

## Dryland Salinity: Soil Processes and Management

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**Abstract:** About 60% of the global food production depends on dryland farming. In dry lands, salt accumulation in the root zone layers is a major constraint to the efficient water use by crops. Dryland salinity aggravates the water shortage problems usually faced by the farming community. Management of salinity in dry lands will revolve around efficient use of water stored in the root zone by crops, which is affected by many soil processes and environmental factors. This essay deals with different types of salinity found in landscapes affected by arid and semi-arid climates, the soil processes leading to salt accumulation, dynamics of soil water influencing the salt effects on plants and options available for management in these regions.

**Key words:** Dryland salinity, transient salinity, groundwater-associated salinity, osmotic effect of salinity, management of transient salinity.

Soils are derived from chemical and physical weathering of rocks and other geological and organic materials and hence, usually contain some soluble inorganic and organic materials. When soil and environmental factors contribute to the accumulation of soluble salts, mainly inorganic, in soil layers above a level that adversely affects crop production, health of the soil environment and also the economy of the region, soil salinity is considered as a major issue of land degradation.

Historically, soil salinity associated with irrigation schemes has threatened many civilisations in ancient times and also in recent periods. Soil salinisation in southern Mesopotamian and in several parts of the Tigris-Euphrates valley destroyed ancient societies that had successfully thrived for several centuries (Jacobsen and Adams, 1958). In modern times, specifically in the

past two centuries, impacts of irrigation salinity on agricultural productivity have been recognised in many parts of the world. Since the beginning of the last century, the scientific study of the processes and management of soil salinity induced by irrigation has gained importance in more than 100 countries of the world, with the pioneering work done by the United States Salinity Laboratory.

Agricultural practices are considered as 'dryland farming' in arid or semi-arid regions where annual rainfall is less than the evapotranspiration and without supplementary water input by irrigation. Successful agriculture has been practised in many regions globally with annual rainfall between 250 and 600 mm where soil management and agronomic strategies are developed to suit the rainfall pattern.

Efficient capturing of rainfall, storage in soil layers, and subsequent water use

Table 1. Estimated global dryland and dryland cropping areas in semi-arid and subhumid climates (Hopkins and Jones, 1983)

Continent	Semi-arid	Dryland area subhumid (1000 km <sup>2</sup> )	Total	Dryland crop area (km <sup>2</sup> )
Africa	4,490	4,190	8,680	55,540
Asia	5,560	5,110	10,670	97,310
Australia	2,470	810	3,280	13,110
Europe	360	1,120	1,480	34,360
North America	2,890	2,150	5,040	76,120
South America	1,640	1,580	3,220	13,560
Total	17,410	14,960	32,370	290,000

by crops are critical factors in sustaining productivity in dryland. Salt accumulation in the root zone layers of dryland soils becomes a major constraint to the efficient water use by crops, and in general, agricultural productivity. Dryland salinity aggravates the water shortage problems faced by the farming community. Limitation of soil water affects crop production in approximately 75% of the world's arable soils.

Management of salinity in dry lands will revolve around efficient use of water stored in saline soils by crops, which is affected by many soil processes and environmental factors. This essay deals with these processes and the options available for management in saline dryland regions.

### Extent of Dryland Area

Dryland regions occupy about 32 million km<sup>2</sup> of land area spread over all the continents of the world where population density is also significant. This includes arid regions having between 1 and 59 growing days, semi-arid regions having between 60 and 119 growing days, and dry subhumid regions having between 120

and 179 growing days (Stewart *et al.*, 2006). Growing days are the number of days during a year when rainfall exceeds half the potential evapotranspiration in addition to the days required to use 100 mm of water stored in the soil profile. Dryland farming and rain fed farming supply 60% of the global food production. Table 1 gives an estimated global dryland and dryland cropping areas in semi-arid and subhumid climates. Current cropping area should be larger than in the table, because of increasing demand for food from lands in the recent decade.

