Research Aspects for Crop Salt Tolerance under Irrigation with Special Reference to Root Environment

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Dedicated to my dear colleague Prof. Dr. Dr. Ewald Schnug on the occasion of his 50th birthday

Summary

Due to the lack of good quality water for human consumption and industry, in many countries irrigated agriculture is exposed to increasing pressure to expand the use of brackish and even high-saline waters for crop production. The application of lower quality waters requires special management practices, which are not yet fully understood with respect to optimization of plant growth on saline soils. Generally, the evaluation of crop salt tolerance and the calculation of irrigation water requirement for brackish water is based on crop yields related to the average salinity of the rooted soil layer (FAO and USDA). However, this concept often fails when brackish water is often applied frequently (e.g. drip irrigation). The approach presented in this paper considers not only the effect of water applications on the vertical salt movement (salt leaching), but also reflects the effect of lateral water and salt movement of saline soil solutions induced by roots, which differ in their root morphology. This lateral flow of water is caused by the transpiration of plants, which results in a flow of distant saline soil solution directed to the water absorbing root surface. As most salts are excluded from root uptake, they usually accumulate in the rhizospheric soil (soil in direct contact with the root surface including the cylinder formed by root hairs). A concentration gradient between distant and rhizospheric soil solution develops, the rhizospheric soil solution may become several times more saline than the average or distant soil solution (bulk soil). The effects of dynamic processes between bulk and rhizospheric soil under irrigation and with respect to root morphology are not yet understood. It is postulated that roots forming a large rhizocylinder (deeply rooting, high rooting density, long root hairs) are contributing to a higher salt tolerance as roots forming a smaller rhizocylinder. It can be expected that a more profound understanding of these processes may essentially contribute to optimize brackish water irrigation and to define goals for breeding more salt tolerant crops.

Keywords: *brackish water, irrigation, rhizosphere, root morphology, root water uptake, saline soils, salt tolerance, soil salinity, soil water availability*

Zusammenfassung

In vielen Ländern der Trockengebiete führt der zunehmende Mangel an Wasser guter Qualität für den menschlichen Konsum und die Industrie zu verstärktem Druck auf die Bewässerungslandwirtschaft, auch Wasser minderer Qualität wie Brackwasser und salzhaltige Abwässer in der Pflanzenproduktion einzusetzen. Der Einsatz von Bewässerungswasser minderer Qualität erfordert spezielle Managementpraktiken, die unter anderem auch dem Pflanzenwasserbedarf, der Wasserqualität, Bodeneigenschaften und der Salztoleranz der Pflanze Rechnung tragen. Nach FAO und USDA wird die Abschätzung des Wasserbedarfes bei Bewässerung mit Brackwasser im Wesentlichen auf Grund der Beziehung zwischen Ertragsverlusten (Relativerträge) und der durchschnittlichen Versalzung der Wurzelzone eines Bodens ermittelt. Dieses Konzept ergibt jedoch in vielen Fällen unbefriedigende Resultate, insbesondere wenn in häufigen kleineren Gaben bewässert wird (drip irrigation). Das hier vorgestellte Konzept berücksichtigt dagegen nicht nur die Wirkung von Bewässerung auf die vertikale Wasserbewegung im Boden (Salzauswaschung), sondern analysiert darüber hinaus auch die Bedeutung der lateralen Bewegung salzhaltiger Bodenlösung, wie sie durch den Wasserentzug von Wurzeln unterschiedlicher Morphologie erfolgt. Antrieb dieser lateralen Wasserbewegung ist die Transpiration, die einen Fluss salzhaltiger Bodenlösung aus dem wurzelferneren Boden in Richtung auf Wasser aufnehmende Wurzeloberflächen auslöst. Da der überwiegende Teil der Salze von der Aufnahme durch die Wurzel ausgeschlossen wird, reichern sie sich im wurzelnahen Boden ('Rhizoboden': Boden in unmittelbarem Wurzelkontakt und innerhalb des Wurzelhaarzylinders) an, so dass ein Konzentrationsgradient zwischen wurzelnaher und wurzelferner Bodenlösung entsteht. Die Salzkonzentration wurzelnaher Bodenlösungen kann daher im Vergleich zur wurzelfernen Bodenlösung um ein Vielfaches höher liegen. Die Bedeutung dieser dynamischen Prozesse zwischen wurzelnahem und wurzelfernem Boden unter dem Einfluss von Bewässerung und unter Berücksichtigung wurzelmorphologischer Eigenschaften wird bis heute nur ansatzweise verstanden. Es wird postuliert, dass Eigenschaften wie Wurzelbehaarung, Durchwurzelungstiefe und -dichte, die die Ausbildung des Rhizozylinders bestimmen, auch wesentlich zur Salztoleranz von Pflanzen beitragen. Ein vertieftes Verständnis von Wechselwirkungen zwischen Wurzeln und Boden

wird wesentlich zur Optimierung der Bewässerung mit Brackwasser und zur Festlegung von Züchtungszielen für salztolerantere Pflanzen beitragen.

Schlagwörter: *Bewässerung, Bodenversalzung, Brackwasser, Rhizoboden, Salztoleranz, Wasseraufnahme, Wasserverfügbarkeit, Wurzelmorphologie*

Introduction

Worldwide, but especially in most of the developing countries, irrigated agriculture plays an increasing role for the food supply of a growing population. According to FAO it is assumed that a share of about 30% of the irrigated area suffers from salinity problems, which corresponds to an area of more than 100 million ha worldwide. For some countries the percentage of salt-affected land is even higher: for Egypt, Pakistan and Iraq 35 to 50% of the irrigated land is considered as saline. It is estimated that annually 10 million ha of irrigated land are abandoned because of salinity problems (Hamdy, 1999). A land resource of 1 billion ha (saline deserts, coastal soils) can be developed for food production, when more salt-tolerant plants such as halophytic species could be cultivated (Boeer & Ghais, 1999).

