and the production of species normally grown in the region has to be analyzed. The effect of salinity is first of all related to the osmotic effect (Hayward, 1957, Bernstein and Hayward, 1958). As the soil solution salinity increases, the osmotic potential decreases and thus reduces the availability of water to

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the plant. At high salinity levels, the thirsty effect is accompanied by an unbalanced absorption of ions which could cause plant toxicity.

In order to analyse the influence of salinity on the functioning and the production of plants, two approaches are possible:

- The empirical approach where the canopy is considered as a "black box" taken as a whole. It is often accepted to consider soil salinity as related only to yield.
- The mechanistic approach that consists in describing the salt-induced water stress at the plant level, then to analyse its consequences on the physiological mechanisms of the plant (water status, osmotic adjustment, gaseous exchange, metabolism) that govern yield. In some few studies this characterization is made during the whole growing cycle in order to analyze the consequences on the leaf area formation, on dry matter accumulation and final yield.

In this paper, the steps followed in the mechanistic and operational approaches will be presented and before illustrating the most significant results. This presentation will be accompanied by a critical analysis that shows the advantages and limits of each of these approaches. Finally, we will underline the interest of an approach that associates the observations made during the vegetation cycle on the influence of salinity on the plant water status, its gaseous exchanges and its water balance with the observations related to growth and crop yield.

I. RESEARCH WORK ON THE EMPIRICAL RELATIONSHIPS BETWEEN SALINITY AND CROP YIELD.

1. Relative yield evolution in relation to the salinity of the environment

The simplest approach consists in determining the relative yield as a function of salinity of the environment; in other words, the relationship between the crop yield on a saline soil with respect to the yield of the same crop on a non-saline soil, the other conditions being equal, (climate, soil texture, irrigation depth…). The salinity of the environment is expressed referring to the salt content in the irrigation water or in the soil (it is generally assumed that there is a fixed relationship between these two parameters, Ayers et Westcot 1988). Ample literature has been devoted to these works and hereby we simply mention the references where detailed works can be consulted (Bernstein 1964, Unesco 1970, Maas et Hoffman 1977, Ayers et Westcot 1988, Gupta et Sharma 1990).

Table I presents the evolution of relative yield in relation to the salinity of irrigation water. Figure I presents the same ratio versus the salinity of the soil, taken in spring and autumn in the 0-80 cm depth layer, in the framework of an experiment in Tunisia.

Generally speaking, the relationship between relative yield and salinity is almost rectilinear. In most cases, relative yield remains close to one until soil salinity is less than a threshold level. Below this level, relative yield decreases linearly with the increase in salinity in the soil. This type of relationship is relatively simple to determine; it allows to classify the considered species depending on their tolerance to salinity (Table I). However, it is not sure that the relationships found allowed to the estimate the absolute yield in saline environment with enough accuracy for a sound planning. In fact, other factors in addition to salinity of the environment play a role (soil texture, evapotranspiration demand, presence or absence of a drainage system, growth stage ...) to increase or reduce the impact of salinity on plant functioning in saline environment and, consequently on crop yield (Van Hoorn 1972, Frenkel 1984).

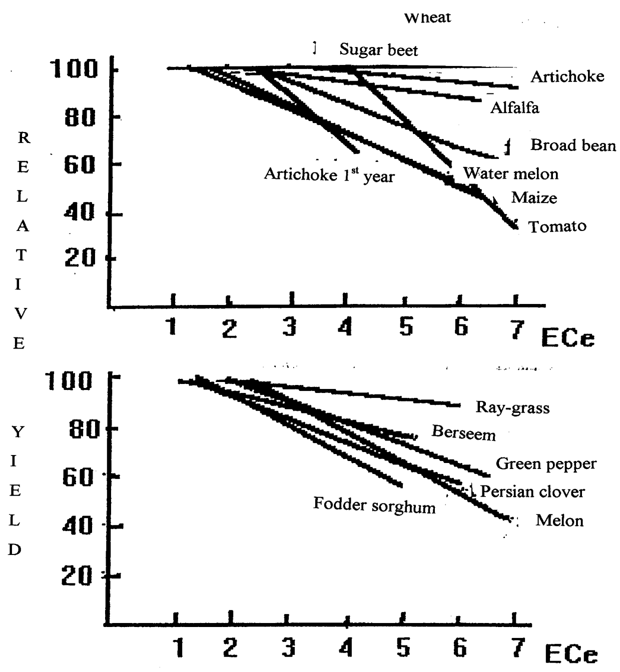

Fig. 1 Relationship of relative yield to salinity of the saturated paste extract in a soil layer of 0-80 cm (From: UNESCO, 1970).

