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Soil processes affecting crop production in salt-affected soils

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Abstract. Salts can be deposited in the soil from wind and rain, as well as through the weathering of rocks. These processes, combined with the influence of climatic and landscape features and the effects of human activities, determine where salt accumulates in the landscape. When the accumulated salt in soil layers is above a level that adversely affects crop production, choosing salt-tolerant crops and managing soil salinity are important strategies to boost agricultural economy. Worldwide, more than 800 million hectares of soils are salt-affected, with a range of soils defined as saline, acidic–saline, alkaline–saline, acidic saline–sodic, saline–sodic, alkaline saline–sodic, sodic, acidic–sodic and alkaline–sodic. The types of salinity based on soil and groundwater processes are groundwater-associated salinity (dryland salinity), transient salinity (dry saline land) and irrigation salinity. This short review deals with the soil processes in the field that determine the interactions between root-zone environments and plant responses to increased osmotic pressure or specific ion concentrations. Soil water dynamics, soil structural stability, solubility of compounds in relation to pH and pE and nutrient and water movement all play vital roles in the selection and development of plants tolerant to salinity.

Additional keywords: dynamics of soil salinity, salinity categories, salinity types.

Introduction

Soils are derived from chemical and physical weathering of rocks and other geological and organic materials. Thus, they always contain some soluble inorganic and organic compounds. Rain can also lead to the accumulation of salt over time, although it contains only small amounts of salt. Wind-transported materials from soil or lake surfaces are another source of salt. Application of soluble fertilisers and soil amendments, poor quality irrigation water and capillary rise of shallow saline groundwater can all contribute to the salinisation of the soil layers. Even seawater intrusion onto land, which is a growing problem as sea levels rise in many parts of the world, can deposit a large amount of salts in soils of coastal lands. The particular processes contributing salt, combined with the influence of other climatic and landscape features and the effects of human activities, determine where the salt accumulates in the landscape. Plants also determine where salts accumulate in the vertical horizon of the soil profile.

Soil salinity becomes a major issue in global agriculture when soil and environmental factors contribute to the accumulation of salts in soil layers above a level that adversely affects crop production. Worldwide, more than 800 million hectares of land are estimated to be salt affected (FAO 2008). These soils cover a range of soils defined as saline, saline–sodic and sodic (Ghassemi *et al*. 1995). Even though the general assumption is that salt affected soils occur primarily in arid and semiarid climates, these soils are actually found in every climatic zone in every continent except Antartica. All soil types with diverse morphological, physical, chemical and biological properties may be affected by salinity (Rengasamy 2006).

Crop growth responds to salinity in two phases: a continuous osmotic phase that inhibits the water uptake by plants due to osmotic pressure of saline soil solution lowering its potential energy (water always moving from a higher to lower potential energy levels); and a slower ionic phase when the accumulation of specific ions in the plant over a period of time leads to ion toxicity or ion imbalance (Munns and Tester 2008). Elucidation of these mechanisms as well as the development of plants tolerant to salinity, in many instances, are based on the evaluation of the genetic materials in simplified conditions such as solution culture, hydroponics or sand culture. Sometimes genetic materials are evaluated in lysimeter or micro plots filled with saline or sodic soils or in actual field conditions. However, the interactions between root-zone environments and plant responses to increased osmotic pressure or specific ion concentrations in the field are complicated by many soil processes such as soil water dynamics, soil structural stability, solubility of compounds in relation to pH and pE (electron concentration related to redox potential) and nutrient and water movement in soil. This short review based on the results of experiments using soils – either in pots or in the field – emphasises the soil processes to be considered in the evaluation of salt tolerance of plants and the activities related to plant development to adapt to saline lands.

Classification of salt-affected soils

The constituent cations of total soluble salts in soils are usually sodium, calcium and magnesium; the anions are chloride, sulfate and carbonate (including bicarbonate). However, sodium dominates the cations and chloride the anions in the majority of saline Australian soils to the extent that sodium chloride comprises from 50 to 80% of the total soluble salts (Northcote and Skene 1972). As sodium is adsorbed by soil particles above a certain level the soil becomes 'sodic' and soil structure and

