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Extent of Global Salinization and Management Options for Sustainable Crop Production

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ABSTRACT: Irrigated acreage in arid regions of the world has recently stopped increasing and it will be difficult to even maintain existing levels of irrigation in these regions. At the same time the amount of salt affected soils in the world, continues to increase, with a major part being secondary salinization in irrigated lands. Since this salinization is caused primarily by over irrigation, more uniform irrigation application systems allow for reductions in quantities of water applied, and paradoxically may reduce soil salinity, due to lowering of shallow water tables. Model simulations of irrigation with saline waters confirms field data indicating that existing guidelines overestimate water quantities needed for salinity control in the root zone. The sodicity hazard associated with application of saline water has been generally overlooked, due primarily to lack of consideration of the adverse impact of even small quantities of rain on physical properties of the soil surface. Recent improved understanding of the effects of salinity on plant growth provides numerous approaches for improving the salt tolerance of sensitive species.

Food Production and Irrigated Land

There has been a dramatic increase in total global food production over the last 50 years. In addition to the increase in cultivated land, there has also been an increase in production on a per-acre basis. This increase is generally attributed to the development of improved crop varieties and management practices (green revolution), however an important part of this increase is related to an increase in the amount of irrigated acreage. Irrigated lands have much higher productivity and economic return per acre as compared to non-irrigated lands. It is estimated that globally, irrigated lands represent 15% of the cultivated land, yet they produce over 30% to 40% of the world's food (Ghassemi *et al.*, 1995; Postel, 1999). In arid regions the impact of irrigation is much greater than for the world in general, both because dry land production is low in these regions and because arid lands located in high temperature environments can be almost continually cropped, with multiple harvests. The 35% increase in irrigated land from 1970 to the late 1980s thus provided a significant part of the increase in world food production, and was a major factor in avoiding large scale famine.

Since the 1980s, there has been a decline in the rate of growth in the world's irrigated land. By the start of the 21st century total irrigated acreage reached a constant value. The stabilization or leveling in total irrigated acreage is due primarily not to lack of additional suitable arable land, but rather to the lack of new developable water supplies in most of the arid and semiarid regions that can most benefit from irrigation.

The situation with respect to sustainability of irrigation in arid regions is grave. Supplemental irrigation in more humid regions has increased, masking the actual decline in irrigated acreage in arid regions. Globally, irrigated agriculture uses approximately 65% of the total fresh water used, with industrial and municipal use making up the balance. California in the U.S. has experienced significant declines in irrigated acreage. For example, during the 2009 irrigation season over 180,000 ha have been taken out of irrigation in the Central Valley, with the likelihood that there will not be sufficient water in the future to bring this land back in to production. "Land banking" is occurring in other irrigation districts, such as Palo Verde and Imperial where long term contracts have been signed transferring former irrigation water to municipal water entities. Additional declines in irrigated acreage are occurring due to partial restoration of natural water flows for environmental considerations. Future declines are anticipated due to declining ground water supplies as well as increasing urban and environmental water demands. Currently the percentage of fresh water used by agriculture in California has declined from 75% as recently as 20 years ago, to below 50%, with a corresponding increase by percentage used by the municipal sector and a decrease in overall use.

Unfortunately, most arid regions do not have new developable surface waters and the current large fresh water extractions of ground water required for irrigated agriculture cannot be increased. Of greater concern is the consideration that irrigation is not sustainable at current fresh water utilization rates. This-over utilization of fresh water utilizing what is often called fossil water, is particularly severe in drier regions of the world, where population density, poverty, and food demands are greatest. Over drafting of groundwater has resulted in declining water tables, loss of shallow fresh water for municipal use, and sea water intrusion in coastal regions. In the early 1990s, approximately one fifth of the U.S.'s irrigated lands were extracting groundwater water in

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excess of the natural recharge (Postal, 1997). The data are not completely known, but the situation appears more severe in many less developed nations in arid and semi arid regions.