### Soil Salinity

When input of salts from different sources exceeds the output from a soil layer, salts accumulate in that layer. The different sources of input salts include the materials from soil weathering, salts deposited from rain or irrigation water, rising water table containing saline water, seawater intrusion onto lands (coastal regions), wind-transported (aeolian) materials from soil or lake surfaces and agronomic inputs such as fertilizers and pesticides. The output of salts will depend on the solubility of the products after soil chemical reaction and

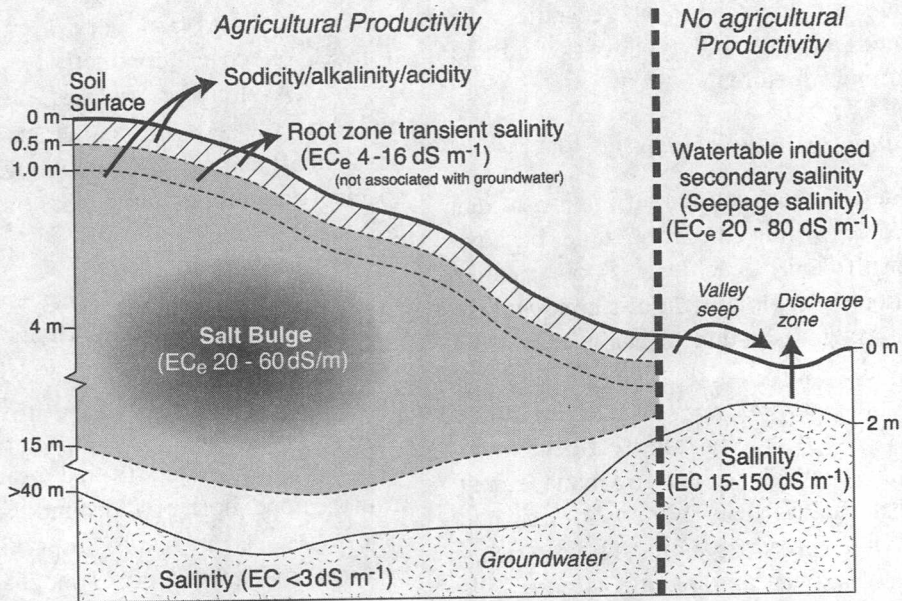


Fig. 1. Different types of dryland salinity in a landscape (after Rengasamy, 2002).

the movement of the soil solution from a given layer controlled by the hydraulic properties of the soil.

There are three major types of salinity based on soil and groundwater processes found all over the world (Rengasamy, 2006) and these are different from the normal classification of 'Primary' or 'Secondary' salinity used in the literature (eg. Ghassemi *et al.*, 1995).

*Groundwater-associated salinity (GAS)*

In discharge areas of the landscape, water exits from groundwater to the soil surface bringing the salts dissolved in it. The driving force for upward movement of water and salts is evaporation from the soil plus plant transpiration. Generally, the watertable in the landscape is at or very close to the

soil surface and soil properties at the site allow a maximum rate of water movement through the surface layers. Salt accumulation is high when the watertable is less than 1.5 metres below the soil surface (Talsma, 1963). However, this threshold depth may vary depending on soil hydraulic properties and climatic conditions.

*Non-groundwater-associated salinity (NAS)*

In landscapes where the watertable is deep and drainage is poor, salts, which are introduced by rain, weathering and aeolian deposits are stored within the soil solum. In drier climatic zones, these salt stores are usually found in deeper solum layers. However, poor hydraulic properties of shallow solum layers can lead to the accumulation of salts in the topsoil and

subsoil layers affecting agricultural productivity. In regions where sodic soils are predominant, this type of salinity is a common feature.

#### *Irrigation associated salinity (IAS)*

Salts introduced by irrigation water are stored within the root zone because of insufficient leaching. Poor quality irrigation water, low hydraulic conductivity of soil layers as found in heavy clay soils and sodic soils, and high evaporative conditions accelerate irrigation-induced salinity. Use of highly saline effluent water and improper drainage and soil management increase the risk of salinity in irrigated soils. In many irrigation regions, rising saline groundwater interacting with the soils in the root zone can compound the problem. Fig. 1 is a schematic diagram of different types of dryland salinity generally found in a landscape.