In the near future the share of low quality brackish/saline waters and saline soils in irrigated agriculture will strongly increase, as in many developing countries there is a strong pressure on good quality water sources. This pressure comes from competing users demanding a high water quality such as growing industries and increasing number of households due to population growth. The competition for fresh water between nations may even cause military threats as e.g. between India and Bangladesh for water of the Ganges River, Farakka Barrage (Schleiff, 1999; Shiva, 2002).

Several countries, where the fresh water supply of a growing population became already critical, follow the strategy to replace good quality waters by marginal waters (brackish as well as treated waste water) for agriculture (Kuck, 1999). So, plant growth under saline soil conditions and salt tolerance of irrigated crops is not just as an academic exercise, but this research is of high practical relevance for agriculture and environment of many developing countries.

Research in recent decades already achieved distinct progress in the application of saline waters for crop irrigation. One significant indicator for the growing experience is the adjustment of critical ranges for the evaluation of irrigation water quality (Tab. 1). In 1954 EC-values of waters in the range of 0.75-2.25 dS m^{-1} were considered as highly saline, whereas almost 50 years later in 1992 water of 10-25 dS m^{-1} is classified as highly saline.

Tab.1: Evaluation of irrigation water salinity changing within time

	EC of water in dS m^{-1} (=mS cm^{-1})		
Classification	USDA 1954	FAO 1976	FAO 1992
non-saline	<0.25	<0.75	<0.7
slightly saline			0.7 - 2.0
moderately saline	0.25 - 0.75	0.75 - 3.0	2 - 10
highly saline	0.75 - 2.25	>3.0	10 - 25
very highly saline	2.25 - 5.0		25 - 45

sea water: >45 dS m^{-1}

Aspects of salinity management in irrigated agriculture

The safe use of saline waters for sustainable crop production is a challenge that has to consider besides technical aspects economic, climatic, social and hydro-geological conditions (Hamdy, 1995). Consequently there is no single way to combat damages by salinity at field level as well as at project and regional level.

In Fig. 1 the most important technical and environmental aspects that may contribute to affect saline agriculture are summarized. It may serve as a useful tool to identify possible causes of detrimental effects of salinity under defined field conditions. Based on the results of such a complex analysis, a bundle or single measures to improve the present situation can be elaborated.

Additionally, Fig. 1 demonstrates the complexity of the problem of salinity, which can not be addressed in total in the presented contribution. Nevertheless, Fig. 1 reflects innovative ideas and research activities in this field of research and summarizes strategies to improve management of crop growth under saline conditions.

The main emphasis of current research activities with respect to crop salt tolerance focuses on the rhizosphere (rhizospheric soils), the contact zone between plant and soil, at the soil/root-interface. Based on the presented research concept for further progress in the management of saline soil breeding programmes for crop salt tolerance (root morphology) might be initiated.