***Table 1**.* Relative yield of several plant species in relation to the salinity of irrigation water (ECw) or of the soil saturation extract (ECe) (From Ayers et Westcot 1988)

Crop species	100%		90%		75%		50%		0%		Salt tolerance
	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	
Barley	8.0	5.3	10	6.7	13	8.7	18	12	28	19	Tolerant
Cotton	7.7	5.1	9.6	6.4	13	8.4	17	12	27	18	Tolerant
Sugar beet	7.0	4.7	8.7	5.8	11	7.5	15	10	24	16	Tolerant
Sorghum	6.8	4.5	7.4	5.0	8.4	5.6	9.9	6.7	13	8.7	Moderately tolerant
Durum wheat	5.7	3.8	7.6	5.0	10	6.9	13	8.7	20	13	Moderately tolerant
Soybean	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5.0	10	6.7	Moderately tolerant
Groundnut	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.6	4.4	Moderately sensitive
Rice	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11	7.6	Moderately sensitive
Sugar cane	1.7	1.1	3.4	2.3	5.9	4.0	10	6.8	19	12	Moderately sensitive
Maize	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7	Moderately sensitive
Flax	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7	Moderately sensitive
Broad bean	1.5	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12	8.0	Moderately sensitive
Green bean	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2	Sensitive

2. Evolution of relative yield in relation to relative evapotranspiration

To obtain more reliable results on the crop yield in saline environment different authors have tried to find out a relationship between relative yield and relative evapotranspiration, i.e. the evapotranspiration of a crop grown in a saline soil with respect to the same crop in a non-saline soil. The argument is that relative evapotranspiration allows to appreciate, on a more or less long time-basis (day, ten-days, growing cycle), to what extent crop water requirements have been satisfied. This ratio represents, then, an indicator of water supply conditions to crops; moreover, it integrates a number of pedo-climatic variables and should consequently lead to stricter relationships.

The literature reports several works (Childs and Hanks 1975, Hanks et al. 1978, Stewart et al. 1977, Parra and Romero 1980, Frenkel et al. 1982) who refer to this approach but they are definitely less numerous than those who relate relative yield to salinity of the environment, since there are few data on crop evapotranspiration in saline environment are available.

From this work the following remarks are drawn:

- A proportionality relationship observed between the reduction in evapotranspiration due to the increase in salinity and the corresponding reduction in relative yield (cf. synthetic references of Letey 1993). The yield response of crops to saline water stress or resulting from soil dryness (cf. synthetic references by Doorenbos and Kassam 1979) is thus similar.
- When comparing, under given pedo-climatic conditions, the characteristics of the linear relationship (slope and ordinate at the origin) observed between evapotranspiration and relative yields under conditions of saline water stress or related to soil dryness, the authors agree to conclude that a unified linear relationship can be applied to these two situations (Hanks et al., Van Hoorn et al. 1993). An example of these results concerning Maize is presented in figure 2 according to a bibliographic synthesis made by Feddes (1985).
- The slope of the relationship between absolute yield and cumulated evapotranspiration during the growing cycle allows to determine water efficiency for the considered species. Many studies are available at present (Katerji et al. 1992, Van Hoorn et al. 1993); they are a useful tools to plan crop growing in saline environment.

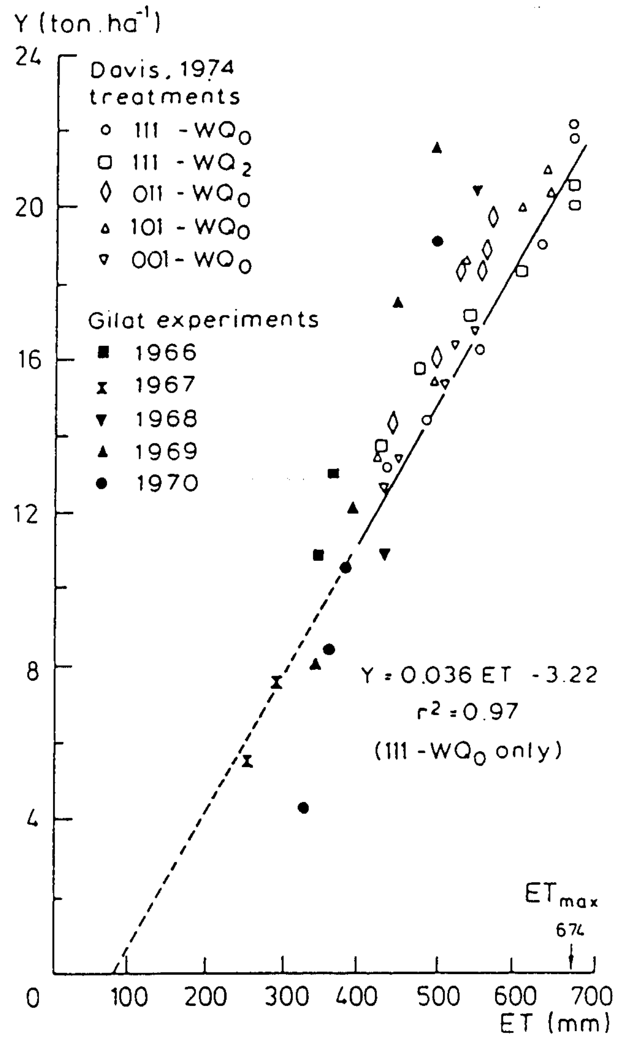

Fig. 2 Relationships observed on maize grown at Davis (United States) and Gilat (Israel) between the total values of dry matter and evapotranspiration. Treatment 111-WQ2 was obtained by using saline water (From: FEDDES, 1984).