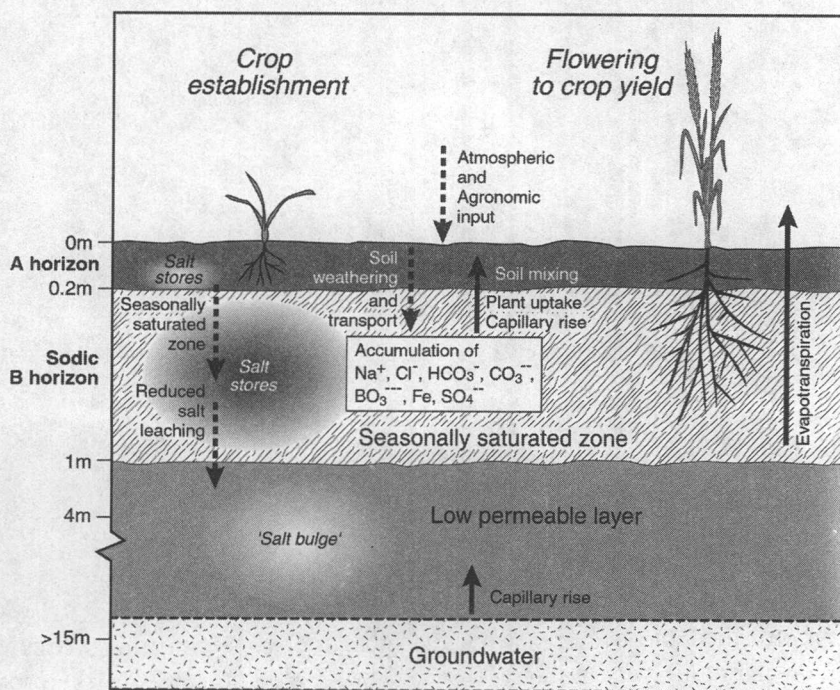
#### **Groundwater-associated Salinity**

Groundwater-associated salinity (also commonly known as 'seepage salinity' and incorrectly thought of as the only form of dry-land salinity) is the visual scalding of soil surfaces associated with a rising saline watertable. At the foot of slopes and in valley floors, the water table is shallower and closer to the surface than in higher regions of the landscape. In some instances, groundwater is forced to the surface in upper catchments due to barriers to flow or thin regolith, before deep valley sediments have filled with water. Under native vegetation, leaching of salts from the permeable soil due to natural processes led to salt storage in deep regolith or the accumulation of salts in the shallow

groundwater. The salinity of the groundwater is often very high, ranging from EC (electrical conductivity) 15 to 150  $\text{dS m}^{-1}$ . As long as the water table is 4 m below the surface, saline groundwater does not affect native vegetation while some species could cope with shallower water tables.

With the clearance of perennial native vegetation and the introduction of agriculture, the equilibrium levels of the water table have changed. In low-lying regions, with shallow water tables, water, with salt, has leaked to the groundwater from the upper horizons. Groundwater levels have risen as a result. Introduction of pastures and annual crops led to a lower evapotranspiration of water captured from rainfall than occurred under the natural ecosystem, where deep percolation of still more water occurred down the profile. As the saline groundwater approached the surface, soil layers (top 1 m) were salinized and waterlogged. Generally, water tables around 2 m depth in the valley floors can cause salinity in the surface soils. Salts reach the surface in the discharge zones (areas of the landscape where water exits from groundwater to the soil surface) by capillary rise of saline water. On valley sides of the landscape, saline groundwater can seep to the soil surface.

The presence of groundwater-associated salinity in many parts of the world has been documented while the total global area has not been collated. In Australia, approximately  $5.7 \times 10^4 \text{ km}^2$  of agricultural and pastoral zone have a high potential for developing salinity through shallow water tables (Rengasamy, 2006). Perhaps



the area once thought to be at risk from rising water tables has to be reconsidered as a result of climate change-induced changes in groundwater levels.

**Transient Salinity**

“Transient salinity” is the term used to denote the salt accumulation in root zone layers without the influence of groundwater processes (Rengasamy, 2002). Because of the seasonal variations in rainfall, salt levels fluctuate within the root zone and hence, transient. While groundwater-associated salinity has been given much attention world wide, transient salinity, being less obvious, is not commonly addressed by land managers.