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hydraulic properties deteriorate. These effects of sodicity (characterised by exchangeable sodium percentage, ESP, of soil or sodium adsorption ratio, SAR, of soil solution) are evident only when salts are leached below a 'threshold level' and the ionic strength of soil solution is low (for details see Rengasamy and Olsson 1991). As SAR is well correlated with soil sodicity, measuring SAR and EC in soil extracts or hydroponic solutions will characterise any saline condition. Sodium adsorption ratio is defined as follows:

$$SAR = [Na^{+}]/[Ca^{2+} + Mg^{2+}]^{1/2}, \quad (1)$$

where the concentrations Na^{+}, Ca^{2+} and Mg^{2+} are measured in mmol L^{-1}. Examples of calculation of SAR from the concentrations of the various salts in solutions are given in Table 1. ESP is calculated as (exchangeable Na/cation exchange capacity) × 100 where exchangeable Na and cation exchange capacity are expressed as $mmol_c\ kg^{-1}$.

When the rainfall is not sufficient to leach the salts throughout the soil profile, they accumulate in deep subsoils, keeping the layers above as non-saline, but sodic. However, with time, even the sodic layers start accumulating salts because of restricted water movement (Rengasamy 2002*a*). A saline soil dominant in sodium ions is saline–sodic and becomes sodic when salts are leached. Similarly a sodic soil becomes saline–sodic when sodium salts accumulate in soil layers. Generally 'saline', 'sodic' and 'saline–sodic' soils have a spectrum of disorders and the soil solutions have a range of values of SAR and electrical conductivity (EC). Further, as the pH of the soil increases above 8, soil becomes alkaline and carbonates dominate the anions. Thus, salts affect plants through adverse soil properties of alkalinity and sodicity, properties imposed on the soil by mobile salts. The following Figure (Fig. 1) gives the different categories of salt-affected soils generally found in different parts of the world, with criteria mainly based on SAR_e and EC_e of the saturation extracts of the soil and pH measured in 1 : 5 soil–water suspensions. The value of SAR_e of 6 and above ($SAR_e \approx ESP$) to classify a soil as sodic soil is based on the Australian criteria of sodicity (Isbell 1996). The soil structural effects due to sodicity depend on both the levels of SAR and EC. Rengasamy (2002*b*) has given a detailed methodology to determine the threshold electrolyte concentration for a sodic soil below which soil structure is adversely affected. Generally, sandy soils with very low clay content, as found in Western Australia, can only be saline and will not have soil structural problems caused by high SAR, whereas, clayey soils are likely to be sodic with soil structural problems with increased SAR.

Table 1. Examples of calculation of the sodium adsorption ratio (SAR) from the cation concentrations in solutions or soil extracts typical of soils that are not saline (in the first two examples) and saline (in the second two)
K is not included in the calculation of SAR. In sandy soils and in hydroponic solutions, SAR has no significance in relation to soil structural effects

Concentrations of cations (mg L^{-1})				Cation concentration (mmol L^{-1})				SAR
Na	K	Ca	Mg	Na	K	Ca	Mg	
230	46	40	24	10.0	1.2	1.0	1.0	7.1
230	46	230	48	10.0	1.2	5.8	2.0	3.6
990	46	40	24	43.0	1.2	1.0	1.0	30.5
990	46	230	48	43.0	1.2	5.8	2.0	15.5

The categorisation of salt affected soils in Fig. 1 is based on soil analytical values, irrespective of how salt is accumulated in the soil. These categories will apply to soils affected by rising watertables as well as those not associated with groundwater movements. Possible mechanisms by which soils of each category will affect plant growth are also given in Fig. 1. In alkaline sodic soils the pH of a 1 : 5 suspension is usually from one-half to one pH unit higher than that of a saturated soil paste or a soil suspension prepared by using $CaCl_2$ (Northcote and Skene 1972). Similarly, in my experience, the pH of soil–water suspension is greater than the filtered extracts. Saline–sodic and sodic categories of salt-affected soils are based on the dominance of sodium salts ($SAR_e > 6$).

With the recent trend of irrigation of crops using recycled water, containing dominant ions other than Na^{+} (e.g. Smiles and Smith 2004), 'saline soil' category with $EC_e > 4$ and $SAR_e < 6$ has been included in Fig. 1. These soils induce osmotic effects, but do not cause Na toxicity. However, toxicity due to other ions or ion imbalance effect is possible. Cations other than Na^{+} may have effects different to that of Na on soil structure when salts are leached. Future research is needed to clarify the effects of cations other than Na^{+} on soil structure. Therefore, ideally, the ionic composition of soil solution, in addition to the above criteria, should be taken into account for proper interpretation of soil–plant interactions. Table 2 gives the area of different categories of salt affected soils in Australia, mainly based on the earlier documentation by Northcote and Skene (1972).