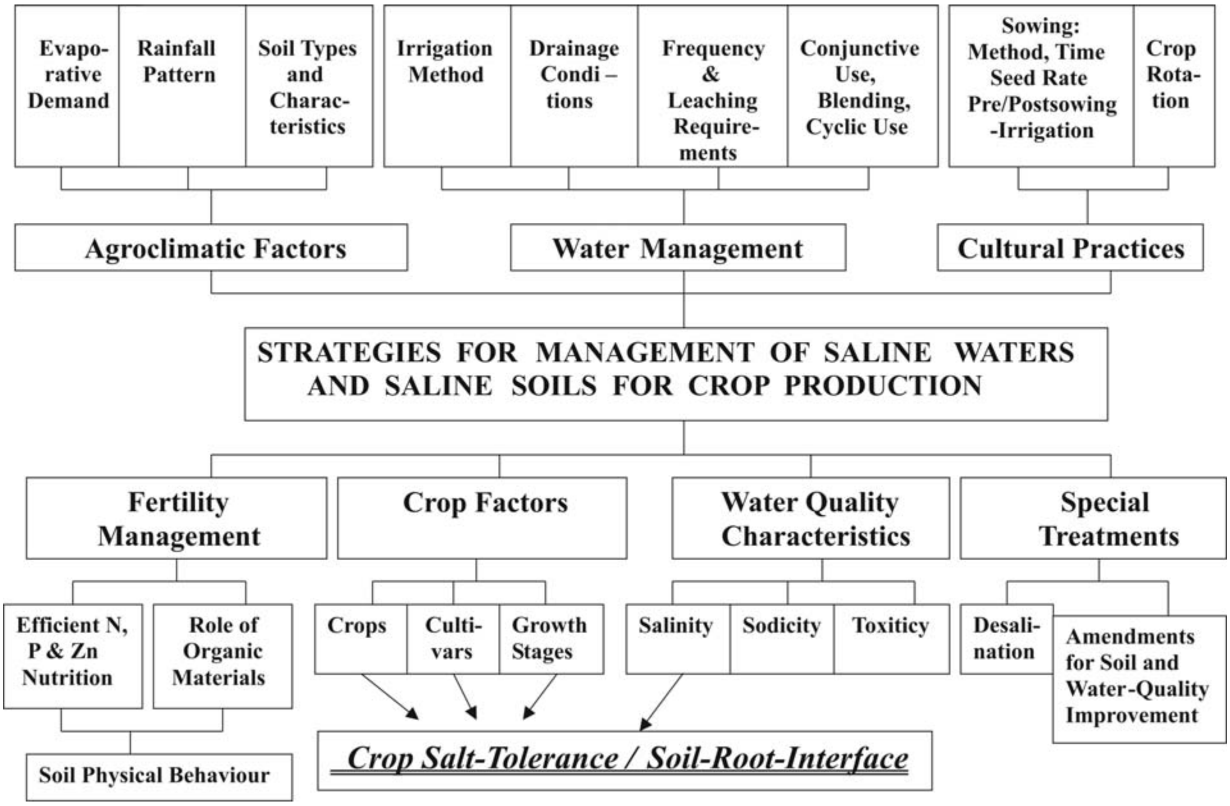

Fig. 1: Management strategies for saline agriculture (Hamdy, 1995; modified after Schleiff)

Rootzone salinity for the evaluation of salt tolerance of crops

The presented evaluation of crop salt tolerance for irrigated agriculture considers the mean root zone salinity expressed as ECse (electrical conductivity of the soil saturation extract in dS m^{-1}) as a key parameter for plant growth. The classification of salinity presented in Tab. 2 summarizes the results gained from systematic field data analysis worldwide (Hoffman, 1981).

In agronomic terms, the salt tolerance of crops is appraised on basis of the relative yield on a saline soil compared with its yield on a non-saline soil under otherwise comparable growth conditions (van Hoorn & van Alphen, 1994). The relative crop yield (Y in %) at a given average soil salinity (ECse) for a specific crop can be calculated according to the following equation (Maas & Hoffman, 1977):

$$(1)\ Y = 100 - b\,(ECse - a)$$

with:

‘b’ = the yield loss in % per unit increase of soil salinity ECse (1 dSm^{-1})

‘a’ = soil salinity threshold value: ECse, where yield decrease starts

Both values ‘a’ and ‘b’ are crop specific and were published by Maas & Hoffman (1977) and Ayers & Westcot (1985). This approach can be helpful to compare the relative advantage of crops or cropping patterns with respect to yield and economic value.

Tab. 2: The threshold of average rootzone critical salinity values for plant growth of different species (Rhoades et al., 1992; modified after Schleiff)

Crop sensitivity against salinity	Critical ECse value (dS m^{-1})	Crop plant
sensitive	0 - 1.5	bean, pea, onion, carrot, orange, peach, clover
moderately sensitive	1.5 - 3.0	maize, broad bean, alfalfa, tomato, grape
moderately tolerant	3.0 - 6.0	sorghum, soybean, wheat, red beet
tolerant	6.0 - 10.0	barley, cotton, sugar beet, date palm
very tolerant	>10	Atriplex, Agropyron, Kochia, Salsola species
no plant growth	>30 - 40	estimated values

As crops differ significantly in their salt tolerance, they endure different levels of soil salinity. If these crop specific levels are exceeded e.g. due to salt import by saline irrigation water, yield losses or even crop failure may occur. Consequently, the permanent control of soil salinity and avoiding excessive values is a key activity and prerequisite for sustainable use of saline soils and brackish waters.

Leaching of salts from the rooted soil layer by excessive soil water percolating into deep and non-rooted sub-soil is the main activity to manage saline crop production. It is the objective of a professional irrigation management to determine the amount of water required for an economic crop yield (crop water requirement, CWR in mm) and to control soil salinity at a crop and yield specific level.

There is a basic need for the quantitative determination of the water requirement for salt leaching from the root-zone (LR = leaching requirement), which is expressed as a fraction (LF = leaching fraction: LF = water leached [mm]/water applied [mm]) of the crop water requirement (CWR in mm) determined for non-saline conditions and which follows the following equation:

$$(2)\ LR = LF = ECi / ECdw = Wdr / Wi$$

with:

ECi = EC of irrigation water in dS m^{-1}
ECdw = EC of drainage (=percolation) water in dS m^{-1}
Wi = applied irrigation water in mm
Wdr = percolated drainage water in mm

The presented approach takes the ECi of the applied irrigation water into consideration, a value, which needs to be available, and the ECdw of the drainage water, which can be accepted according to the salt-tolerance of the crop and which can be assessed from Tab. 3.

Tab. 3: Tolerated salt concentrations of drainage waters (ECdw of soil solution below rootzone) for crops of different salt-tolerance

Salt-tolerance of crop	tolerated ECdw (dS m^{-1})
sensitive	4 - 8
moderately tolerant	8 - 16
tolerant	16 - 24
halophytes	24 - 50

Example: the LF for a maize crop (moderately tolerant: ECdw = 10 dS m^{-1}) under irrigation with slightly saline irrigation water (ECi = 2.0 dS m^{-1}) is 0.2 (2/10) resp. LR = 20% of the crop water requirement for non-saline conditions. When the CWR is 600 mm per season, an LR of 120 mm has to be applied to control soil salinity, which sums up to a total of 720 mm per season.

Soil salinity under controlled irrigation with saline water is, however, never homogeneous within the rooted soil layer as assumed in Tab. 2. When irrigation follows the rules to cover the CWR and the LR, a gradient of soil salinity develops, which increases from the surface versus the bottom layer of the rooted soil. This gradient is the result of leaching processes, which differ in the various soil layers of the profile and can be calculated according to an approach presented more detailed by Ayers & Westcot (1985).

