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World salinization with emphasis on Australia

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Abstract

Salinization is the accumulation of water-soluble salts in the soil solum or regolith to a level that impacts on agricultural production, environmental health, and economic welfare. Salt-affected soils occur in more than 100 countries of the world with a variety of extents, nature, and properties. No climatic zone in the world is free from salinization, although the general perception is focused on arid and semi-arid regions. Salinization is a complex process involving the movement of salts and water in soils during seasonal cycles and interactions with groundwater. While rainfall, aeolian deposits, mineral weathering, and stored salts are the sources of salts, surface and groundwaters can redistribute the accumulated salts and may also provide additional sources. Sodium salts dominate in many saline soils of the world, but salts of other cations such as calcium, magnesium, and iron are also found in specific locations. Different types of salinization with a prevalence of sodium salts affect about 30% of the land area in Australia. While more attention is given to groundwater-associated salinity and irrigation salinity, which affects about 16% of the agricultural area, recent investigations suggest that 67% of the agricultural area has a potential for 'transient salinity', a type of non-groundwater-associated salinity. Agricultural soils in Australia, being predominantly sodic, accumulate salts under seasonal fluctuations and have multiple subsoil constraints such as alkalinity, acidity, sodicity, and toxic ions. This paper examines soil processes that dictate the exact edaphic environment upon which root functions depend and can help in research on plant improvement.

Key words: Dry-land salinity, irrigation salinity, salinity in Australia, soil processes affecting salinity effects, transient salinity, world salinization.

Introduction

Global food production will need to increase by 38% by 2025 and by 57% by 2050 (Wild, 2003) if food supply to the growing world population is to be maintained at current levels. Most of the suitable land has been cultivated and expansion into new areas to increase food production is rarely possible or desirable. The aim, therefore, should be an increase in yield per unit of land rather than in the area cultivated. More efforts are needed to improve productivity as more lands are becoming degraded. It is estimated that about 15% of the total land area of the world has been degraded by soil erosion and physical and chemical degradation, including soil salinization (Wild, 2003).

Salinization is the accumulation of water-soluble salts in the soil solum (the upper part of a soil profile, including the A and B horizons) or regolith (the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported) to a level that impacts on agricultural production, environmental health, and economic welfare. A soil is considered saline if the electrical conductivity of its saturation extract (EC_e) is above 4 dS m^{-1} (US Salinity Laboratory Staff, 1954). However, the threshold value above which deleterious effects occur can vary depending on several factors including plant type, soil-water regime and climatic condition (Maas, 1986). For example, in rainfed agriculture, soil water can be far below field capacity and the salt concentration under field conditions is several-fold higher than measured at soil saturation water content (Rengasamy, 2002). Saline soil water inhibits plant growth by an osmotic effect, which reduces the ability of the plant to take up water and by ion-excess, which affects the plant cells (Munns, 2002; see also Table 1 in Munns, 2005). Soil salinity also induces nutritional imbalances in plants. When salinity is due to sodium salts, it can lead to the formation of sodic soils when salts are leached from the soil profile. Many salt-affected soils are also waterlogged, at least at times, and the

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Table 1. *Global distribution of saline and sodic soils (Szabolcs, 1989)*

Continent	Area (million hectares)		
	Saline	Sodic	Total
North America	6.2	9.6	15.8
Central America	2.0	–	2.0
South America	69.4	59.6	129.0
Africa	53.5	27.0	80.5
South Asia	83.3	1.8	85.1
North and Central Asia	91.6	120.1	211.7
Southeast Asia	20.0	–	20.0
Europe	7.8	22.9	30.7
Australasia	17.4	340.0	357.4
Total	351.5	581.0	932.2

interaction between hypoxia and salt has a powerful depressive effect on plant growth (Barrett-Lennard, 2003).

Salinization of land has threatened civilizations in ancient and modern times. Soil salinization in southern Mesopotamia and in several parts of the Tigris–Euphrates valley destroyed the ancient societies that had successfully thrived for several centuries (Jacobsen and Adams, 1958; Hillel, 2005). In modern times, salt-affected soils are naturally present in more than 100 countries of the world where many regions are also affected by irrigation-induced salinization. Recently, dry-land salinity has become a major issue in natural resource management in Australia and has attracted increasing awareness from both farmers and politicians.