Different types of salinity based on the processes of salt accumulation

There are three major types of salinity based on soil and groundwater processes found all over the world: groundwater associated salinity, transient salinity and irrigation salinity (Rengasamy 2006). Groundwater associated salinity, commonly known as dryland salinity, occurs in discharge areas of the landscape where water exits from groundwater to the soil surface bringing salts dissolved with it. 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 profile. The concentration of salts fluctuates with season and rainfall and salt accumulation in soil layers is a common feature in sodic soils regions. This type of salinity is termed 'transient salinity' (Rengasamy 2002*a*) and is also known as dry saline land or magnesia patches in South Australia.

Irrigation salinity is caused by the salts introduced by irrigation water, which are stored within the root zone because of insufficient leaching. These types are all found in Australia, being the driest inhabited continent with an average annual rainfall of 420 mm, of which more than 80% is lost to evaporation. It is estimated that 5.7×10^{6} hectares of Australia's agricultural and pastoral zones are currently affected by groundwater associated salinity and rising watertables.

Transient salinity exists in 2.5×10^{8} hectares of the agricultural area, being 33% of the total. Irrigation induced salinity affects ~1.2×10^{6} hectares of land area in Australia. Rengasamy (2002*a*, 2006) has described in detail all the

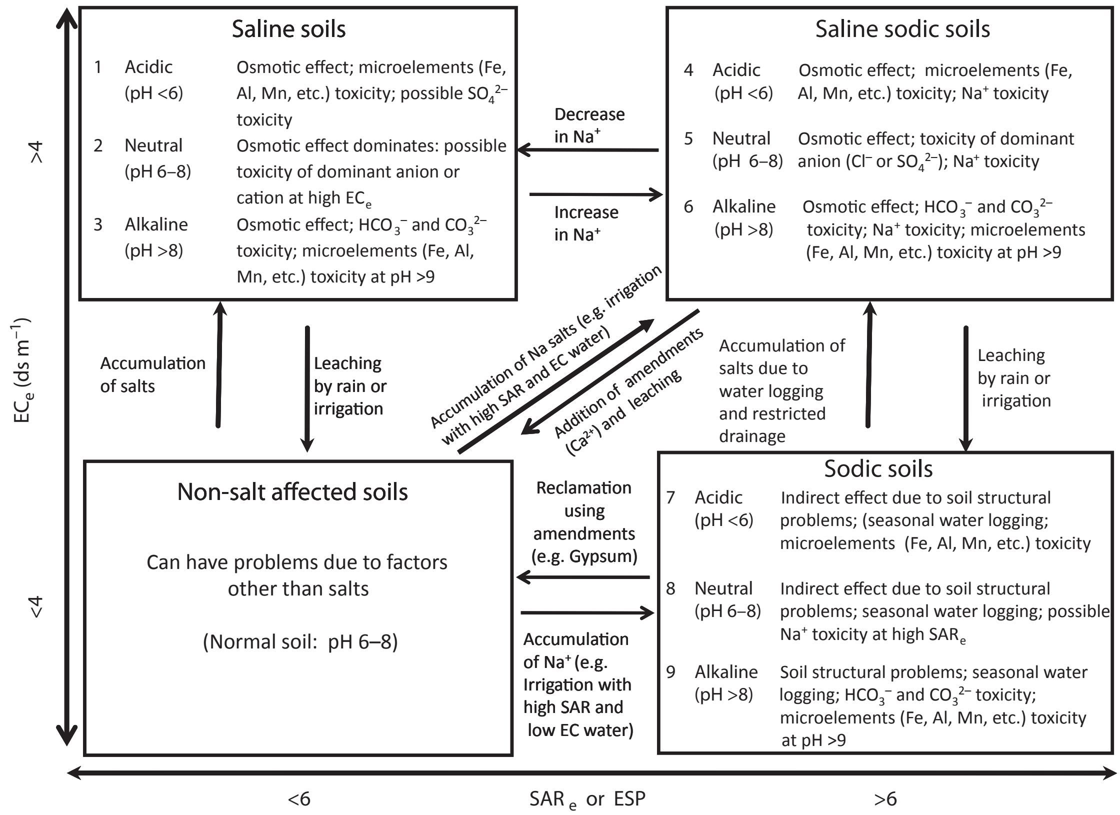

Fig. 1. Categories of salt affected soils based on sodium adsorption ratio (SAR_e) and electrical conductivity (EC_e) measured in soil saturation extract and $pH_{1:5}$ measured in soil water suspension and possible mechanisms of impact on plants. Toxicity, deficiency or ion-imbalance due to other elements (e.g. B, K, N, P) will depend on the ionic composition of the soil solution. The diagram also shows the cyclic changes of the categories as influenced by the climatic factors and land management. (Note: In Australia, 1 : 5 soil : water suspension is commonly used for measurements of EC (and also for SAR) because of the easiness of measurements. Preparation of soil saturation extract is laborious and costly. Saturation extract is prevalently used in USA and other parts of the world and therefore to compare the research data, particularly salt tolerance thresholds for crops based on EC_e, conversion of $EC_{1:5}$ to EC_e (Kelly and Rengasamy 2006) has become a necessity.)

Table 2. Area of different categories of salt-affected soils in Australia

Data compiled from Northcote and Skene (1972). All sodic soils classified by Northcote and Skene (1972) are potentially transient saline soils (Rengasamy 2002*a*) and therefore can be either sodic soils or saline sodic soils

Salinity category as in Fig. 1 (numbers correspond to those in Fig. 1)	Salinity category of Northcote and Skene (1972)	Area (km^2)	Percentage of total land area
Acidic–saline soils (1)	Not identified	95 000[A]	1.3
Neutral saline soils (2)	Saline soils	386 300	5.3
Alkaline–saline soils[B] (3)	Not identified	Not known	Not known
Acidic saline–sodic soils (4) Acidic–sodic soils (7)	Non-alkaline sodic–acid soils	140 700	1.9