Increasing population results in increasing total demand for fresh water for municipal and industrial use as well as for increased food production. Increased fresh water needs are also related to increased per capita water usage associated with improved economic conditions in a region. Increases in living standards are not only related to increased domestic per capita water consumption, but they also result in increased in water consumption related to food production on a per capita basis. This increased demand with improved living standards is related to the increased water requirement for meat production versus grain production (expressed as gallons of water per kcal). It will be a major challenge just to maintain the existing level of irrigation and associated food production in the arid and semiarid regions of the world. An increase in living standards will require yet more water.

Salinity

Extent of salinity problem

Globally, it is estimated that there are 76 million hectares (Mha) of human-induced salt affected land, representing 5% of the world's cultivated land, (Ghassemi *et al.*, 1995). Salt affected lands are those where crop yields are reduced or where less desirable crops must be grown because of the salinity. This human induced salinization is termed secondary salinization, in contrast to regions that were saline in their native condition. This value underestimated the extent of salinity because it does not include large areas where land could be potentially cultivated if not for the native salinity.

Salinity problems are more prevalent in irrigated lands relative to the total cultivated acreages. This is not surprising as irrigated lands are concentrated in more arid regions, where salinity is more prevalent. Also, irrigation results in land application of more water, thus imposing additional drainage needs to the natural hydrologic system. Of the world's 227 Mha of irrigated lands, it is estimated that 45.4 Mha, or 20% are adversely impacted by secondary salinization (Ghassemi *et al.*, 1995).

Salinity is a major threat to current irrigation projects and to the remaining near-surface fresh water supplies in arid regions. The extent of the salinity problem has not stabilized; instead, it is estimated that as much as 2 Mha of irrigated land, representing approximately 1% of the total, is lost from production due to salinity each year (Umali, 1993, in Postel, 1997). Most of the world's salt affected, cultivated lands are in Asia and Africa, where population densities and economic conditions make the problem proportionately more severe. For example, it is estimated that Egypt, Iran and Pakistan had 33, 30 and 26% respectively of their irrigated land impacted by secondary salinization (Ghassemi *et al.*, 1995). However, more developed countries are not immune to these salinity problems. For example it is also estimated that over 20% of irrigated land in the U.S. is salt-affected (Postel, 1999), a value comparable to the global average.

Management impacts

In contrast to salinization of water supplies, soil salinization is generally more readily controlled. Most soil salinization has historically occurred as a result of over-irrigation. For ancient civilizations this can be partially attributed to lack of knowledge concerning water use or requirements relative to quantities of water applied.

In the past two centuries over-irrigation and salinization can mostly be attributed to the design and operation of new irrigation projects. Irrigation projects have been designed without sufficient coordination between plant scientists, irrigation scientists and civil and hydraulic engineers. Irrigation specialists, focused on development of new irrigation projects, have emphasized the need to leach salts out of the root zone to enable maximum yields. The concept was that salts had to be "pushed" down into the profile to avoid surface salinization and crop failure; the more leaching the better.

With initially abundant water, older irrigation systems were typically developed with earthen canals and laterals, non- uniform water application with furrow or wild flooding. These practices combined with the over emphasis on leaching has thus resulted in poor irrigation efficiency and many instances large drainage volume to the subsurface in excess of natural drainage capabilities. Excessive drainage in turn results in subsequent water logging, evaporation of water from the surface, and deposition of salts at or near the soil surface in low lying parts of the irrigation district. Costly drainage systems are subsequently often constructed, controlling the root zone salinity but now discharging large volumes of saline water to the drainage system, causing adverse salt impacts to downstream users.

Increased salinization in arid and semiarid regions is also often caused by leaching of existing salts from the soil during irrigation in regions with high salt containing strata, as well as by application of waters of low quality without proper management. In the instance of soils high in native salts, regional salinization of ground and surface waters is aggravated by excessive water applications. This impact is particularly important when implementing a new irrigation project, but the impacts of leaching salts present before irrigation may be observed for in excess of 120 years after initiation of the irrigation project (Grand Valley, Colorado), depending on the hydrology of the system, type of salts present, and depth and design of the drainage system, if present.