Extent of world salinization

Szabolcs (1989) described the global distribution of saline and sodic soils in different continents (Table 1) based on the FAO/UNESCO soil map of the world and many other maps, data, and material available at that time. According to a more recent report published by FAO in 2000, the total global area of salt-affected soils including saline and sodic soils was 831 million hectares (Martinez-Beltran and Manzur, 2005), extending over all the continents including Africa, Asia, Australasia, and the Americas. The exact location and distribution of salt-affected soils have been studied in varying degrees of detail. Different systems of classification and grouping are employed in individual countries. In addition, the maps have not been prepared on a uniform scale. It should be noted that the threshold electrical conductivity (EC) and exchangeable sodium percentage (ESP) values are not the same in different classification systems, particularly in the Australian classification. For example, while the US system defines sodic soils as those having natric horizons with an ESP greater than 15 (Soil Survey Staff, 1990), Northcote and Skene (1972), in mapping the Australian soils with saline and sodic properties, defined sodic soils as those having an ESP between 6 and 14 and strongly sodic soils as those having an ESP of 15 or more. The recent Australian soil classification (Isbell, 1998) defines 'sodosols' (sodic soils) as soils with an ESP greater than 6 and at the same time, soils with ESP 25–30 are excluded from sodosols, because of their very different land-use properties. Sumner *et al.* (1998) have reviewed the effects of different soil components on the effects of ESP on soil behaviour and advocated the development of a classification system based on soil behaviour rather than on arbitrary threshold ESP criteria. Here the term 'salinity' is used to describe salt-affected soils, which may include sodic soils (as defined by Isbell, 1998); a distinction is not drawn between saline and sodic soils as in Ghassemi *et al.* (1995).

All soils contain some soluble salts, but when soil and environmental conditions allow the concentration in soil layers to rise above a level that impacts on agricultural production, environmental health, and economic welfare, then soil salinity becomes an issue of land degradation. Even though the general assumption is that saline soils occur under arid and semi-arid climates, these soils are found in various climatic zones. For example, 4.5 million hectares of dry-land cropping are affected by salinity in the Canadian prairies (Wiebe *et al.*, 2005). Similarly, all soil types with diverse morphological, physical, chemical, and biological properties may be affected by salt accumulation. Although NaCl is the dominant salt in many saline soils, the occurrence of soluble compounds of calcium, magnesium, potassium, iron, boron, sulphate, carbonate, and bicarbonate have been reported (Szabolcs, 1989). It has to be noted that the presence of gypsum does not affect plant production osmotically because of its limited solubility.

Processes of soil salinization

The dominant sources of salt are rainfall and rock weathering. Rainwater contains low amounts of salt, but over time, salt deposited by rain can accumulate in the landscape. Wind-transported (aeolian) materials from soil or lake surfaces are another source of salt. Poor quality irrigation water also contributes to salt accumulation in irrigated soils. Seawater intrusion onto land, as occurred in recent tsunami-affected regions, can deposit huge amounts 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 salt is likely to accumulate in the landscape.

There are three major types of salinity (Fig. 1) based on soil and groundwater processes found all over the world and these are different from the normal classification of 'Primary' or 'Secondary' salinity or saline and sodic soils as defined by Ghassemi *et al.* (1995).

(i) 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

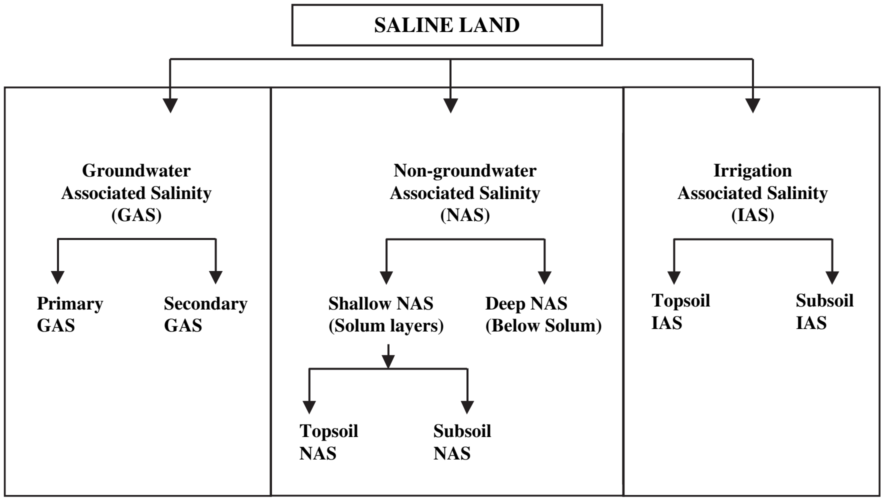

Fig. 1. Major types of salinity in world soils based on salinization processes.