Neutral saline–sodic soils (5) Neutral sodic soils (8)	Non-alkaline sodic and strongly sodic neutral soils	134 700	1.9
Alkaline saline–sodic soils (6) Alkaline–sodic soils (9)	Alkaline strongly sodic to sodic soils	1 721 500	23.6

[A]Area for acid saline soils was from CSIRO Land and Water (2009).
[B]The area of alkaline saline soils in Australia is unknown. This category soils with low sodium but high concentration of soluble carbonates of K^+, Mg^{2+} or Ca^{2+} are rarely found in Australia.

processes involved in these three different types of salinity globally found. Preliminary estimates show that all categories (Fig. 1) of salinity together cost the farming economy in lost production in Australia in the vicinity of A$1.5 billion per year. This is based on the estimate by the National Land and Water Resources Audit (2001) of about A$200 million per year for watertable associated dryland salinity and the estimate by CRC for Soil and Land Management (1999) of about A$1.3 billion per year for sodic soils, which also include saline subsoils affected by transient salinity (Rengasamy 2002*a*).

Effect of osmotic pressure of soil solution on plants

Rengasamy (2010) conducted pot experiments on wheat growth using a sandy loam soil and various electrolyte solutions such as NaCl, $CaCl_2$, Na_2SO_4 and Hoagland nutrient solution, inducing different EC levels of the soil solution. The water content of soils in the pots was maintained at field capacity for the first 25 days of growth. The resulting differences in dry matter production after 40 days of growth indicated the continuous operation of osmotic effect as the EC of the soil solution increased from 0.7 to 41.0 dS m^{-1}. The osmotic effect became dominant and severely restricted plant growth when the soil solution EC increased above 25 dS m^{-1} in this set of experiments. Below this EC value, ionic effects due to Na^+, Ca^{2+}, SO_4^{2-} and Cl^- were also evident.

Kelly and Rengasamy (2006) produced a schematic diagram relating EC of soil solution (and related osmotic pressure of soil solution) on the basis of pot experiments and field observations and concluded that osmotic effect of salinity is an important factor in reducing yield under dry land conditions. Their schematic diagram (Fig. 2) shows that the increases in effect of the osmotic pressure of the soil solution on plant yield were greater when the pressure raised over 700 kPa. It is clear from Fig. 2 that osmotic effect, reducing the plant water uptake, reduces the yield to uneconomic levels when the soil solution osmotic pressure is above 1000 kPa.

The data in Table 3 support that the reduction in yield due to salinity is related to the percentage of available water not taken up by plants in soils affected by transient salinity. The data presented in Table 3 are averages of observations in seven different soils in South Australia. The reduced water uptake by wheat due to salinity has also been shown in pot experiments (Rengasamy 2010). It was found in these pot experiments that as EC of soil solution increased, the unused water in the pot soils increased and a high percentage of unused water (89–96%) was evident when the soil solution EC was >22.6 dS m^{-1}.