Salinization of water resources

In addition to the unsustainable extraction of fresh water, there is a related decline in water quality of existing supplies; thus these factors are not unrelated. There are two general factors contributing to the decline in water quality. Extraction of fresh water from a system reduces the extent of dilution of other natural or man-induced salt loads. Secondly as irrigation brings more salts into a valley, it adds a new source of more saline drainage water to the receiving body of water. These concentrated drainage waters contain both the initial salts present in the irrigation water as well as salts already in the soil that are displaced by the water leaving the root zone. Thus in arid regions, irrigation or even changes in cropping patterns that impact recharge often mobilizes salts that have accumulated over geologic time either in the unsaturated zone, salinizing groundwater (Australia) or displacing saline groundwater into rivers (Grand Valley CO and the Colorado River). Again due to the long flow paths, this additional salt load can continue for in excess of 150 year, consistent with hydrologic model predictions.

Salinity increases in drainage water relative to irrigation water are inevitable. Plants extract water preferentially, thus concentrating these salts in the remaining soil water. Typically, plants extract only 5–10% of the salt associated with the volume of water that they extract. Hence, more efficient irrigation (generally resulting in less water applied more uniformly), while desirable, results in smaller volumes of drainage water, but of greater salinity. The salinity increase is approximately inversely proportional to the change in volume (inverse to volume of irrigation water/volume of drainage water).

Salinization of water resources represents a loss of useable water and may be an increasing source of conflict among nations. Development of new irrigation projects upstream in a river basin inevitably results in adverse consequences to downstream users, either with reduced waters flows, increased salinity, or a combination of both. Increased water utilization also increases downstream salinity by reducing the volume of fresh water available for dilution of natural flows and drainage waters.

Management Options

Improved delivery systems

Ensuring that soils are not over- irrigated and maximizing the food production per unit of water applied requires changes in irrigation systems and management. Most improvements to date have been done on the engineering side, with relatively less change on the agronomic side. For example, conversion of surface flooding or furrow to sprinkler allows for more uniform application of water, reduced need for irrigation water and reduced drainage volumes. Application of drip irrigation systems allows for uniform delivery of water to plants or trees in the field, while avoiding wetting the entire soil surface. These system changes and associated changes in management practices require capital investments and education programs for irrigators. Nonetheless these systems are less costly than development of new water supplies, especially use of desalinized water. In these systems, application of less water results in decreased soil salinity.

In the instance of Grand Valley, Colorado, improved water delivery and management was essential for salinity control in the valley as well as for reduction in salinity in the lower regions of the Colorado River that receive the return flows. Improvements in irrigation system infrastructure and management in Grand Valley Colorado, including concrete lining of canals and laterals, installation of closed pipe delivery systems, and irrigation scheduling have reduced the salt load to the Colorado River by approximately 500,000 tons per year.

Water reuse

As discussed above secondary salinization due to over-irrigation and insufficient drainage is the major cause of soil salinization in irrigated lands. Reuse of drainage water, where feasible provides the opportunity for alternative water resources in water-short regions, as well as water table control. A significant concern regarding reuse of drainage water is its impact on the soil, and potential salinization from applying more saline irrigation water on an already saline soil. However, Corwin *et al.* (1998), observed a decrease in soil salinity and partial reclamation of sodic soil conditions where drainage water more saline than presently formerly used irrigation water was applied. The benefits may be from several factors including a drop in the perched water table below the field, allowing for better drainage, as well as improved infiltration related to application of a more saline water and application of greater volumes of water.

Maintaining irrigation in arid regions will require maximum utilization of sustainable water supplies. Water reuse is a necessary aspect of this system, but it should be looked at as complimentary rather than as an alternative strategy for water management or alternative to reduction in drainage volumes. The ideal water use is still to extract the maximum benefit from the initial fresh water application, minimizing the volume of drainage water generated. This minimizes the need for drainage and avoids the mixing and degradation either of fresh water, if the drainage returns to a water supply such as a river, or else degradation of the drainage water by mixing with a saline ground water. This concept has been often dismissed as impractical. It is argued that as crops vary in salt tolerance, application of water quantities at or near ET is feasible only for salt tolerant crops it the irrigation water has any appreciable salinity.