Under semi-arid conditions, the rainfall has not been sufficient to leach all the salts accumulated below the root zones of native vegetation to the deep groundwater. The clay layers in deep subsoils have hindered the movement of water and salt. As a result, a ‘bulge’ of salt accumulated in the soil layers approximately 4 to 10 m from the surface. The groundwater table was generally below 30 metres depth from the surface, and its quality classified as ‘not very saline’ (EC 3 dS m<sup>-1</sup>). This is different from the situation at the foot of slopes and in valley floors of the landscape, where shallow water tables exist and groundwater processes cause soil salinity. Recent geophysical studies using modern techniques such as airborne electro-

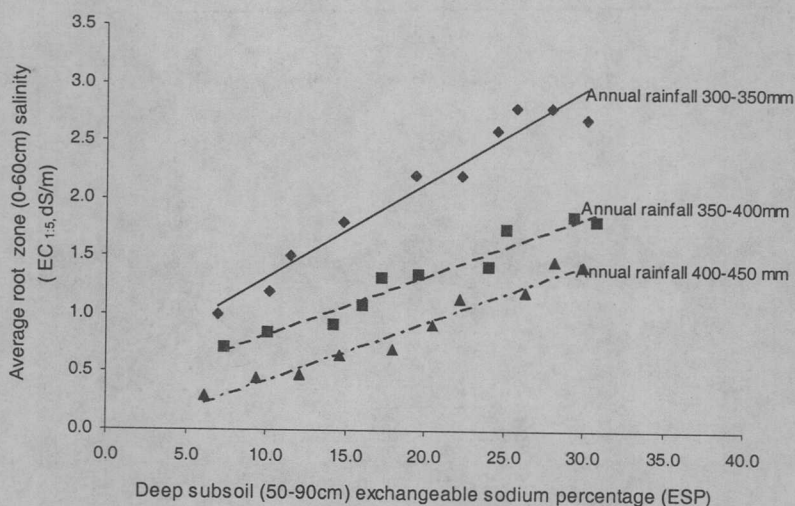


Fig. 3. Salt accumulation in relation to ESP and rainfall.

magnetics have confirmed the occurrence of salt bulges in deeper soil layers in many landscapes in Australia (Lawrie, 2005).

Because of sodium salt movement through soil layers, over 60% of the soils in agricultural zones in Australia have become sodic. Dense sodic subsoils prevent water transmission and restrict leaching; a process that has led to salt accumulation in subsoils (root zone layers) in amounts detrimental to plant growth. This 'transient salinity' fluctuates with depth and its concentration and effect on plant growth changes with season and rainfall. Significantly, groundwater processes do not influence this form of salinity. Figure 2 schematically explains the soil processes leading to transient salinity in root zone layers of sodic soils.

In Australia, the agricultural area of which is about  $7.6 \times 10^6$  km<sup>2</sup>, sodic soils that have a potential for transient salinity

and other root-zone constraints occupy  $2.5 \times 10^6$  km<sup>2</sup>. Whereas 16% of the cropping area is likely to be affected by watertable-induced salinity, 67% of the area is subject to transient salinity and other root-zone constraints, costing the farming economy about Aus \$ 1,330 million per annum, in lost opportunity (Rengasamy, 2002).

In many dryland regions in the world soil salinity does not appear to be caused by perturbed groundwater levels. Rather, the extent and nature of the dryland salinity is influenced by a range of processes occurring in the upper horizons of the soil. For example, loss of organic matter through overgrazing or overcropping has led to reduced permeability, a condition that reduces the ease with which salts can be leached from the soil profile.

#### Seasonal changes in transient salinity

Transient salinity in soils, characterised by high concentration of salts in the subsoil, vary with depth and changes throughout

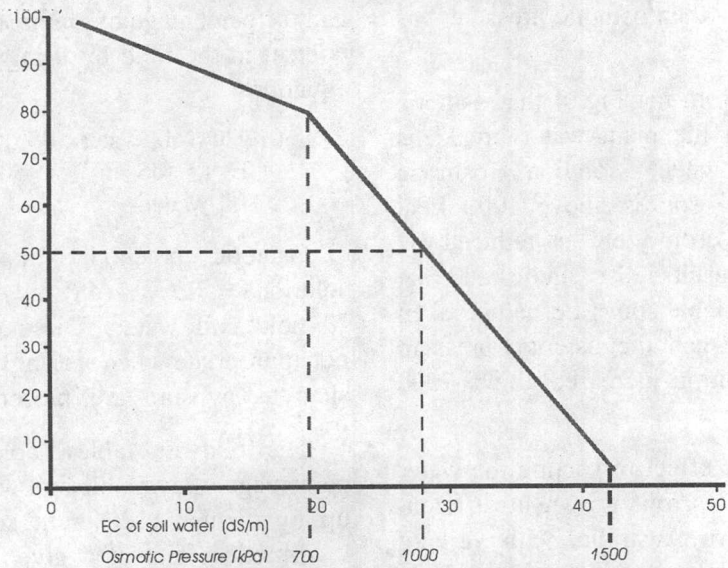


Fig. 4. Schematic diagram of the effect of osmotic effect of salinity on the yield of crops (after Kelly and Rengasamy, 2006).