Together with this positive results, the previously described approach also presents some limits:

- The straight lines resulting from the relationship of the relative yield and relative evapotranspiration relationship are subject to variation according to the pedo-climatic conditions. Very often, this change is related to the vapour pressure deficit (Stegman 1985).
- Relative evapotranspiration imperfectly reflects the water supply conditions of crops when direct evaporation of the soil is high (Katerji et Perrier 1985). It is the case, for instance, of row crops.
- Finally, one should stress that the determination of evapotranspiration requires expensive equipment and a rigorous technical control. These constraints do not allow, at present, to extend such studies (Katerji et Grebet 1988).

Despite these constraints, one should consider that the described approach is much more precise approach than the one described in section 1 to analyse the response of crops to saline water stress.

II. THE MECHANISTIC APPROACH OF THE RELATIONSHIP BETWEEN SALINITY AND CROP PRODUCTION

1. Physiological approach

This approach consists in analysing the effect of salinity on the physiological mechanisms: water status (West et al. 1986, Katerji et al. 1994), gaseous exchanges (Lloyd et al. 1987, Seemann et Critchley 1985, Papp et al. 1983, Ziska et al. 1990, Schwartz et Gale 1984, Downton 1977), growth (Yeo et al. 1991, Thiel et al. 1988, Munns et al. 1988, Schwarz et Gale 1984), metabolism (Osmond et Greenway 1972, Green et al. 1971) that take part in the yield formation. Studies are founded on an accurate description of the process, made on a short-time scale (some minutes to some days) on plants grown under standard laboratory conditions and rarely in the field. An example of these results is presented in figure 3. It underlines the effect of salinity of irrigation water on water status and stomatal conductance in maize seedlings grown in the greenhouse on two soil types of different texture.

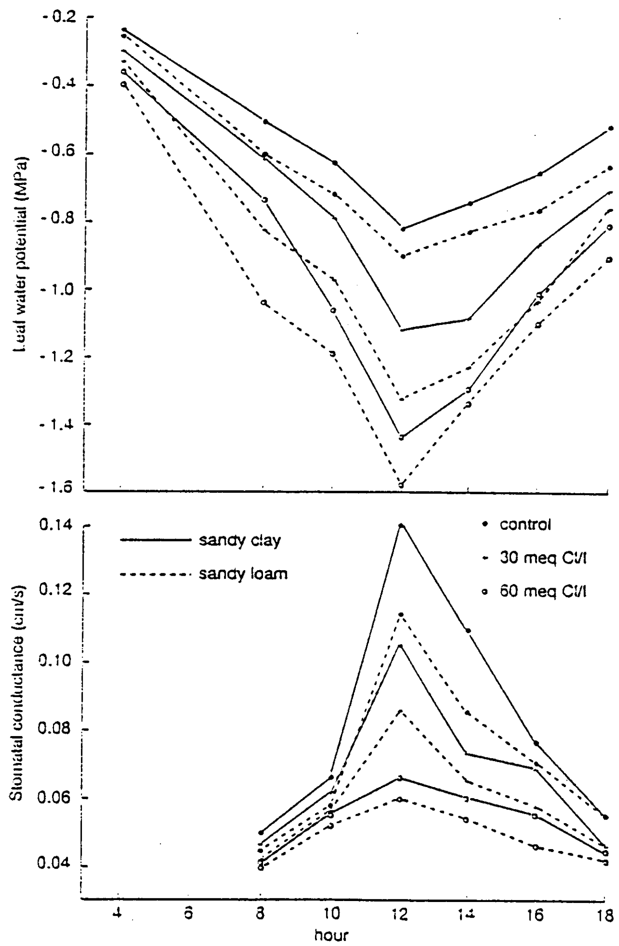

Fig. 3 Observed values of stomatal conductance and leaf water potential on maize grown on two soils of different texture and irrigated with different water qualities (From KATERJI et al. 1994).

The physiological approach meets two objectives (Munns 1993) :

- to understand the mechanisms of plant response to salinity, particularly the adaptation processes of the latter in saline environment (Yeo et al. 1991, Westgate et Boyer 1985, Shalhevet et Hsiao 1986),
- to propose the criteria or the methods to select the species or the varieties susceptible to tolerate saline environment (Zid et Grignon 1991).