Reduction in quantities of leaching water

The possibilities in using saline waters at low leaching fractions have been significantly overlooked due to use of current guidelines, such as Ayers and Westcot (1985). The major justification for application of water in excess of crop requirements has been the need to leach salts out of the root zone and thus control root zone salinity. The leaching requirement concept provides for calculation of a crop-specific quantity of leaching water in addition to that consumed by the crop, that must be applied to avoid yield loss to salinity.

The use of the static leaching requirement calculation is being questioned on several grounds. Most importantly as demonstrated in an example below, the concept does not consider the decrease in water uptake and thus increase in leaching that occurs when plant yield decreases. The leaching fraction is thus not a fixed input variable but rather a result of water applications, potential ET and plant response.

Secondly, the method used to calculate plant yield as related to salinity of irrigation water, usually involves a simplified calculation of root zone salinity, and the root-zone average value is used (Ayers and Westcot, 1985) rather than a water uptake calculated value. Since the salinity in the deeper portions of the profile are greater than that near the surface where the roots are concentrated and where most of the water is taken up by the plants, this calculation of average root-zone salinity over-estimates the salinity experienced by the plant.

Most salt tolerance data was, and is still, collected either in sand culture where the soil water salinity is essentially equal to the irrigation water salinity, or else at high leaching fractions where plant uptake weighted salinity is at most 50% greater than the irrigation water salinity. Also the simplified calculations utilized do not account for the precipitation of calcite and possibly gypsum that occurs during the concentration of salts in the rootzone, nor the nonlinearity between concentration increases and increases in osmotic pressure. The combination of the assumption of fixed crop ET with the salt tolerance calculation from average root- zone salinity estimates or measurements, results in overestimation of the quantity of water needed for leaching. The lower the leaching fraction the greater the discrepancy between average root zone salinity and plant-uptake weighted salinity. This also explains why drip irrigation systems operated at or near the crop water requirement; do not experience measurable yield losses, contrary to predictions based on application of the leaching requirement concept.

Irrigation recommendations can best be made using computer simulations of the dynamic processes, considering crop salt tolerance and crop ET and root zone salinity based on predicted rather than potential water uptake. Letey and Feng (2007), comparing the results of a transient state model to those of a steady state model concluded that the transient model, consistent with field data, indicated that a much lower water application was required to avoid yield loss. Suarez (2010, in press) compared the leaching requirements and prediction of yield loss between UNSATCHEM (Suarez *et al.*, 1997) and the Ayers and Westcot (1985) guideline recommendation for leaching and yield loss due to salinity. An analysis of predicted ET, predicted leaching and crop yield as related to irrigation water salinity is presented below.

The user friendly SWS version (Suarez and Vaughan, 2001, Suarez et al. 2010) of the UNSATCHEM model (Suarez and Simunek, 1997) predicts plant response to water and salt stress under dynamic conditions. The model also predicts soil solution composition as related to variably saturated water and solute transport and chemical processes of adsorption, mineral precipitation-dissolution and cation exchange. The model uses the predicted decreases in plant water uptake to predict the decrease in biomass production. This calculation assumes that yield is directly proportional to water consumption (constant WUE, or water use efficiency).

$$\frac{Y}{Y_M} = 1 - \beta_0 (1 - \frac{ET_a}{ET_p}) \quad (1)$$

where Y is actual yield, Y_M is maximum yield , ET_a is predicted ET and ET_p is potential ET. The parameter β_0 is a crop adjustable parameter which is typically set to 1.0 but varies between 1.0 and 1.3 (Stewart *et al.*, 1977).