force for upward movement of water and salts is evaporation from the soil plus plant transpiration. Generally, the water table 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 water table is less than 1.5 m below the soil surface (Talsma, 1963). However, this threshold depth may vary depending on soil hydraulic properties and climatic conditions.

(ii) Non-groundwater-associated salinity (NAS). In landscapes where the water table 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 the 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.

(iii) 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.

Salinity in Australian landscapes

Government agencies and the community in Australia are concerned about the impact of salinity on the value of land and water resources. The major attention for salinity in Australia is on irrigation-induced salinity in the Murray Darling Basin and dry-land salinity associated with shallow groundwater, particularly in Western Australia. Rengasamy (2002) has reviewed this topic in detail, particularly referring to sodic soils in the Australian landscape. The following brief account of dry-land salinity in Australia will also explain the common features found in many landscapes in the world.

Groundwater-associated salinity (also commonly known as '*s*eepage 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 water table. 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 was often very high, ranging from EC (electrical conductivity) 15–150 dS m^{-1}. As long as the water table was 4 m below the surface, saline groundwater did 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 (Hatton *et al*., 2003). 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 National Land and Water Resources Audit (2001) estimates that approximately 5.7×10^4 km^2 of Australia's agricultural and pastoral zone have a high potential for developing salinity through shallow water tables. The report also warns that unless effective solutions are implemented, the area could increase to 17×10^4 km^2 by 2050 (for comparison, the area of the UK is about 24×10^4 km^2). This form of salinity affects around 350×10^4 km^2 in the world (Szabolcs, 1989).

Over many thousands of years, salt has been accumulating in the soil solum delivered by wind and rain. The total salinity and the composition of many saline groundwater samples in Australia are similar to seawater. Studies on the stable isotopic composition of saline groundwater (Herczeg *et al*., 2001) indicate that the source of salinity in the Australian continent is mainly through rainfall. The groundwater chemistry is a combination of atmospheric input of marine- and continentally-derived salts and removal of water by evapo-transpiration over tens of thousands of years of relative aridity (Herczeg *et al*., 2001). During salt flow through soil layers, chemical reactions such as cation and anion exchange, complex formation, precipitation and dissolution involving different ionic species have resulted in the composition of groundwater being similar to seawater.

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 4–10 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^{-1}). 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-magnetics (Lawrie, 2005) have confirmed the occurrence of salt bulges in deeper soil layers in many landscapes in Australia.

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, a country whose agricultural area is about 7.6×10^6 km^2, sodic soils that have a potential for transient salinity and other root-zone constraints such as alkalinity, acidity, and toxicity due to boron, carbonate, and aluminium occupy 2.5×10^6 km^2. Whereas 16% of the cropping area is likely to be affected by water table-induced salinity, 67% of the area is subject to transient salinity and other root-zone constraints, costing the farming economy about Aus$1330 million per annum, in lost opportunity (Rengasamy, 2002). Figure 3 illustrates the different forms of dry-land salinity found in the Australian landscape. The problem of transient salinity is not, however, confined to Australia. About 5.8×10^6 km^2 of soils around the world are sodic (Bui *et al*., 1998) and have the potential for transient salinity. Perhaps the large areas once thought to be at risk from rising water tables have to be reconsidered as a result of climate change-induced changes in groundwater levels.