On the other hand, these research works do not provide direct information on crop yield in natural environment.

2. Eco-physiological approach

This approach consists in studying the physiological mechanisms related to the introduction of a species in its cropping systems. The physiological mechanisms already identified are integrated here in the environmental factors. So, pedo-climatic factors are taken into account to describe the saline water deficit on the hydraulic and photosynthetic functioning of the plant and their consequence on crop growth, development and yield. The studies are based on the observations made under field conditions both on single plants and on the canopy as a whole.

The eco-physiological approach is particularly interesting to identify the sensitivity of the different growth stages to salinity.. A number of works relative to this time scale are mentioned in the literature. Here we mention particularly the works by Howell et al 1984 on cotton, Kluitenberg et Biggar 1992, on sorghum, Katerji et al. 1992 on broad bean, Van Hoorn et al. 1993 on potato and wheat and Katerji et al. 1996 on maize and sunflower.

The main results of an echo-physiological study made on two crops, maize and sunflower, are presented here as an example. This study is made on the experimental site of the MAI-Bari and is described in details in a previous publication (Katerji et al. 1996). We simply remind that this site consists of 30 identical drainage lysimiters above the ground, half of which are filled with clay soil and half with loamy soil.

Figures 4 and 5 show, under the two observed crops, the effect of irrigation water salinity on the plant water status (leaf water potential and stomatal conductance) during the growing cycle. The long term effect of salinity on leaf area growth and dry matter is presented in figures 6 and 7. Finally, the combined effects of the use of saline water and soil texture on the water efficiency in the considered crops are presented in table 2.

The eco-physiological approach is an interesting procedure for the following reasons:

- it maintains the natural climatic fluctuations in the analysis of one or several parameters related to the canopy.
- it allows to look for the explicatory factors of the plant behaviour and obtained yields.
- finally, the analysis allows to establish the forecast models of the plant behaviour.
- The major limits of the eco-physiological studies refer to:
- the need to make observations in field conditions give rise to very constraining conditions,
- the eco-physiological studies are generally based on rather sophisticated methods to characterize the behaviour, of the considered crops. As for the characterization of the hydraulic behaviour, this difficulty is partially solved through the methodological studies (Katerji et al. 1988) that allowed to propose simple and routine methods.

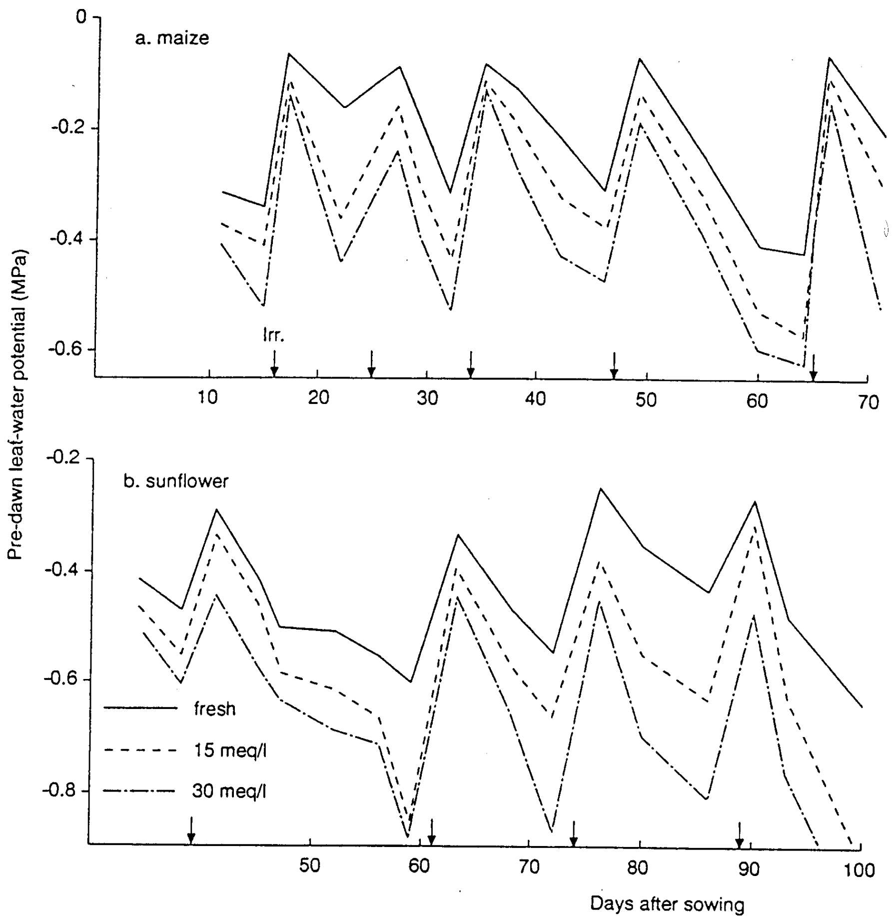

Fig. 4 Effect of salinity of irrigation water on the pre-dawn leaf water potential during the growing cycle of maize (a) and sunflower (b) grown in a loamy soil (From KATERJI et al., 1996).