the season in response to rainfall, surface evaporation, water use by vegetation and the leaching fraction (hydraulic conductivity) of the clay layer. Analyses of several profile samples in southern Australian dryland regions have revealed a high correlation between sodicity (reflecting the reduced leaching fraction) and the salt accumulation. This relationship varies with seasonal rainfall as shown in Fig. 3.

Seasonal changes in rainfall pattern and evaporation are important factors in the accumulation of salts in soil layers. Transient salinity increases with decreasing rainfall. It also increases with increasing sodicity. Transient salinity generally occurs in soil layers above the sodic clay layers.

#### *Soil water dynamics and salinity effects*

Experiments in our project have shown that transient salinity (accumulation of salt in root zone layers, not influenced by

watertable) affects crop yield and growth in dry land regions mainly by reducing water-use efficiency of crops through osmotic effect, while toxic effects of individual ions such as sodium can also cause yield reduction.

Kelly and Rengasamy (2006) experimenting on wheat crops grown in pots using Hoagland solutions of different salinities, but containing the same proportion of macro and micro nutrients, concluded that osmotic effect of salinity is an important factor in reducing yield under dryland conditions. Their major conclusion is shown schematically in Fig. 4. When the osmotic pressure of the soil solution was <700 kPa, there was a low rate of reduction in crop yield. However, for osmotic pressures >700 kPa the rate of crop yield reduction was severe. Their results on treatments using other salt solutions indicated the specific ion effect, particularly of sodium, in addition to osmotic effect. This specific ion effect

was significant when osmotic pressure was <700 kPa.

It is clear from the Fig. 4 that osmotic effect reducing the plant water uptake is predominant when solution osmotic pressure of the soil is above 1000 kPa. At this value crop yield is reduced by 50%. Their results also indicated that 80-95% of available soil water is not taken up by plants when the osmotic pressure of the soil solution increased above 1000 kPa.

The osmotic effect restricting the water uptake by wheat crops grown in different sites in southern Australia, with varying salinity levels, is also seen from the Table 2.

Table 2. Percentage of available water not taken up by plants in saline dryland soils in southern Australia (P.Rengasamy, unpublished)

Average EC (dS m <sup>-1</sup> ) of soil water under field condition	Percentage of available water not taken by plants due to osmotic effect
0.7	0.0
2.8	5.1
10.6	5.9
22.6	50.2
30.8	59.6
41.0	84.8
63.9	95.4

In dry land cropping, fluctuating soil moisture level during the growing season is an important factor while considering the effects of transient salinity on crops. Actual salinity (EC) of the soil in the field and the osmotic pressure of the soil solution in the field can be calculated from the laboratory measured soil salinity (EC<sub>1.5</sub>)

and the percentage of gravimetric soil water content in the field by using the following equations:

$$\text{EC of field soil water (dS m}^{-1}\text{)} = \frac{[\text{EC}_{1.5} \text{ (dS m}^{-1}\text{)} \times 500]}{\% \text{ field soil water}}$$

Osmotic potential (kPa) field soil solution =  $\frac{[\text{EC}_{1.5} \text{ (dS m}^{-1}\text{)} \times 18,000]}{\% \text{ field soil water}}$ . These equations are not appropriate when sparingly soluble salts such as gypsum are present.

The following table (Table 3) gives the percentage of available soil water not taken up by plants in different soil types due to osmotic effect of a given salinity. The available soil water range for each soil type, under non-saline conditions, was calculated from the laboratory measured field capacity and wilting point values. In dryland cropping, changing soil water content during growing season is an important factor influencing the effects of salinity on crop production..