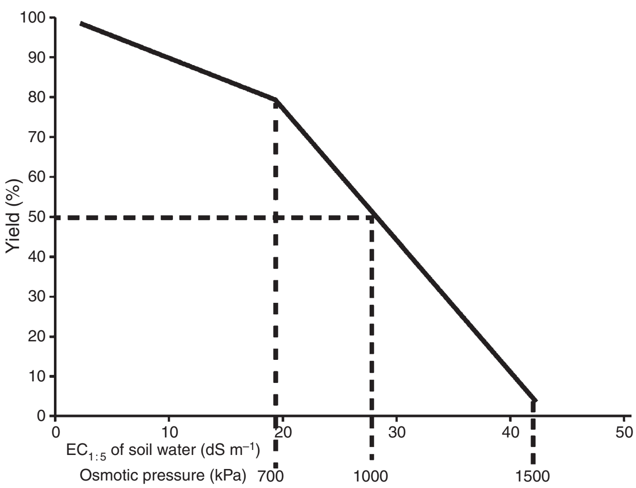

Fig. 2. Schematic diagram of the effect of electrical conductivity (EC) and osmotic pressure of the soil solution on the yield of wheat (from Kelly and Rengasamy 2006).

Osmotic or ionic effects at different levels of salinity

Munns *et al*. (2006) suggested that the two responses to salinity – osmotic stress and ion-specific stress – can occur sequentially, giving rise to a two-phase growth response. Using the model suggested by Munns *et al*. (2006) and Rengasamy (2010), growing wheat in pot soil treated with NaCl or Hoagland nutrient solution at different salinity levels, concluded as follows: (i) at a low level of salinity (7.0 dS m^{-1}), the osmotic effect was continuous during the entire period of growth. However, after ~25 days of growth, there was a difference between NaCl and Hoagland solution, indicating the ionic effect of Na in reducing growth. This agrees with the conclusions by Munns *et al*. (2006); (ii) however, at a higher level of soil solution salinity (30.0 dS m^{-1}), the osmotic effect was predominant and the ionic effect of Na was minimal. Thus, it appears that above a 'threshold value of soil solution EC', osmotic effect is the dominant mechanism and ionic effect may be significant at lower levels of EC. Recently, Tavakkoli *et al*. (2010) have confirmed these results in a replicated trial using two varieties of barley.

In saline soils, particularly when soil fertility level is low and nutrient deficiency is an issue, application of fertilisers alleviates the salinity stress on plants (e.g. Irshad *et al*. 2002). Elgharably *et al*. (2010) found that, at low salinity, addition of nitrogen to a sandy loam soil increased the dry matter production compared with control (non-saline) treatment. However, at high salinity levels, addition of nitrogen was not beneficial because of increased osmotic pressure of soil solution. Similarly, adding a small amount of calcium has been reported to enhance salt tolerance of plants at moderate levels of NaCl salinity (Cramer 1992). However, our experiments have shown that even calcium can reduce the plant growth at higher concentrations (Rengasamy 2010).

Soil water and osmotic pressure dynamics in the field as related to climate

The soil salinity measured in the laboratory either as $EC_{1:5}$ (in 1 : 5 soil : water suspension) or EC_e (in soil saturation extract) may be low to moderate because of high soil water contents. In the field, generally, soil water is near field capacity after rain or irrigation events. As the soil dries due to evapotranspiration, the salt concentration increases, as does the

Table 3. Percentage of available water not taken up by plants in soils affected by transient salinity in southern Australia (P. Rengasamy, unpubl. data)

The values are average of several observations from seven locations in southern Australia

Average EC (dS m^{-1}) of soil water under field condition	Percentage of available water not taken by plants due to osmotic effect
0.7	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

osmotic pressure of soil water. Concomitant changes in matric and osmotic potentials determine plant water uptake in the field. The influence of soil texture and type of clay on plant-available water compounds the effect of matric plus osmotic potentials (Rengasamy 2006). Figure 4 in Rengasamy (2006) shows that in a loamy soil, in the absence of salt ($EC_{1:5}$ of 0.16 dS m^{-1}), the plants can take up water from the soil having 25–5% water content (field capacity to wilting point), but when the soil is saline ($EC_{1:5}$ of 1 dS m^{-1} or higher), the plants cease to take up water even when the soil dries only to 18% water content because the total water potential (matric plus osmotic) in the field soil, at that point, reaches –1500 kPa. In these experiments, while soil water matric potential was measured, osmotic pressure of soil solution was calculated using the following relationship between EC and osmotic pressure: EC of 1 dS m^{-1} = 36 kPa of osmotic pressure.