This approach does not take into account the root-zone as a 1-layered profile, but as a 4-layered profile, where the root water uptake follows a pattern reflecting rooting density. The top one-quarter is expected to contribute 40%, the lowest quarter only 10% of the total CWR:

- 40% from the top one-quarter
- 30% from the second quarter
- 20% from the third quarter
- 10% from the lowest quarter

The gradient of soil water salinity (ECfc = ~ECdw) for each quarter of the rootzone can be calculated, when the effect of soil water extraction from the different soil layers on the LF from each layer is considered quantitatively.

The consequences of a stepwise calculation of salt-leaching on soil water salinity for a given situation are demonstrated in Fig. 3. On average soil water salinity in the whole rooted soil is about 6 dS m^{-1} in both cases as calculated from ECdw of the relevant layers:

(3) **1-layer-profile:**

$$(ECi+ECdw)/2 = (2+10)/2 = \underline{6.0\ dS\ m^{-1}}$$

4-layer-profile:

$$(ECdw0+ECdw1+ECdw2+ECdw3+ECdw4)/5 =$$

$$(2+3+4.8+8+12)/5 = \underline{5.96\ dS\ m^{-1}}$$

When the evaluation of salinity is done for the 4-layered profile, it is obvious that the salinity of the upper 3 layers will be significantly lower than for the 1-layer profile. This means that salinity stress to crops tends to be overestimated when soil water salinity evaluation is based on a 1-layered profile.

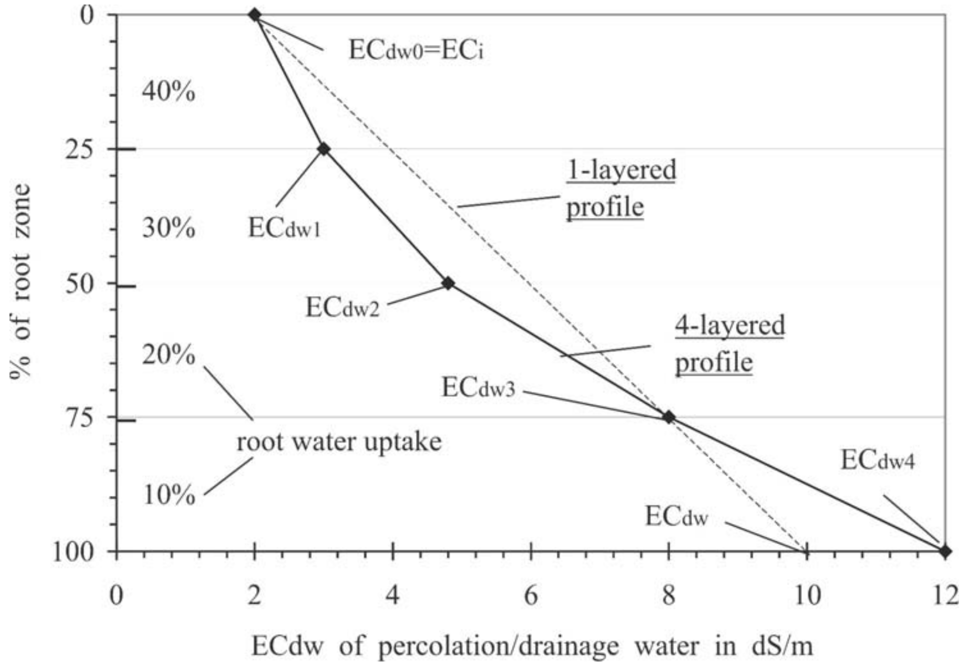

Fig. 2: Soil salinity developing after long-term use of saline irrigation water (ECi = 2 dS m^{-1}) in a 4-layered soil profile root zone as compared to a 1-layered profile

When the salinity of soil water (ECdw) in a soil layer is known, soil salinity (ECse) can be calculated by dividing ECdw by 2 for medium textured soils and by dividing ECdw by 4 with sandy soils:

(4) Loamy soil: ECse = ECdw/2 = 6/2 = 3 dS m^{-1}
Sandy soil: ECse = ECdw/4 = 6/4 = 1.5 dS m^{-1}

Under practical field conditions salinity values of the percolating soil water often deviates from the calculated concentrations. This deviation reveals that not all soil water, which percolates through a profile also participates in salt leaching. The reduced leaching efficiency comes from the fact that part of the soil water entering a soil layer does not mix with the soil solution. The leaching efficiency coefficient (fi) was introduced to take leaching inefficiency into consideration. Here, fi tends to affect water requirement for salt leaching more on heavy soils (soil water bypassing in large pores and cracks, when dry: e.g. fi 0.5 to 0.8) than on medium or sandy textured soils under frequent irrigation (e.g. fi 0.9 to 1.0). More details are presented by van Hoorn & van Alphen (1994).

Doubtless the 4-layers-concept simulates the actual vertical salt distribution under controlled irrigation better than the simpler 1-layer-concept and thus contributes to improve the calculation of the amount of water required for effective leaching.

The water requirement to keep soil salinity at a crop specific level is also affected by the irrigation technique. Experience shows that LF is often lower under high-frequency drip irrigation (daily or more) than under low-frequency irrigation according to the following equation:

(5) LF=ECi / (2 * maxECse)

whereby maxECse defines the theoretical maximal ECse when the yield potential is zero, which means that the crop ceases. This value is high (~25-30 dS m^{-1}) for salt tolerant plants (barley, sugar beet, cotton, date palm) and low (5-10 dS m^{-1}) for salt sensitive plants (groundnut, phaseolus beans, pepper, orange, strawberry; Ayers & Westcot, 1985).