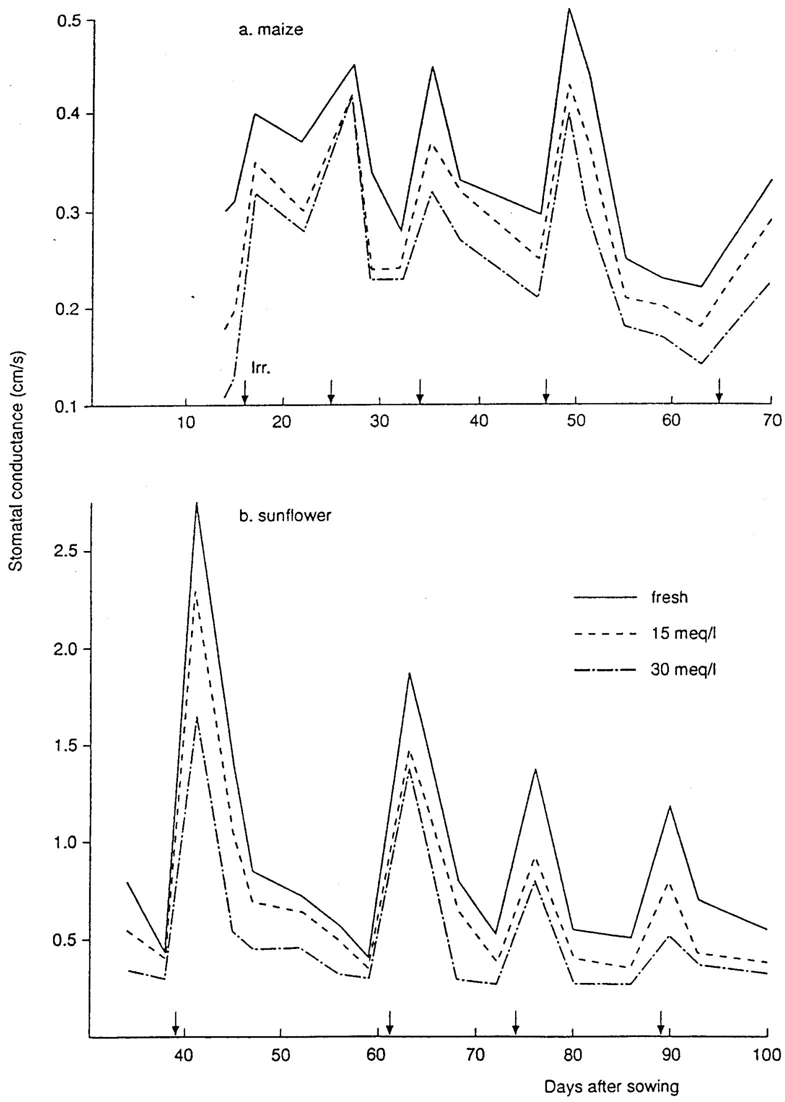

Fig. 5 Effect of saline irrigation water on stomatal conductance measured during the growing cycle of maize (a) and sunflower (b) grown on a loamy soil (From KATERJI et al., 1996).