#### Management of transient salinity

It is important that salts are leached below the root zone. When the rainfall is average or above, crop selection should allow a fraction of the captured water move below the subsoil so that salts are leached. In low rainfall regions, crops such as lucerne with high evaporative demand, can concentrate more salt in the root zone.

In order to facilitate leaching, structure of sodic subsoil should be improved. We analysed soil profiles in farmers' fields where gypsum has been applied in field trials. The results indicate that gypsum application improves leaching of salts. Table 4 shows the leaching of salts by gypsum

Table 3 Percentage of available soil water not taken up by plants in different soil types due to osmotic pressure of soil water salinity in relation to laboratory measured soil salinity and gravimetric field soil moisture (Kelly and Rengasamy, 2006)

Laboratory measured soil salinity EC <sub>1:5</sub> (dS m <sup>-1</sup> )	Gravimetric field soil moisture (%) below which osmotic pressure due to salinity is		Percentage of available soil water not taken up by plants due to osmotic pressure (>1000 kPa) of soil water salinity			
	>1000 kPa	>1500 kPa	Sand	Sandy loam	Clay loam	Clay
0.25	4.5	3.0	25	0	0	0
0.39	7.0	4.7	50	0	0	0
0.50	9.0	6.0	70	25	0	0
0.72	13.0	8.7	100	50	15	0
1.00	18.0	12.0	100	81	40	4
1.11	20.0	13.3	100	94	50	12
1.25	22.5	15.0	100	100	63	22
1.50	27.0	18.0	100	100	85	40
1.64	29.5	19.7	100	100	98	50
1.75	31.5	21.0	100	100	100	58
2.00	36.0	24.0	100	100	100	76
2.33	42.0	28.0	100	100	100	100

application (5 t ha<sup>-1</sup>) in 2003 to a sodic duplex soil in South Australia with an annual rainfall ~ 400 mm per year.

The use of salt tolerant varieties to overcome salinity effects is highly desirable. Efforts by plant breeders in different parts of the world have produced salt tolerant plant species, particularly irrigated crops and pastures, and are being adopted by farmers. In dryland farming, fluctuating soil moisture is a major constraint in developing suitable varieties. Genetic yield increases in dryland environment have historically challenged plant breeders with genetic gains in yield being low compared to that made in irrigated crops (Passioura, 2004), due to complex physiology-environment interactions. Water uptake in many soils is often limited by the presence of a number of subsoil factors, in addition to salinity,

such as physical, chemical and biological constraints (Rengasamy *et al.*, 2003).

#### Issues of Transient Salinity in Relation to Agricultural Production

The following soil related processes need to be investigated to improve productivity under dryland saline conditions.

- Under dryland conditions, concomitant changes in matric and osmotic potentials of soil water determine plant water uptake. The influence of soil texture and type of clay on plant-available water compounds the osmotic effects. For example, in a loamy soil, when there is no salt, plants are able to take up water until the soil dries to 5% water content. Whereas, when the soil EC<sub>1:5</sub> is only 0.6 dS m<sup>-1</sup> plants can take water only up to 14% water content (Rengasamy

Table 4. Movement of salts in plots with gypsum and no gypsum measured in 2006 (Average of 4 replicates). Wheat was grown continuously

Soil depth (cm)	No gypsum			Gypsum (5 t ha <sup>-1</sup> )		
	Ca <sup>2+</sup>	Na <sup>+</sup>	EC due to NaCl (dS m <sup>-1</sup> )	Ca <sup>2+</sup>	Na <sup>+</sup>	EC due to NaCl (dS m <sup>-1</sup> )
0-20	50	79	0.24	54	42	0.22
20-40	42	160	0.63	62	64	0.43
40-60	10	210	0.88	58	89	0.46
60-80	6	250	1.16	107	92	0.52
80-100	8	320	1.48	105	98	0.54

*et al.*, 2003). Thus, during drier periods in the growing season, even small amounts of salt can affect plant growth. Salinity levels, site-specific soil properties and dynamics of soil water – all interactively influence the salinity effects.

- In areas affected by transient salinity where the watertable is deep (around 15 m), species with high evapotranspiration can concentrate more salt in the root zone and hinder the production of other plants; in saline areas where the watertable is shallow (around 2 m), the same species may help in deepening the groundwater levels. However, the increasing accumulation of salts will decrease plant leaf area indices and their transpiration rates. Thus, soil processes specific to each type of salinity dictate the strategies for plant-based solutions to different forms of salinity.
- Although sodicity is a major problem in salt-affected soils, a number of soils have multiple problems in different layers in their soil profile (Rengasamy *et al.*, 2003). For example the topsoil can be sodic while the subsoil is saline.