Basically, the concept of high frequency irrigation at smaller application rates assumes a lower salinity stress to plants as changes in soil osmotic and matrix water potential between irrigation intervals are smaller. However, there are cases where this concept failed. Pasternak et al. (1986) reported from field experiments with tomatoes drip irrigated with water of 10 dS m^{-1} that tomato yields were 20% lower when daily irrigated as compared to an irrigation cycle of 2 days with the same total water quantity.

Similar results were found in pot experiments with maize irrigated with water of 5.3 dS m^{-1} (Schleiff, 1983a). Yields were 25% higher when water was applied every 3 days than on a daily basis. Higher chloride contents of leaves under the daily irrigation cycle indicated that plants were exposed to higher soil salinity stress. The results reveal that the concept to reduce salinity stress of plants by frequent irrigations is not generally valid. This further shows that not all mechanisms of water acquisition from saline soils are fully understood.

Horizontal salt distribution around plant roots

The presented overview has shown so far that there exists a theoretically clear and generally accepted concept for saline crop irrigation and its effects on bulk soil salinity, plant growth and crop yield. The concept even considers the effects of salinity on root water uptake rates following changes in rooting density, which usually decreases with soil depth and which affects the leaching of salts.

This concept only considers the vertical movement of soil water and dissolved salts, which predominates at soil water contents exceeding field capacity and being the key process for salt leaching. It does not take into account the lateral movement of soil water and salts, which predominates during periods of soil water uptake by plant roots following irrigation. Leaf transpiration is the driving force that initiates the lateral flow of water from a distance into the rhizosphere. Water and nutrients are taken up by roots, whereas most salts are excluded from uptake. Consequently during periods of water depletion, salts accumulate in the soil solution of the rhizosphere. The effect of this basic process within irrigation cycles on shoot water supply has been discussed earlier (Schleiff, 1982a).

Riley & Barber (1970) and Sinha & Singh (1976) first observed an accumulation of easily soluble salts around the roots of soybeans and maize. From field experiments with onions in Saudi Arabia using drainage waters of different salinities (2.4 to 8 dS m^{-1}) Schleiff (1979, 1980, 1981a) concluded that salt accumulation in the rhizosphere is not unlimited. In pot experiments with maize, barley and sugar beets it was shown that the degree of salt accumulation in the rhizospheric soil solution might be plant specific. For young maize plants representing a less salt-tolerant species a maximum osmotic potential of about -0.8 to -0.9 MPa cannot be exceeded (Schleiff, 1981b). Using micro suction cups, Vetterlein & Jahn (2002) confirmed this critical value for the rhizospheric soil solution of young maize roots. Using a specific vegetation technique Schleiff (1987a) determined for more salt-tolerant crops such as barley and sugar beet maximum values of around -3.0 MPa that were found after an adaptation of shoots to saline conditions (Schleiff, 1982b, 1982c, 1982d, 1983b). For young sugar beet a close relationship between the osmotic water potential of weakly wilting leaves and the rhizospheric soil solution was reported (Schleiff, 1982b). This observation principally opens the possibility to estimate the maximum salt concentration around roots (where root water uptake and transfer of salts from the bulk soil into the rhizosphere is close to zero) from the shoot osmotic potential at wilting.

The presented results clearly indicate that the osmotic potential in soil solutions contacting the root surface is one key factor for root water uptake and plant water supply and that there are big differences between plants. But there are further factors involved in the complex process of root water acquisition under saline soil conditions.

From field observations it is also known that salinity stress may alter root morphology. Shoots and roots of 5- to 6-months old sweet potatoes growing on saline soils showed no visible symptoms, but no tubers were produced (Schleiff, 1989). The reason is that plants adapt to saline soils by improving the efficiency of their root system for water uptake and that no tubers were produced, because all assimilates were transferred to the roots, where they were required for the acquisition of soil water.

From experience with perennial crops it is well-known that roots are involved in plant salt-tolerance. Rootstocks of grape, citrus and avocado affect the salt-tolerance of the shoot significantly (Rhoades et al., 1992, p.39). It is not always clear, which root property is effective. The exclusion of damaging ions (Cl, Na) from the shoot is often mentioned as one decisive factor.

Fig. 3 outlines required research to significantly improve knowledge about salt tolerance and for optimizing irrigation procedures with saline waters. The graph is combining the effect of the already well-known approach (vertical profile of soil salinity) to evaluate crop salt tolerance with interactions between root and soil properties at the soil-root interface (horizontal salinity profile). Basically, the research concept follows selected aspects of root and soil properties in order to acquire a better understanding of factors affecting nutrient acquisition in the rhizosphere (Jungk, 2002).