Irrigation in Australia has been developed over a wide range of climatic zones including the Mediterranean, tropical and subtropical climates and uses 10.2 million mega litres of water annually on 1.84 million ha (Rengasamy and Olsson, 1993). The major irrigation developments have occurred on the Murray River and its tributaries. The quality of water from river sources used for irrigation is usually good with a very low salt content (EC 0.1–0.6 dS m^{-1}). However, discharge of effluents and drainage waters into the river has increased the salinity of the river water in South Australian sections, particularly during summer and low flow situations. Most of the irrigated soils are sodic, with low hydraulic conductivity increasing the probability of salt build-up over time. Furthermore, because of the flat landscape in irrigation areas, recharge of water has led to an increase in water-table levels in recent years and groundwater salinity is generally high, ranging between 4 and 150 dS m^{-1}. Lack of drainage schemes to avert a shallow water table has led to salinity under irrigation. The efforts to pump the saline groundwater to reduce water-table levels and the reuse of it for irrigation have resulted in salinization of the soil layers and, where leaching is sufficient, the soils are becoming sodic. Recent trends in using industrial effluents (with high pH and salinity) and recycled water for irrigation (Radcliffe, 2004) also promotes soil salinization and sodification. The long-term future of irrigated agriculture in Australia depends on maintaining the salt balance through drainage and irrigation methods, soil management, and the choice of suitable plant species and varieties.

Soil processes affecting salinity effects on plants

In dry-land cropping, fresh water stored in the subsoil is critical for crop production. Although the salt concentration in soils with transient salinity may not be as high as that in

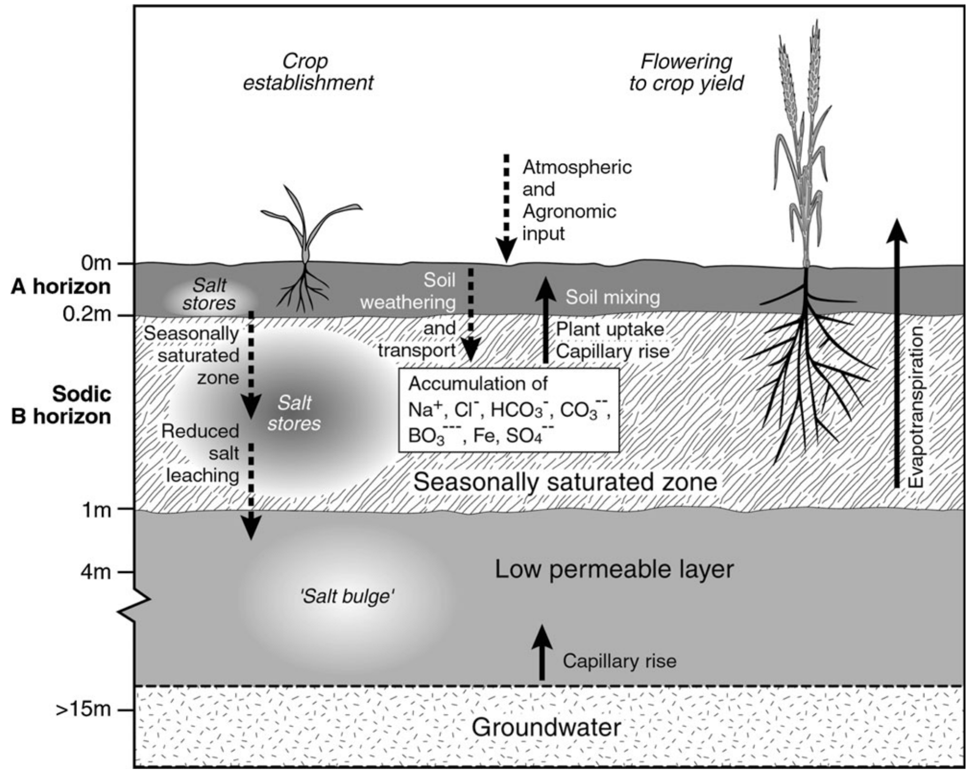

Fig. 2. Soil processes and accumulation of salt in root zone layers of sodic soils (after Rengasamy, 2002 and reproduced by kind permission of CSIRO Publishing).