Prediction of the yield of individual plant parts (such as seed or fruit) can be obtained by consideration of the relation of reduction in plant water uptake and yield response of the plant part of interest. The model predicted root zone salinity and relative yield can be contrasted to predictions based on salt stress from guideline predictions.

Suarez (2010) used the SWS model (Suarez *et al.*, 2010) to predict plant yield reduction from salt stress. A perennial crop with a 100 cm root zone depth on a loam soil (k_s =25 cm/d) was irrigated for 200 d. The first irrigation of 11cm was applied after 10 days. After another 10 d, 22 cm of water was applied over 2 d followed by irrigations of 22 cm every 20 d thereafter for a total of 209 cm of applied irrigation water. The potential ET of the crop for full yield was 200 cm and we assumed a constant potential crop ET (ETp) value of 1 cm/d. The initial soil water and irrigation water composition was that of a predominately NaCl system with lesser quantities of Ca, Mg, SO_4 and bicarbonate. The $h_{\phi 50}$ or osmotic stress was set at -50 m, using the equation

$$\alpha_\phi(h_\phi) = \frac{1}{1 + (\frac{h_\phi}{h_{\phi 50}})^p} \quad (2)$$

where α_ϕ osmotic stress response function (scaled from 0 to 1.0 where 1.0 equals no stress), h is the calculated osmotic stress, and h_{50} is the model input osmotic stress at which there is a 50% reduction in water use and relative yield.

The same scenario was also evaluated using the Ayers and Westcot (1985) procedure. In this calculation we consider the crop requirement of 200 cm of water and the applied water quantity of 209 cm. The average root zone salinity was calculated from the average salinity of the root zone, using the irrigation water salinity and the salinity at the bottom of each of the 4 quarters of the root zone.

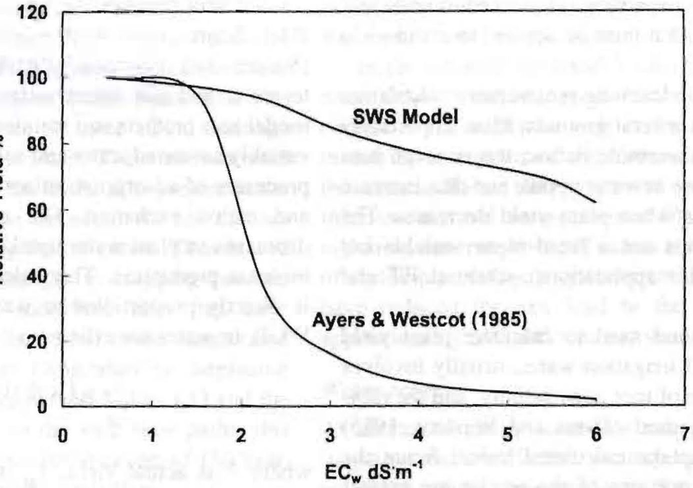

Figure 1. Comparison of SWS model and Ayers and Westcot (1985) predicted crop relative yield as related to irrigation water EC_i, for a crop with an h_{50}= -50 m (-0.5MPa), ET_p=200 cm and 209 cm applied water.

Salinity in each quarter was based on the assumption that water uptake is 40% in the first quarter, 30 % in the second quarter, 20 % in the third quarter and 10% in the fourth quarter. The average root zone salinity was thus calculated and converted to osmotic pressure using the conversion factor O. P. (MPa) = -0.4 EC (dSm^{-1}) and using Equation 2 the stress factor and relative yield was obtained.

The SWS model predicted relative yield as related to irrigation water salinity is shown in Figure 1. The model predicts a gradual decline in relative yield with increasing irrigation water salinity. With an irrigation water EC of 4.0 dS m^{-1} the relative yield is still at 81%, despite the application of only a small amount of water above the crop potential ET. In contrast, as shown in Figure 1, the Ayers and Westcot (1985) calculated yield decreases rapidly above EC 1.5 dS m^{-1}. We conclude from the guideline calculations that for this salt tolerance data (h_{50} = -0.5 MPa) irrigation with water above EC=2.0 dS m^{-1} is not feasible for efficient irrigation practices at a leaching fraction of 0.05. As seen in Figure 1, at higher irrigation water salinities there is a dramatic difference between the model and guideline prediction. A similar result to that obtained by calculation from the FAO guidelines (Ayers and Westcot, 1985) would also be obtained using the steady state WATSUIT (Rhoades and Merrill, 1976) calculation.