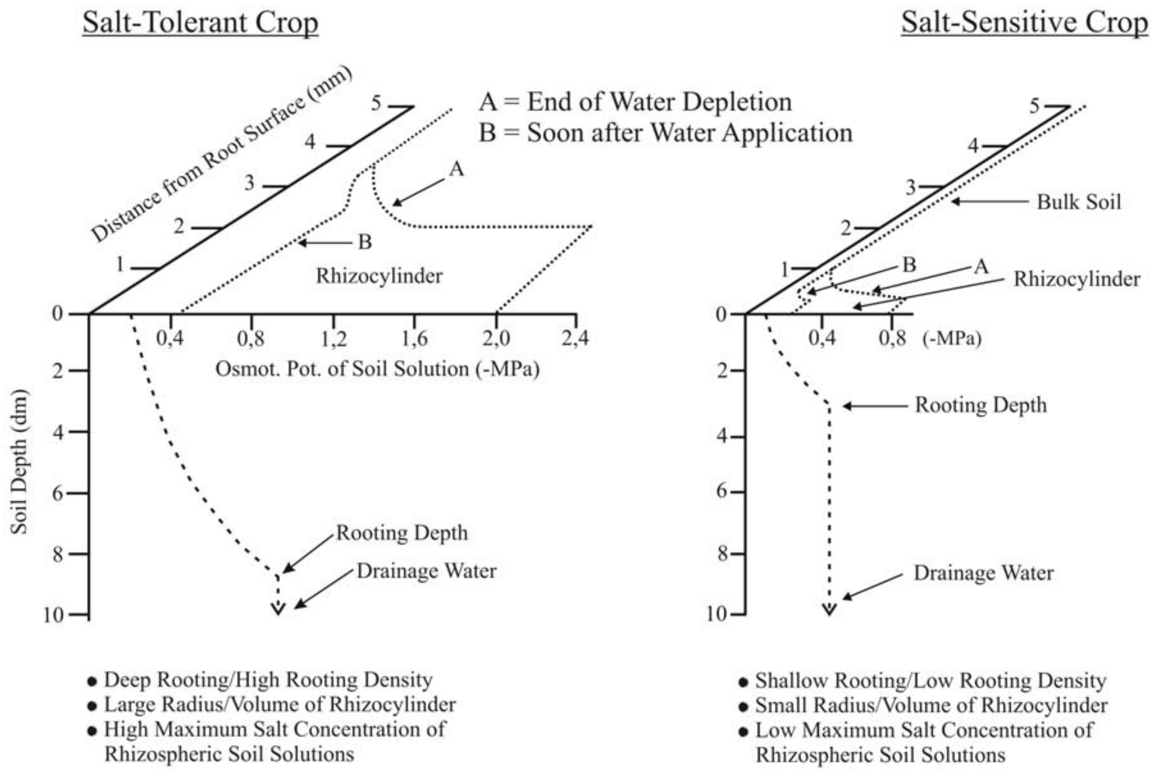

Fig. 3: Salt dynamic processes in the rhizosphere of crops under irrigation with saline water and the effect on crop salt-tolerance (after Schleiff, 2003)

The three following factors play an important role for crop salt tolerance and water acquisition by roots under saline soil conditions (see Fig. 3):

- Rooting depth and density
- Maximum rhizospheric salt concentration that ceases root water uptake
- Effect of root hairs on water uptake by roots

The vertical salinity profile under controlled irrigation as shown in Fig. 3 reflects the depth and density of the root system (see above). However it is not just the relative rooting depth as shown schematically in Fig. 2 that affects crop salt tolerance, but it is the absolute rooting depth that determines the rooted soil volume. The right half of Fig. 3 indicates that a shallow root system is expected to support the sensitivity of plants to soil salinity, whereas a deep root system (left half of Fig. 3) tends to improve the crop salt tolerance as the access to a larger volume of easily available soil water is facilitated. Principally there is no further increase in the salinity of the soil water, when the water is leached from the rooted soil layer (drainage water) and effects of percolating water and saline groundwater can be excluded.

Especially under (semi)arid climates (high transpiration rates) water depletion by roots is expected to create horizontal salinity profiles around roots within irrigation cycles. However, the development of salinity profiles between bulk and rhizospheric soil is expected to vary between plants and soil moisture conditions. Fig. 3 addresses this aspect of different salt-tolerance for plants in relation to time: curve B, which is the salinity profile at the beginning of a period of water depletion (soon after irrigation) and curve A, which shows the salinity profile at the end of a period of water depletion (before the next irrigation).

Curve B in Fig. 3 shows for both crops that there is just a small gradient between soil salinity of the bulk and the rhizospheric soil soon after a water application. This gradient will be principally affected by the water application rate. Higher application rates will reduce this gradient stronger than lower application rates. Only very high application rates would result in the disappearance of the salinity gradient. During the following period of soil water depletion a continuous flow of saline soil solution from the bulk soil to the root surface will initiate a salt accumulation in the rhizospheric soil. As reported earlier in this paper, the continuously increasing salinity of the rhizospheric soil decreases root water uptake and consequently affects plant growth. The 'maximum salt concentration of the rhizospheric soil solution' (expressed as the osmotic potential in -MPa) as outlined in Fig. 3 indicates the plant specific salinity level, which ceases root water uptake. This salinity level is principally lower for salt-sensitive crops, and higher for salt-tolerant crops. It may vary between -0.6 MPa for very salt-sensitive crops (e.g. *phaseolus vulgaris*), around -2.0 to -3.0 MPa for salt-tolerant crops and up to -4.0 MPa for halophytes.

The principal effect of root hairs on crop salt-tolerance is shown in Fig. 3. There are large differences in the volume of the rhizospheric cylinders among plants (Jungk, 2002). Length of root hairs, their density and life span are relevant factors for nutrient uptake, which may also interfere with plant water supply under saline soil conditions. This is concluded from the fact that the transpiration-induced salt accumulation close to the roots may occur in the rhizospheric soil volumes or water volumes that differ significantly. When a definite amount of saline soil solution is transferred from the bulk soil into a small rhizocylinder to cover the transpiration demand, there will occur a sharp increase of salinity (=strong decrease of soil osmotic water potential). In case the same amount of saline soil solution is transferred into a larger rhizocylinder, a significantly lower increase of rhizospheric salinity is expected. It is concluded that root hairs may be very efficient with respect to improve plant water supply from saline soils and crop salt-tolerance.