In dryland 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 ($EC_{1:5}$) and the percentage of gravimetric soil water content in the field by using the following equations (Kelly and Rengasamy 2006):

$$\text{EC of field soil water } (\text{dS m}^{-1}) = [\text{EC}_{1:5}\,(\text{dS m}^{-1}) \times 500]/\ \%\text{ field soil water content}, \quad (2)$$

$$\text{osmotic potential (kPa) field soil solution} = [\text{EC}_{1:5}\,(\text{dS m}^{-1}) \times 18\,000]/\%\text{ field soil water content}. \quad (3)$$

These equations are not appropriate when sparingly soluble salts such as gypsum are present. The solubility of gypsum in water is 2 g L^{-1} but that of NaCl is 360 g L^{-1}. For example, if a soil contains 3% salt as NaCl, the entire salt will dissolve in the soil water content range between 100 and 10%. Whereas, if a soil contains 0.2% gypsum, the solubility will vary from 0.2 to 0.02 g in the same water content ranges. Therefore, if sparingly soluble salts are present, psychrometric measurement of osmotic potential will be necessary.

The following table (Table 4) 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. During wheat growing season in 2003, we measured the soil water content of a clay loam (20–60 cm) layer of a calcareous sodosol (Natrixeralf) in South Australia, affected by transient salinity, on the first week of every month from April to November, including 3 different days in September when there was a prolonged dry period. The laboratory measured salinity, $EC_{1:5}$ was 1 dS m^{-1}. The gravimetric soil water content (%), the measured matric potential and total water potential (which includes measured matric potential and the calculated osmotic potential using the above, Eqn 3) are plotted in Fig. 3. If the soil was non-saline, the plants would have the ability to use the soil water during the entire period of growth as the lowest value of matric potential of soil water was –400 kPa. However, the soil being saline, water availability to plants diminished significantly between 15 September and first week of October, because the total (matric plus osmotic) soil water potential ranged between –1000 and –1500 kPa. This occurred during the critical physiological period of wheat growth – flowering and grain filling. Even though the wilting plants recovered after the rainfall in the second week of October, the final grain yield was reduced by 50% compared with the yield in non-saline soils in the district (Cooper 2004).

In saline soils influenced by saline groundwater, commonly found in Western Australia, salt concentrations are high in topsoils in the beginning of the sowing season Similar situation occurs in 'magnesia patches' found in South Australia. High concentrations of salt combined with low rainfall in the start of the season severely affect the germination of seeds. As the season progresses and with normal rainfall, salt concentration may decrease and germinated plants can survive. However, in Western Australia, there is a probability of increasing soil

Table 4. 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 $EC_{1:5}$ (dS m^{-1})	Gravimetric field soil moisture (%) below which osmotic pressure due to salinity is >1000 kPa	>1500 kPa	Percentage of available soil water not taken up by plants due to osmotic pressure (>1000 kPa) of soil water salinity: 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