As shown in Figure 2 the guideline assumes constant water consumption even as yield approaches zero. The model predictions show the decrease in plant water uptake associated with salt stress, thus increased leaching with

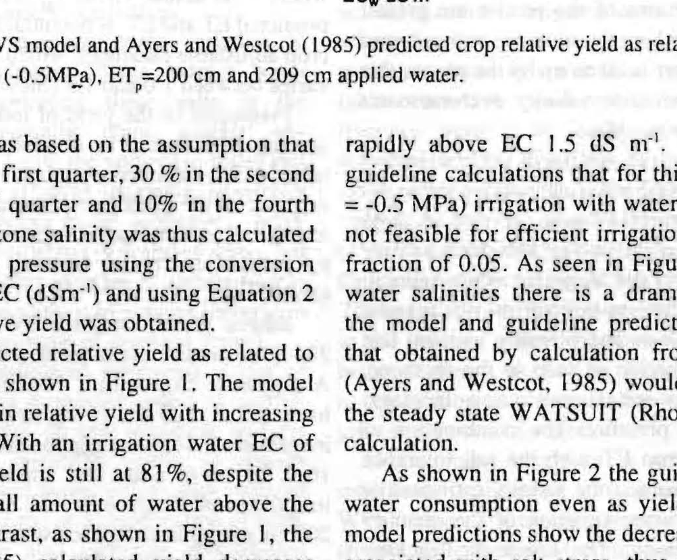

Figure 2. Comparison of SWS model and Ayers and Westcot (1985) predicted leaching fraction as related to irrigation water EC_i, for a crop with an h_{50}= -50 m (-0.5MPa) salt tolerance value, ET_p=200 cm and 209 cm applied water.

increased salinity of irrigation water. The reduction in water uptake moderates the increase in root zone salinity. Consideration of the actual water budget is essential for calculation of the actual salinity in the root zone. The increased leaching and decreased water uptake was due entirely to salt (osmotic stress).

The major discrepancy between these calculations and the SWS predictions is the failure of these calculations to predict the reduction in water consumption by the crop and thus the root zone salinity and leaching fraction. The leaching fraction was assumed to be 0.043 based on applied water and crop water demands (ET), however the SWS model predicted reduced water uptake and a LF=0.42. The differences between the model predictions (less stress) and the simple calculation method are even greater when we consider waters that precipitate gypsum in the soil, thus reducing the salt concentrations in the soil.

While the above example is somewhat extreme in terms of the close correspondence between water application and crop water demand (209 cm vs. 200 cm), such irrigation efficiency is not unusual for new irrigation technologies, such as drip irrigation. It appears that dynamic modeling is necessary for irrigation management when low- target leaching fractions are the objective under conditions of potential yield loss due to salinity.

As observed by data collected from drip systems, water applications can be greatly reduced and still maintain yield in most environments. This in turn suggests that less drainage water of higher salinity will be generated, thus disposal for maintaining ground water levels will be reduced.

Water quality considerations

Waters of increased salinity inevitably contain greater proportions of Na and to a lesser extent Mg relative to Ca, due to solubility considerations. The adverse effect of sodium on soil structure, clay dispersion and water infiltration is well documented. This adverse sodium effect is a major concern when used lower quality waters for irrigation. The SAR (sodium adsorption ratio, defined as $Na^+/(Ca^{2+} + Mg^{2+})^{0.5}$ where concentrations are in millimoles$_c$ L^{-1}) increases with increasing salinity due to both the change in the relative proportions of ions and the square root term for divalent ions in the SAR expression. The SAR is directly related to the exchangeable sodium percentage in the soil, thus irrigation with more saline waters almost always results in increased exchangeable sodium.