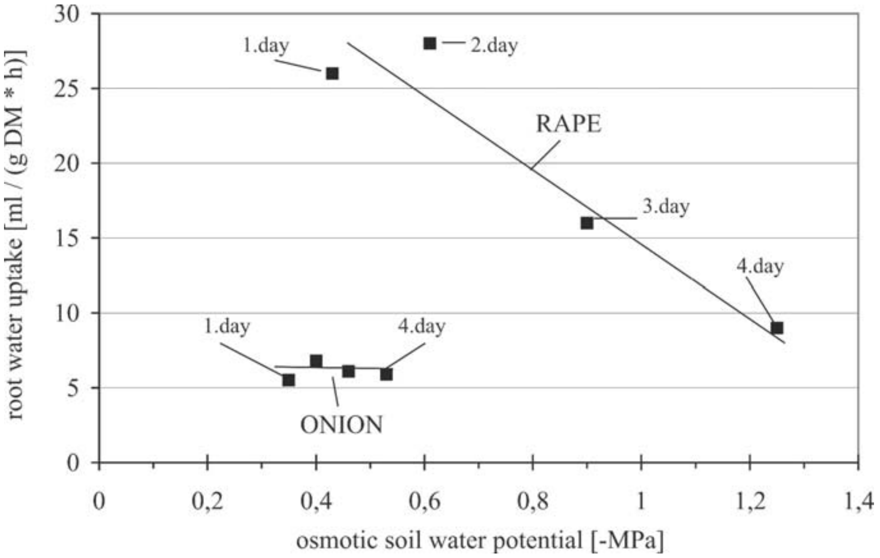

Fig. 4: Water uptake rates by roots of onions and oilseed rape [based on root dry matter] from saline soil solutions following a water application with 50 meq l^{-1} NaCl (Schleiff, 1983, unpublished data)

Empirical support of the hypothesis that root morphology may be relevant for water uptake from saline soils is rare, but a primary result obtained from a pot experiment with onions (very short root hairs, small rhizocylinder) and oilseed rape (long root hairs, large rhizocylinder) confirms this hypothesis (Schleiff, 1983). In this experiment oilseed rape and onion were chosen as their root systems are known to differ significantly in their morphology, but shoots of both plants may adapt to saline conditions to a similar degree. From experiments with nutrients (P, K) it was concluded earlier that roots of oilseed rape form a rhizocylindric soil volume that is about 20- to 30-fold larger than the volume of onion roots (Jungk, 2002). This factor explained significant differences in the efficiency of nutrient uptake, especially when relatively immobile nutrients are considered.

Comparable results were obtained when water uptake rates by roots of onion and oilseed rape from saline soils were analyzed as presented in Fig. 4. Water uptake rates of oilseed rape roots (25 - 30 ml g^{-1} root-DM h^{-1}) were 5 to 6-fold higher than for onion roots (5 - 7 ml g^{-1} root-DM h^{-1}) at a rooting density of 0.3 to 0.4 g l^{-1} root-DM for both plants, when the soil osmotic water potential varied between -0.35 and -0.6 MPa and the soil matrix water potential was about field capacity, or slightly lower (Schleiff, 1983c). Similar results were obtained, when water uptake rates by roots of leek and oilseed rape were compared (Schleiff, 1986, unpublished data). Even when the presented results have to be discussed from other aspects than root morphology such as stomatal characteristics, there is circumstantial evidence that root morphology plays an important role for crop salt tolerance and water acquisition from saline soils. In the past decades, the aspect of root morphology was neglected, due to the lack of appropriate analytical techniques. However further research in this field is required for a better understanding of the influence of salinity at the soil-root interface. This field of research is a lot more promising for optimizing irrigation than to further deepen research in the already comprehensively addressed aspect of K/Na- and other mineral element ratios.

Effects of soil osmotic and matrix water potential on plant water supply

There is no doubt that the crop water supply is good when the soil moisture is close to field capacity and soil salinity is low. Decreasing soil water contents reduce water uptake by roots. This reduction of root water uptake is even higher when soil salinity is involved. Since Wadleigh & Ayers (1945) and Ayers & Westcot (1985) it is postulated for saline soils that the plant water supply and plant available soil water are closely related to the total soil water potential (ΨT), which is the sum of the soil matrix (ΨM) and soil osmotic (ΨO) water potential (ΨT = ΨM + ΨO). Both types of soil water potentials usually (with the exception of some halophytes) tend to reduce water uptake rates by roots, but it is doubted that both components of ΨT will affect root water uptake to the same degree, at least when root water uptake from the rhizospheric soil is evaluated.

Root water uptake of young wheat from a loamy soil dropped drastically, when the ΨT-value of the non-saline rhizospheric soil ranged between -0.2 and -0.3 MPa (ΨT = ΨM), but was just slightly affected when salinity (ΨO) was involved (Schleiff & Schaffer, 1984). Differences between soil osmotic and matrix potentials on root water uptake seem to be even more distinct in sandy soils. Water uptake by barley roots from a non-saline sandy loam ceased at -0.2 MPa, but was still high at around -1.0 MPa, when ΨO dominated (Schleiff, 1986). Same results were obtained with young oilseed rape plants cultivated in a sandy soil under well controlled conditions in a growth chamber as presented in Fig. 5 (Schleiff, 1987). Under non-saline conditions root water uptake nearly ceased when ΨT dropped to -0.2 MPa, but decreased at the same ΨT only by 30-40% of the optimum, when salinity was involved. Working with a saline silt soil, Schmidhalter & Oertli (1991) confirmed for young carrots that decreasing ΨM affected plant growth much stronger than decreasing ΨO.