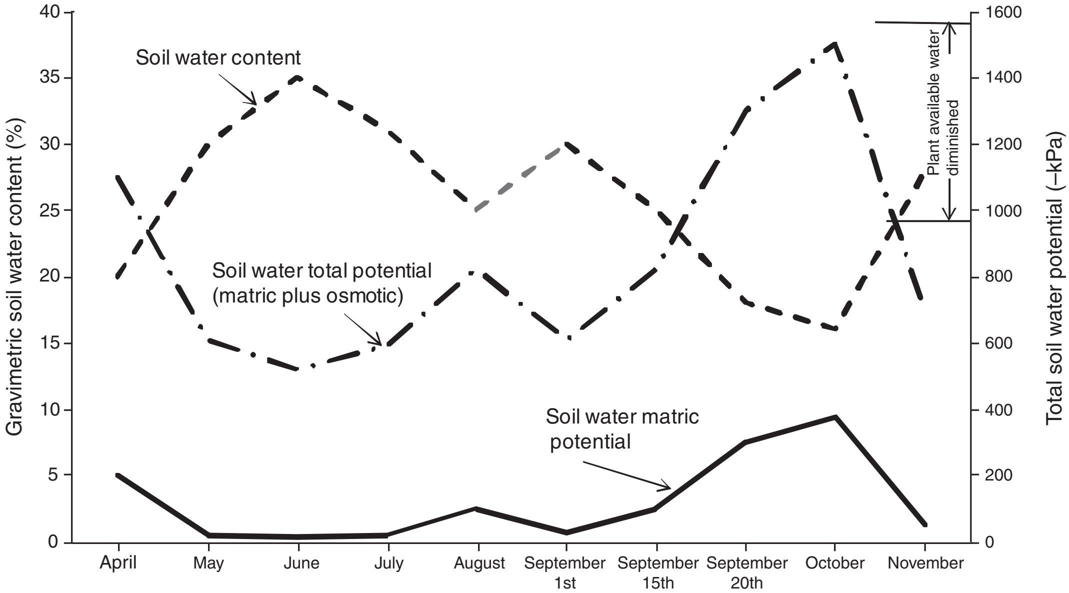

Fig. 3. Gravimetric soil water content (%), matric potential of soil water (–kPa) and total (matric and osmotic) soil water potential (–kPa) of a clay loam layer (20–60 cm) in a Natrixeralf with an ($EC_{1:5}$ of 1 dS m^{-1}) during wheat growing season in 2003.

salinity at the end of the season, when rainfall may be scanty (T. Setter, pers. comm.).

Thus, changes in salt concentration (and, hence, osmotic pressure) with the changes in soil water content during the growing season, as influenced by seasonal rainfall and temperature, have implications on screening and selection of salt tolerant crops. First, the salt tolerance criteria developed using hydroponics or lysimeter may not be valid under field conditions, particularly under dryland cropping. Second, the tolerance mechanism also may change during the growing season, ionic effect being valid at high soil water contents and osmotic effect gaining prominence at low soil water contents. Third, salt tolerance for germination should be considered as a screening method in the selection of varieties suitable for soils affected by high salinity in topsoils at the beginning of the season as experienced in magnesia patches or soils affected by rising watertable.

Seasonal changes in transient salinity

Transient salinity in soils, characterised by a high concentration of salts in the subsoil, varies with depth and changes throughout 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 soil samples in southern Australian dry land 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. 4. Seasonal changes in rainfall pattern and evaporation are important factors in the accumulation of salts in soil layers. Transient salinity is greater in regions with lower rainfall. It is also greater in soils with higher levels of sodicity. Transient salinity generally occurs in soil layers above the sodic clay layers in sodic soils (Rengasamy 2002*a*).

Other soil processes in relation to crop production in salt-affected soils

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, that are being adopted by farmers. In dry land 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 gain in yield being low compared with 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 several subsoil factors, in addition to salinity, such as physical, chemical and biological constraints (Rengasamy *et al*. 2003). Recently, Tavakkoli *et al.* (2010) found that the effects of salinity on two barley varieties Clipper and Sahara differed between the hydroponic and soil systems at comparable salinity levels. Genetic differences in growth, tissue moisture content and ionic composition were not apparent in hydroponics, whereas significant differences occurred in experiments using soil.

It is important, as a part of soil management to alleviate salinity, that salts are leached below the root zone. In the case of soil categories, 'sodic', 'acidic–sodic' and 'alkaline–sodic', poor soil structure and physical properties hinder the leaching process. Even in 'saline–sodic' soils, when the salts are leached below a 'threshold' level, soil structure deteriorates and leaching is minimised (Rengasamy and Olsson 1991). Gypsum application to these soils improves the soil structure facilitating leaching of salts, even under dry land conditions. Table 5 shows the leaching of salts by gypsum application (5 t ha^{-1}) in 2003 to a sodic duplex soil in South Australia with an annual rainfall ~400 mm (Kelly and Rengasamy 2006).