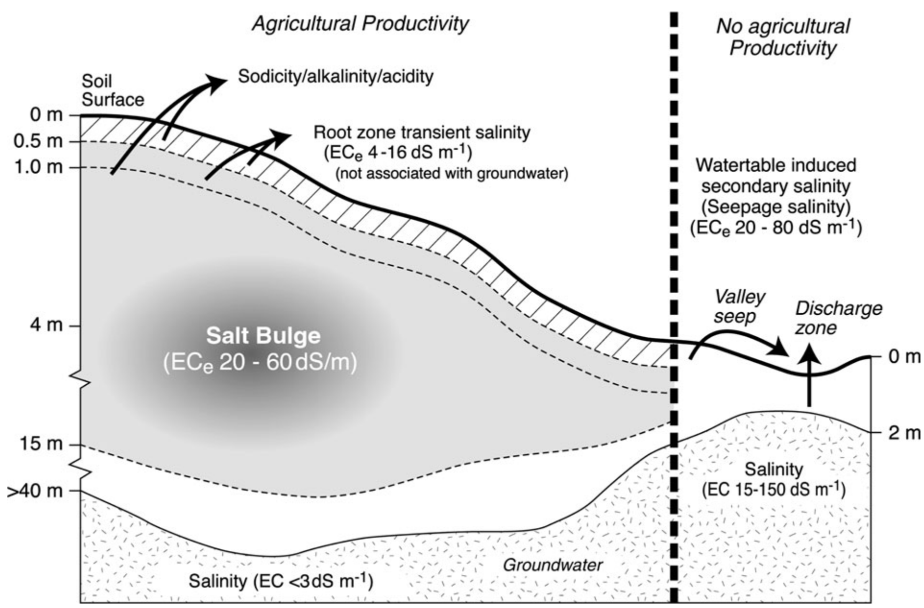

Fig. 3. Different types of salinity in Australian landscapes (after Rengasamy, 2002 and reproduced by kind permission of CSIRO Publishing).

soils affected by seepage salinity, subsoil salinity usually ranges between EC_e (electrical conductivity of the soil saturation extract) of 4 and 16 dS m^{-1}. This amount of salinity can cause an increasing osmotic effect as the soil layer dries due to evapotranspiration. Low osmotic potentials resulting from soil salinity can restrain water uptake by plants and reduces their ability to survive and produce. Under dry-land conditions, concomitant changes in matric and osmotic potentials determine plant water uptake (Rengasamy, 2002). The influence of soil texture and type of clay on plant-available water compounds the effect of matric and osmotic potentials. Figure 4 (data from Rengasamy *et al.*, 2003) illustrates the energy input (equivalent to soil matric plus osmotic potential) needed by plants to remove water as the soil moisture and salinity levels change in a sandy loam 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 salinity measured in the laboratory as $EC_{1:5}$ (1:5 soil:water extract) is 0.64 dS m^{-1}, they can get water only up to 14% water content. When the measured salinity increases to 1 dS m^{-1}, plants cease to take up water at 18% water content.

In areas affected by transient salinity where the water table 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 water table 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 Australia, a number of soils have multiple problems in different layers of their soil profile (Rengasamy, 2002). 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 saline-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 Australia. Multiple problems can arise when the salts accumulated contain borates and carbonates in toxic amounts, as found in extensive areas of Australia with alkaline subsoil pH (Rengasamy, 2002) and also in the Indian subcontinent (Gupta and Abrol, 1990) and other parts of the world (Shainberg and Letey, 1984).

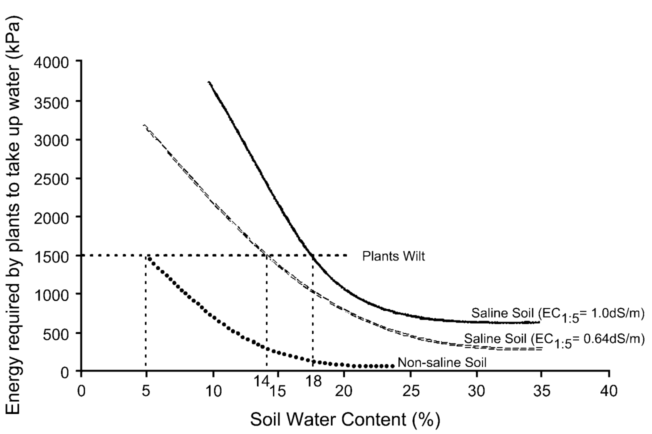

Fig. 4. Energy (equivalent to soil matric plus osmotic potential) required by plants to take up water from a loamy soil as influenced by $EC_{1:5}$ and % soil water content.

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 the effects of these factors will need to be overcome for developing varieties adapted to the 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 idealized conditions. Successful development of boron-resistant wheat varieties in Australia has been achieved through attention to soil-based problems (Rathjen *et al.*, 1999). A co-operative effort by a team of scientists from the different disciplines of soil science, hydrology, agronomy, plant physiology, and plant breeding including genetic engineering, is necessary to combat the problem of world salinization.

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