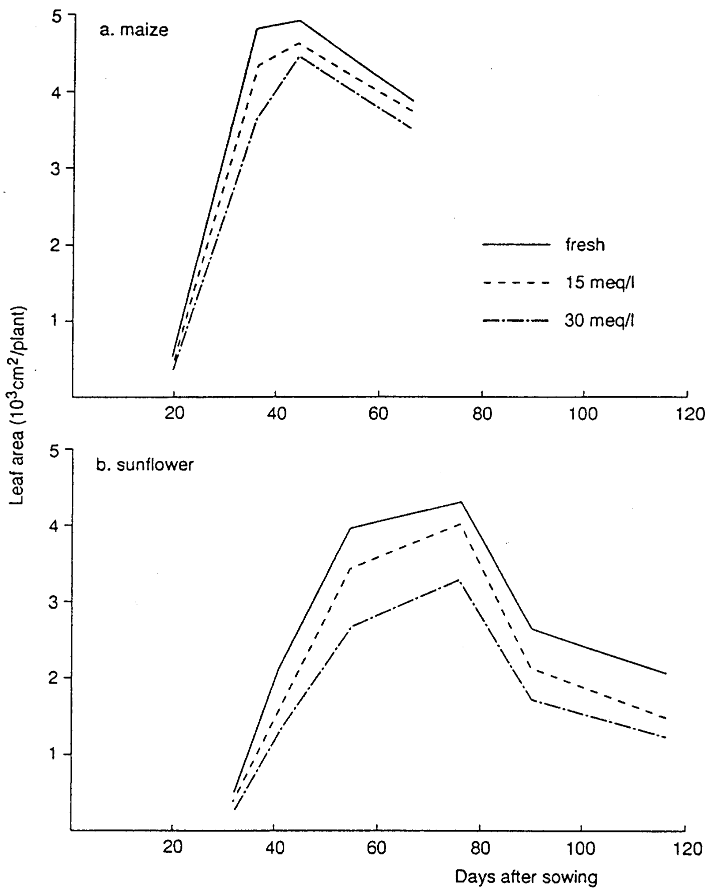

Fig. 6 Effect of irrigation water salinity on leaf area measured during the growing cycle of maize (a) and sunflower (b) grown on a loamy soil (From KATERJI et al., 1996).

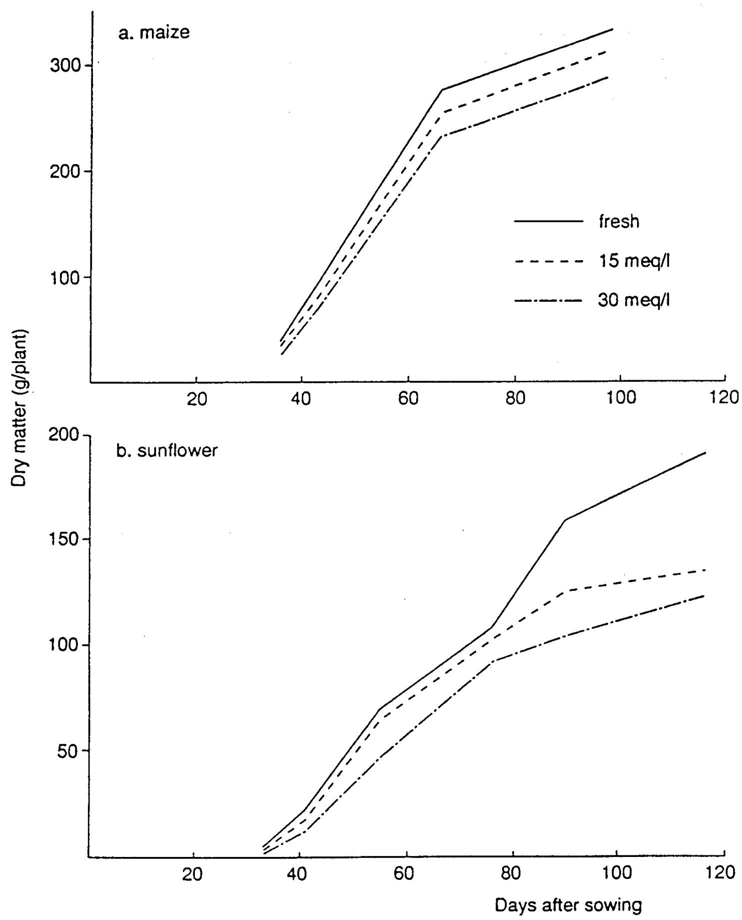

Fig. 7 Effect of salinity of irrigation water on dry matter measured during the growing cycle of maize (a) and sunflower (b) grown in a loamy soil (From KATERJI et al., 1996).

Table 2 Grain and dry matter yield water efficiency observed on sunflower and maize treatments in relation to soil texture and irrigation water salinity (From KATERJI et al., 1996).

Sunflower

	Loam			Clay		
	Fresh	15 mEq. l^{-1}	30 mEq. l^{-1}	Fresh	15 mEq. l^{-1}	30 mEq. l^{-1}
Grain yield (Kg m^{-2})	0.351	0.291	0.263	0.216	0.193	0.154
Total canopy dry matter [kg m^{-2}]	1.039	0.818	0.744	0.597	0.514	0.385
Grains/plant	1280	1183	1159	950	926	831
Weight of 1000 grains [kg]	0.062	0.056	0.051	0.051	0.047	0.042
ECe [dS m^{-1}]	0.8	2.7	3.8	0.8	2.0	3.9

Maize

	Loam			Clay		
	Fresh	15 mEq. l^{-1}	30 mEq. l^{-1}	Fresh	15 mEq. l^{-1}	30 mEq. l^{-1}
Grain yield (Kg m^{-2})	0.678	0.674	0.533	0.548	0.486	0.414
Total canopy dry matter [kg m^{-2}]	1.466	1.387	1.269	1.324	1.192	1.133
Ears/plant	1.20	1.24	1.03	1.06	1.00	1.00
Grains/ear	522	487	505	526	486	441
Weight of 1000 grains [kg]	0.244	0.254	0.232	0.221	0.226	0.212
ECe [dS m^{-1}]	0.8	1.8	3.0	0.8	1.9	3.7

CONCLUSIONS

The previous presentation concerning the different possible approaches to characterize the crop response to saline water stress, has highlighted the advantages and limits of each of them.