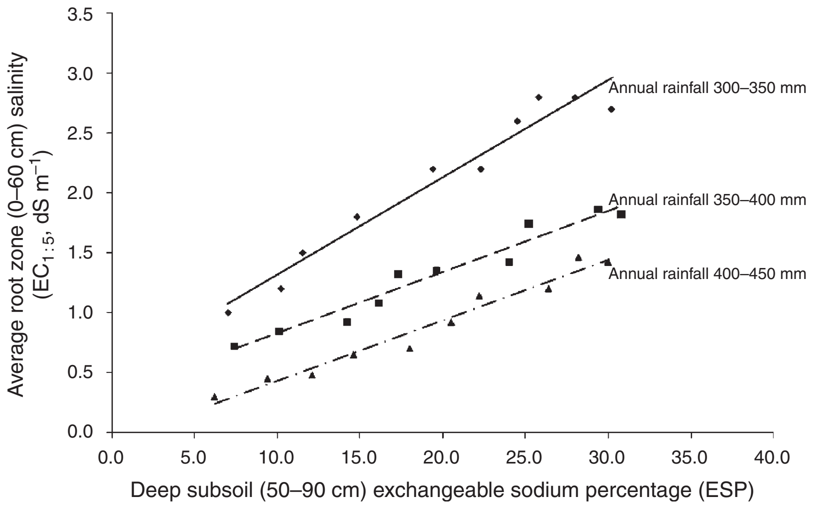

Fig. 4. Salt accumulation (average root zone salinity) in relation to sodicity (ESP) of subsoils and average annual rainfall in southern Australian dry land regions.

Table 5. Movement of salts in plots with gypsum applied compared with no gypsum

Concentrations of calcium and sodium in different soil depths (and EC due to NaCl) in gypsum applied plots are lower compared with no gypsum soils, indicating salt leaching facilitated by gypsum improving soil structure. The results are average of four replicates. Gypsum was applied at 5 t ha^{-1} in 2003 and the following analysis was done on samples collected in 2006

Soil depth (cm)	Gypsum not applied			Gypsum applied (5 t ha^{-1})		
	Ca^{2+} (mg L^{-1})	Na^{+} (mg L^{-1})	EC due to NaCl (dS m^{-1})	Ca^{2+} (mg L^{-1})	Na^{+} (mg L^{-1})	EC due to NaCl (dS m^{-1})
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

In irrigation regions, the quantity of water applied should include leaching requirements. In dry land cropping areas 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 areas affected by transient salinity where the watertable is deep, species with high transpiration can concentrate more salt in the root zone and hinder their production as well as other plants. In saline areas where the watertable is shallow (~2 m), the same species may help in deepening the groundwater levels (Rengasamy *et al.* 2003). However, the increasing accumulation of salts will decrease plant leaf area indices and their transpiration rates. Thus, soil processes specific to each types of salinity dictate the strategies for plant-based solutions to different forms of salinity.

Although sodicity is a major problem in salt affected soils, several soils have multiple problems in different layers in their soil profiles (Rengasamy *et al*. 2003). For example, the topsoil can be alkaline–sodic while the subsoil is saline–sodic. When a salt-tolerant 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), salt tolerance character of the wheat variety being not utilised. Variations in soil characteristics in topsoil versus subsoil, such as acidic–sodic, neutral alkaline–sodic, sodic–saline and alkaline sodic–acidic, have been commonly found in southern Australia.

In alkaline–saline soils, alkaline saline–sodic soils and alkaline–sodic soils, the dominance of bicarbonate and carbonate species induces toxicity effects on plants. Although additional osmotic effect may be prevalent in alkaline–saline soils, the soil structural problem may induce water logging in alkaline–sodic soils. Because of increased solubilities due to changes in pH and pE ($-\log[e^-]$) associated with waterlogged soils, element toxicities during water logging include Mn, Fe, Na, Al and B (Setter *et al*. 2004). Sposito (1989) has detailed the different ionic species of these elements in relation to proton and electron concentrations in waterlogged or flooded soils. With alkaline–sodicity being prevalent in subsoils in Australia, water saturation of poorly structured subsoils (i.e. water logging) provides toxic amounts of these elements in the root zone environment. Further, alkaline pH induces severe soil structural problems than neutral sodic soils at comparable sodicity (SAR) levels. Our preliminary investigations show also that chemistry of aluminium and carbonates in soils is completely different when the soil pH is above 9.5 compared with pH between 8.2 and 9.5.

Future research

In salinity research, it is common to assume the salt is NaCl. However, the salt-affected soils may contain other types of salts such as carbonates and sulfates and salts of Ca, Mg and K. Further research is needed to assess how these different types of salts influence soil structure and, hence, salt accumulation or leaching. This is important to improve productivity in irrigated crops, particularly with the increasing use of recycled water for irrigation. 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 and the field soil water content changes with seasonal weather conditions. Thus, it is essential to develop new guidelines on salt tolerance of plant species taking into account soil water dynamics. There is also 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, in addition to salinity of soil layers.

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