Using more sophisticated instruments such as micro-tensiometers for measuring soil matrix water potentials in the rhizosphere (Vetterlein et al., 1993) and micro-cups to determine the osmotic water potential of the soil solution, Vetterlein & Jahn (2004) only recently checked the classical concept, too. The authors doubt that 'soil solution osmotic and matrix potential are really additive in respect to plant water availability'. However, there is one major shortcoming in their experimental approach, which is the fact that the measuring range ceases at relatively high matrix potentials (-0.07 to -0.08 MPa). This means that data from the range of -0.08 to -0.5 MPa, where water uptake by roots is still significant, are completely missing. Due to current technical limitations it is not expected that this approach will not give a full and clear picture on water availability from saline soils.

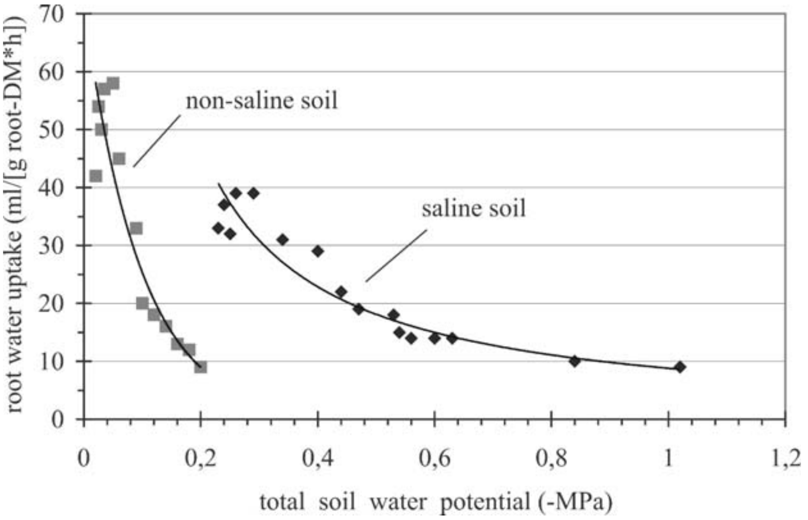

Fig. 5: Root water uptake rate (ml g^{-1} root-DM h^{-1}) of young oilseed rape plants in relation to the total soil water potential of sandy soil

Conclusions

There are certainly many cases where salt-induced lack of various nutrients (Ca, K, N, P and micronutrients) limit plant growth as reported by Schleiff & Finck (1976) and recently summarized by Bernstein & Kafkafi (2002). Fortunately, technical tools to identify (soil chemical analysis combined with plant tissue analysis) and to compensate nutrient deficiencies by fertilization are available. So it is not expected that further research in this particular field will bring new insights which will improve the management of saline irrigation on production fields.

In comparison, knowledge about processes in the contact zone between soil and plant under saline irrigation is very limited. Without doubt the analysis of rapidly changing processes in the root environment will be extremely complex and research will face severe problems with appropriate experimental setups, the direct measurement of important parameters (ions, soil water potential, root properties) and their evaluation with respect to crop salt tolerance. Nevertheless, research is expected to yield significant knowledge about crop salt tolerance, and finally contribute to improve practical recommendations for saline irrigation and breeding of salt tolerant crops (Lieth et al., 1997).

As long as direct measurements of basic parameters such as matrix and osmotic water potentials at decreasing soil water contents ($\Psi M < \sim -0.07$ MPa) of the rhizospheric soil are not possible, indirect investigation methods such as the vegetation technique developed by Schleiff (1987a) seem most promising to improve the knowledge about processes and effects in the rhizosphere. The potential of this technique quantifying the effect of soil matrix and soil osmotic water potential on root water uptake and plant growth has been outlined (Fig. 4). Additionally, it is expected that the applied vegetation technique may also give other quantitative data on root properties that are supposed to be relevant for crop salt tolerance. Modifications of the vegetation technique supposedly provide answers to questions about interactions between the rhizospheric and non-rhizospheric soil volume on root water uptake. Following Helal et al. (1996) the dynamic turnover of developing root systems, which affects nutrient uptake, should not be neglected for root water uptake from saline soils either.

The practical relevance of the concept of horizontal salt distribution around roots for saline crop production, especially under high frequency irrigation, was clearly shown in the experiments of Pasternak and Malach (1986) with tomatoes. Yield of tomatoes under drip irrigation with water of 10 dS m^{-1} were 20% higher in the 2-days irrigation cycle than in the daily cycle. This result is only surprising, when the average salinity of a soil profile is considered in the 1-layer and 4-layer concept as presented earlier in this paper (equation 3 and 5). Following this concept yields should be highest under daily irrigation, as frequent irrigations are generally expected to lower salinity stress to roots.

Obviously concepts based on the vertical salt distribution under saline irrigation are not appropriate to explain the higher salinity stress under frequent irrigation. In pot experiments with maize irrigated with water of 5.3 dS m^{-1} daily, in a 2- and 3-days cycle Schleiff (1983a) found similar results. The higher salinity stress for plants under daily irrigation was even confirmed by the corresponding change of the chloride contents in older and younger leaves, which were always highest under daily irrigation.

This opens the question why salinity stress seems to be higher under frequent irrigation, which is usually not the case at lower soil salinity. The explanation is supposedly that the lower water application rates given under frequent intervals are probably less effective to leach very high salinity from the rhizospheric soil, while higher application rates at longer intervals are more effective in this respect.

There is no doubt that root environment under saline irrigation is complex and rapidly changing. Research in this field causes difficulties in experimental setups, measurement of parameters, diagnosis and prediction of consequences. However, it promises a better understanding of plant growth under saline conditions, an improve of irrigation management and new targets for breeding plants with a higher salt tolerance.

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