When a saline-tolerant durum wheat variety was grown in this type of sodic soil, the yield was similar to that of a less salt-tolerant variety. On further investigation it was found that topsoil sodicity and alkaline pH (9.6) prevented the roots from reaching the saline subsoil layer (Cooper, 2004). Waterlogging and/or nutrient deficiency are also commonly associated with salinity in some parts of dryland regions. Multiple problems can arise when the salts accumulated contain borates and carbonates in toxic amounts, as found in extensive areas with alkaline subsoil pH.

- In salinity research, it is common to assume the salt is NaCl. However, the soils affected by transient salinity may contain other types of salts such as carbonates and sulphates and salts of Ca, Mg and K. How these different types of salts influence soil structure and hence salt accumulation or leaching will depend on soil conditions and processes. This has to be researched to improve productivity.
- Current knowledge of salt tolerance of plants is based on saturation water

contents of soils (e.g. Maas, 1986). However, in dryland conditions soils are never saturated with water. It is highly essential to develop new guidelines on salt tolerance of plant species taking into account soil water dynamics.

- Under transient salinity (where water table is deep enough), the major aim is to leach salts below the root zone. Soil management and agronomic practices have to be developed to achieve this aim.
- There is a gap in our knowledge in identifying the predominant, or a common, factor when different issues cause constraints to plant growth in different soil layers. The uncertainty in our ability to separate effects of these factors will need to be overcome for developing varieties adapted to various physico-chemical constraints of soil layers. The lack of success of breeding programmes in developing commercially successful salt tolerant crops is due to breeders' preference for evaluating their genetic material in idealised conditions.

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### References

- Cooper, D.S. 2004. Genetics and agronomy of transient salinity in *Triticum durum* and *T. aestivum*. Ph.D. Thesis, The University of Adelaide, Australia.
- Ghassemi, F., Jakeman, A.J. and Nix, H.A. 1995. *Salinisation of Land and Water Resources. Human causes, Extent, Management and Case Studies*. University of New South Wales Press Ltd., Sydney.
- Hopkins, S.T. and Jones, D.E. 1983. Research Guide to the Arid Lands of the World. Oryx Press, Phoenix, AZ., USA.
- Jacobsen, T. and Adams, R.M. 1958. Salt and silt in ancient Mesopotamian agriculture. *Science* 128: 1252.
- Kelly, J. and Rengasamy, P. 2006. *Diagnosis and Management of Soil Constraints: Transient salinity, Sodicty and Alkalinity*. The University of Adelaide and Grain Research and Development Corporation, Australia.
- Lawrie, K.C. 2005. Salinity hazard and risk mapping—a multi-disciplinary approach for complex regolith landscapes in Australia. *Proceedings of International Salinity Forum, Riverside, California*. April 2005, 281-284.
- Maas, E.V. 1986. Salt tolerance of plants. *Applied Agricultural Research* 1: 12-25.
- Passioura, J. 2004. Water use efficiency in the farmers' field. In *Water Use Efficiency in Plant Biology* (Ed. M.A. Bacon), pp. 302-321. Blackwell Publishing, UK.
- Rengasamy, P. 2002. Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: An overview. *Australian Journal of Experimental Agriculture* 42: 351-361.
- Rengasamy, P. 2006. World salinisation with emphasis on Australia. *Journal of Experimental Botany* 57: 1017-1023.
- Rengasamy, P., Chittleborough, D. and Helyar, K. 2003. Root-zone constraints and plant-based solutions for dryland salinity. *Plant and Soil* 257: 249-260.
- Stewart, B.A., Koohafkan, P. and Ramamoorthy, K. 2006. Dryland agriculture defined and its importance to the world. *Dryland Agriculture, 2<sup>nd</sup> edition. Agronomy Monograph no.23*: 1-14.
- Talsma, T. 1963. The control of saline groundwater. Thesis for the degree of Doctor in Land technology, University of Wageningen. *Reprint of Bulletin of University of Wageningen* 63(10): 1-68.