To date, the eco-physiological approach is the most interesting method in that it is based on the description of the hydraulic behaviour of plants in saline environment. This behaviour integrates other variables like soil texture and the climate, which may modifying the crop response to the salinity of the environment. Subsequently, the analysis of the relationship between the hydraulic behaviour observed and the agronomic yield of plants will allow to perform a more appropriate and reliable analysis of the consequences of salinity on crop yield.

REFERENCES

Ayers R.S., Westcot D.W. 1988 - La qualité de l'eau en agriculture. Bul. FAO d'Irrig. et de Drain. 29 rev.1, Rome, 180 p.

Bernstein L., Hayward H.E.1958 - Physiology of salt tolerance. Annu.Rev. Plant Physiol., 9, 25-46.

Childs S.W., Hanks R.J.1975 - Model of soil salinity effects on crop growth. Soil Sci. Soc. Am.Proc., 29, 617-622.

Doorenbos J., Kassam A.H.1979 - Yield response to water. FAO Irrigation and Drainage paper 33, Rome 193p.

Downton W.J.S.1977 - Photosynthesis in salt-stressed grapevines. Aus. J. Plant Physiol., 4, 183-192.

Feddes R.A. 1984 - Crop water use and dry matter production : State of the art. **In**: Les besoins en eau des cultures. Conf. Int. CIID Paris. PERRIER A., RIOU C. (eds) p. 221-234.

Frenkel M., Mantel A., Meiri A.1982 - Irrigation of cotton with saline sodic water using sprinkler and drip methods. Agric. Res. Org. Volcani Center Inst. Soil water Res.Rapport 302/047

Frenkel H.1984 - Reassessment of water quality criteria for irrigation. Ecolog. Studies, 51, 172-173.

Green P.B., Erickon R.O., Buggy Y.1971 - Metabolic and physical control of cell elongation rate. In vivo studies in Nitella. Plant Sci. 47, 423-430.

Gupta S.K., Sharma S.K.1990 - Response of crops to high exchangeable sodium percentage. Irrig. Sci., 19,173-179.

Hanks R.J, Ashcroft G.L., Rasmussen V.P., Wilson G.D.1978 - Corn production as influenced by irrigation and salinity Utah studies. Irrig. Sci., 1, 47-59.

Hamdy A., Lacirignola C. 1992 - An overview of water resources in the Mediterranean countries. **In**: Workshop on Water resources: Development and management in Mediterranean Countries IAM Bari Editeur, 11 1-32.

Hayward H.E. 1957 - La croissance des plantes en milieu salin. **In**: Utilisation des eaux salines. Collection compte rendu de recherche UNESCO Edition, 39-75.

Howell T.A., Hatfield J.L., Rhoades J.D., Meron M.1984-Response of cotton water stress indicators to soil salinity. Irrig. Sci. , 5, 25-36.

Katerji N., Perrier A.1985 - Détermination de la résistance globale d'un couvert végétal à la diffusion de vapeur d'eau et de ses différentes composantes. Approche théorique et vérification expérimentale sur une culture de luzerne. Agric. For Meteorol., 34, 2-3, 105-120.

Katerji N., Grebet P.1988 - Methods for determining actual evapotranspiration in plots. **In**: Delynn R. Hay (ed) "Planning now for irrigation and drainage in the 21st century" National Conference on irrigation and Drainage

Engineering, ASCE, Lincoln, Nebraska USA, 18-21/07/1988, ASCE, New York USA, ISBN 0-87262-666-0, 520-527.

Katerji N., Itier B., Ferreira I.1988 - Etude de quelques critères indicateurs de l'état hydrique d'une culture de tomate en région semi-aride. Agronomie, 8, 5, 425-433.

Katerji N., Van Hoorn J.W., Hamdy A., Bouzid N, El-Sayed Marous S., Mastrorilli M.1992 - Effect of salinity on water stress, growth, and yield of broadbeans. Agric. Water. Manag., 21, 107-117.

Katerji N., Van Hoorn J.W., Hamdy A., Karam F., Mastrorilli M. 1994 - Effect of salinity on emergence and on water stress and early seedling growth of sunflower and maize. Agric. Water. Manag., 26, 81-91

Katerji N., Van Hoorn J.W., Hamdy A., Karam F., Mastrorilli M. 1996 - Effect of salinity on water stress, growth, and yield of maize and sunflower. Agric. Water. Manag., 30, 237-249.