It is generally considered that the elevated SAR associated with saline waters is not of concern since the infiltration of these waters is not adversely impacted according to guidelines for sodium hazard (Ayers and Westcot, 1985). However this analysis does not consider the impact of rain, which results in a rapid decrease in soil salinity at the surface, with a much slower reduction in the exchangeable Na. Computer simulations of changes in exchangeable sodium upon rain on a sodic soil (Suarez *et al.*, 2006) confirm the observed decrease in infiltration that is observed in studies with cyclic rain and irrigation events over an irrigation season (Suarez *et al.*, 2006, 2008). Thus even in regions where rainfall is an insignificant contribution to the water budget, the dispersive effect of sodium is a significant concern and generally indicates the need to apply a surface soil amendment (such as gypsum).

Crop quality and economic considerations

The classification and consideration of the suitability of saline and brackish waters for irrigation have focused on the threshold salt tolerance levels and leaching necessary for full maximum production. As indicated earlier, the leaching needs of current guidelines are excessive. Equally important such calculations do not consider the farmers objective to optimum profit and the societal need for optimum use of resources. Profitability and societal needs for local food production may make even large decreases in relative yield still feasible, especially when alternative water supplies do not exist. These economic considerations should be inputs to the decisions regarding water use, crop selection and acceptable yields. Selecting more salt tolerant crops that do not have projected yield losses may also not be optimal. For example tall wheat grass is more salt tolerant than alfalfa, however alfalfa out-yielded tall wheat grass in controlled studies at EC soil water of 15 dS m^{-1} (Grattan *et al.*, 2004).

In some instances the adverse impacts of reduced yields may be compounded by reduced crop quality such as smaller fruit size, thus decreasing marketability. However in some instances crop quality may improve under saline conditions; at least partially offsetting yield reductions. Recently Grieve (2010) examined the characteristics or composition variables that were improved by salinity for a variety of crops. These benefits include increased sugar content of many crops, including tomato, carrots, onions and melons, among others. Salt stress may also increase antioxidants and improve fruit flavor and firmness (Grieve, 2010)

Potential for increased salt tolerance

Biotechnology in combination with conventional breeding practices holds great promise to improve salt tolerance, especially of crops that are sensitive or moderately sensitive to salinity. It is generally assumed that the adverse response of plants to elevated concentrations of salt is due to the increased osmotic pressure of the soil water. The plant is considered to divert energy into extracting low salinity water from the more saline soil water, thus impacting plant growth. However there is a very wide range in salt tolerance, starting at very low salinity levels such as less than 1.0 dS m^{-1} for strawberry. There is strong evidence that specific ion toxicity is the major impact on salt sensitive species.

Munns and Tester (2008) considered that plant response to salinity could be represented by a two part process, with the initial adverse response being related to increased osmotic pressure and a later response related to specific ion toxicity. They consider that the toxic ion effect dominates for salt sensitive species that lack the ability to control Na^+ transport and that for all other plant species the ionic effect is important only at high salinity. Development of salt tolerant varieties of sensitive species can thus be accomplished by focus on development of improved Na^+ (and to a lesser extent Cl^-) exclusion by the roots and restriction of translocation to the leaves. Additionally tissue tolerance to salinity by plants is achieved by compartmentalization of Na^+ and Cl^- at the cellular and intracellular level.

Conclusions

There is very limited potential for using fresh water for increased development of irrigation in arid regions. More realistically there will be a significant decrease in fresh water use, due to current unsustainable extractions of fresh water. More efficient use of available resources includes use of new irrigation technologies, reuse of drainage water, use of treated municipal waste water, use of brackish water and reduced leaching for salinity control. Replacement of current simplified guidelines for leaching with more realistic computer models will enable better salinity management and use of resources. Opportunities also exist for development of improved salt tolerance for varieties of salt sensitive plant species.

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