Kluitenberg G.J., Biggar J.W.1992 - Canopy temperature as a measure of salinity stress on sorghum. Irrig. Sci., 13, 115-121.

Letey J. 1993 - Relationship between salinity and efficient water use. Irrig. Sci.14, 75-84.

Lioyd J., Syvertsen J.P., Kriedemann P.E.1987 - Salinity effects on leaf water relations and gas exchange of Valencia, orange, *Citrus sinensis* (L.) Osbeck, on rootstocks with different salt exclusion characteristics. Aust. J. Plant Physiol., 14, 605-617.

Maas E.V. and Hoffman G.J. 1977 - « Crop salt tolerance current-assessment ». ASCE J. Irrig. and Drain. Div., 103, 115-134.

Munns R., Gardner P.A., Tonnet M.L., Rawson H.M.1988 - Growth and development in NaCl-treated plants.II. Do Na^+ or Cl^- concentrations in dividing or expanding tissues determine growth in barley. Aust. J. Plant Physiol., 15, 529-540.

Munns R. 1993 - Physiological processes limiting plant growth in saline soils : Some dogmas and hypotheses. Plant Cell Environ., 16, 15-24.

Osmond C.B.,Greenway H.1972 - Salt responses of carboxylation enzymes from species differing in salt tolerance. Plant Physiol., 49, 260-263.

Papp J.C., Ball M.C., Terry N.1983 - A comparative study of the effects NaCl salinity on respiration, photosynthesis, and leaf extension growth in *Beta vulgaris* L.(Sugar beet). Plant Cell Environ., 6, 675-677.

Parra M.A., Romero G.C.1980 - On the dependence of salt tolerance of beans (*Phaseolus vulgaris* L..) on soil water matric potential. Plant and Soil, 56, 3-16.

Schwarz M., Gale J.1984 - Growth response to salinity at high levels of carbon dioxide. J. Exp Bot., 35, 193-196.

Seemann J.R.,Critchley C.1985 - Effects of salt stress on the growth, ion content, stomatal behaviour and photosynthetic capacity of a salt-sensitive species, *Phaseolus vulgaris* Planta, 164, 151-162.

Shalhevet J.,Hsiao T.C.1986 - Salinity and drought a comparaison of their effects on osmotic adjustment, assimilation transpiration and growth. Irrig. Sci., 7, 249-264.

Shalhevet J 1984- Using water of marginal quality for crop production: major issues. Agric Water Manag 25, 233-269.

Stegman E.1984 - Efficient water scheduling regimes for corn production. In: Les besoins en eau des cultures. Conf. Int. CIID. Paris. PERRIER A., RIOU C. (eds) p. 635-648.

Stewart J.L., Danielson R.E., Hanks R.J., Jackson E.B., Hagan R.M., Pruitt W.O. Franklin W.T., Riley J.T.1977-Optimizing crop production through control of water and salinity levels in the soil. Utah Water Lab TRWG 151-1 Logan, UT, 191 p.

Thiel G.,Lynch J. Läuchli A.1988 - Short-term effects of salinity stress on the turgor and elongation of growing barley leaves. J.Plant Physiol., 132, 38-44.

UNESCO 1970 -Recherche et formation en matière d'irrigation avec des eaux salées. Tech. Rpt / UNESCO / UNDP. TUN5 . 243 p. + Annexe.

Van Hoorn J.W. 1972 - Qualité de l'eau d'irrigation, limites d'utilisation et prévision des effets à long terme. Bull. FAO Irrig. Drainage 7, 117-135.

Van Hoorn J.W., Katerji N., Hamdy A., Mastrorilli M.1993 - Effect of saline water on soil salinity and on water stress, growth and yield of wheat and potatoes. Agric. Water Manag., 23, 247-268.

West D.W., Hoffman G.J., Fisher M.J.1986 - Photosynthesis, leaf conductance and water relations of cowpea under saline conditions. Irrig. Sci., 7, 183-193.

Westgate M.E., Boyer J.S. 1985 - Osmotic adjustment and the inhibition of leaf, root, stem and silk growth at low water potentials in maize. Planta, 164, 549-549.

Yeo A.R., Lee K.S., Izard P., Boursier P.J., Flowers T.J.1991 - Short- and long-term effects of salinity on leaf growth in rice (*Oryza sativa* L.). J. Exp. Bot., 42, 881-889.

Zid E., Grignon C.L., 1991 - Les tests de sélection précoce pour la résistance des plantes aux stress. Cas des stress salin et: hydrique. **In:** L'amélioration des plantes pour l'adaptation aux milieux arides. Eds Aupelfuref, Libbey J., Eurotext. Paris 91-108.

Ziska L.H., Seemann J.R., Delong T.M.1990 - Salinity induced limitations on photosynthesis in *Prunus salicina*, a deciduous tree species. Plant Physiol., 93, 864-870.