Australian Government
Land & Water Australia

What to plant where: effectively positioning plants in saline/waterlogged landscapes

SGSL Pasture Theme Final Report

Land and Water Australia Project: UWA30

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CRC FOR PLANT~BASED MANAGEMENT OF DRYLAND SALINITY

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Section 1: Executive Summary

> 'The final aim of the pasture theme is to be able to diagnose the capability of saltland sites with data that that can be collected from only one or two visits to a site. Plant species and management practices can then be recommended for the site that will realise its potential capability and thus maximise the production potential of the site.'

Progress on the theme started with a very successful workshop in April where the original 12 questions were prioritised into four main questions; matching plants to sites; plant performance and site conditions; survival and grazing; and husbandry. These questions will be answered in a review on the ecology of saltland and in further subsequent publications.

The salinity/ waterlogging matrix developed by Ed Barrett-Lennard in his book 'Saltland Pastures in Australia: A Practical Guide' has been widely adopted but requires further quantification. The aim of the Pasture Theme is to provide the required quantification. Initially this was to be through a review on the ecology of saltine landscapes. This uses saltland marshes and inland salt lakes as examples to be followed in the zonation of saltland pastures, discusses the development of the salinity/ waterlogging matrix and a land capability assessment and finishes with a discussion on the important issues concerning germination, plant performance and survival, and animal husbandry. However, the review has grown such that it is now likely to be split into three separate publications; a) the ecology of saline landscapes; b) a practical land capability assessment, that includes the salinity/ waterlogging matrix; and, c) a publication on the agricultural issues influencing successful saltland pastures: germination, establishment, production, survival under grazing and animal husbandry.

The practical land capability assessment paper is the most advanced and will be completed in January 2007. This paper discusses some fundamental questions that need to be answered on a per paddock basis before successful saltland pastures can be established and maintained. These are;

1. Can the plant drink the groundwater – salt tolerance of pasture plants and shrubs
2. Can the plant get oxygen to its roots – depth to watertable and soil characteristics
3. If the plant can't drink the groundwater then what other water is available – depth to watertable, perched watertable, rainfall etc.

The conclusions to arise from the publication are that plant species sown together will separate themselves into 'preferred' locations within the landscape in relation to their tolerance to salinity and/ or waterlogging and their competitive ability with other sown species. There is a need for this hypothesis to be tested both in the field with two to three season transplant trials and under controlled conditions with pots of known and varying levels of salinity and waterlogging. Also, simple practical methods are required to determine seasonally average levels of salinity and waterlogging in combination with soil texture and depth to watertable that match plants to sites.

Data obtained from both the SGSL Research Sites and SGSL Producer Network Sites will be used to quantify the questions posed in the conclusion of the review. Data from the Producer Network Database is currently being queried and explored. Early results suggest that there will be some useful data on watertable depths, salinity levels and associated species that can be combined using multivariate analysis to determine different species positions in the matrix. Data from the Research Sites will be used to more rigorously test some of the results of the multivariate analysis using further multivariate and multi-site statistical methods.

Section 2: Theme Assessment

Milestone 2:

1. Final Report
2. Review on Ecology of Saltland Pastures

Achievement Criteria:

Acceptance of Final Report by Land and Water Australia

Extent to which project met its objectives:

1. *Prioritisation of Theme Questions*

   These were prioritised at the Pasture Theme workshop which was report in the Milestone 1 report in April 2006. The final agreed prioritised Theme Questions were;

   - Matching plants to sites (establishment, minimum datasets, indicator species, etc.)
   - Plant performance and site conditions
   - Survival and grazing
   - *Husbandry (spanning across the above three questions).*

2. *Completion of Review on Ecology of Saltland Pastures*

   Although the review has been in progress for the last nine months, we have recently questioned the flow of the material within it and whether it would be better to split it into two or three separate publications. A copy of the original review is given in Appendix 1. The original review includes; a) introductory material on the ecology of saline landscapes including saltland marshes, inland salt lakes and agricultural saltland pastures; b) the salinity/ waterlogging matrix, and a discussion on measurements of salinity and waterlogging and their interaction; and, c) agricultural factors affecting the success of saltland pastures, including plant germination, establishment, performance, survival under grazing and animal husbandry. The middle section of the initial review is the most advanced as a separate publication and it will be completed during January 2007. This publication is titled 'From principles to practicalities – diagnosing the capability of land affected by salinity and waterlogging'. A copy is provided in Appendix 2. This will be submitted to either the Australian Journal of Experimental Agriculture or to the International Salinity Forum as a Journal Paper. The abstract is given below.

Abstract

This review considers the issue of targeting plants to saline landscapes. A range of recent research has shown that saltland varies in its ability to support plant growth: economic gain is achieved by focusing revegetation into areas of highest capability. The review focuses on two factors that affect capability – salinity and waterlogging. Both salinity and waterlogging are

highly temporally and spatially variable. Plant ecological zonation on saltland is a reflection of the ability of plants to integrate and adapt to this variation.

The review has three parts:

1. We summarise the current means by which salinity and waterlogging are measured in Australia.
2. We summarise how salinity and waterlogging affect the "competitive advantage" of plants on saltland in southern Australia.
3. We suggest three criteria by which saltland may be broadly categorised in terms of its capability for economic production. These are: (a) can a plant use the groundwater for growth, (b) is the soil water above the water-table suitable for use, and (c) is oxygen available for root-growth and function.

We conclude that broad land capability assessments may be possible by considering the distribution of rainfall, and by examining the depth, salinity and pH of the groundwater, the soil texture above the water-table and the bulk salinity of the soil as determined by electromagnetic induction using the EM38.

3. *Querying Producer Network Database for answers to Theme questions*

The Producer Network Database holds information such as watertable depth, soil salinity, species composition and soil texture for a number of sites across southern Australia. Sites are labelled by landholder and by state. At many sites, transects were taken, along which species composition, soil salinity and soil texture was determined. On each site there are also at least two observation bores, from which soil salinity and watertable depth measurements were taken. Northings and eastings are given for the exact location of transects and observation bores.

To find relationships between the above listed variables and plant zonation, information from the database is being collated into excel spreadsheets. Species composition along each transect (of which there are at least two on each site) can be related to soil salinity (EM38) and soils texture. Watertable depth and water salinity will be estimated from values obtained at the bores and the provided snapshot data.

Snapshot data was collected directly around each bore and includes species composition, watertable depth, water pH, water salinity and soil salinity was collected. Using the Snapshot data, drivers of ecological zonation, such as watertable depth, soil salinity and soil texture will be related to species composition. Snapshot data are available for only 49 of the Producer Network Sites.

4. *Querying Research Site Database for answers to Theme questions*

This component of the project has yet to commence in detail as we have had to wait for data from the sites to be entered into the database. Final reports have now been received from all the sites. The main sites to be used for the pasture theme will be WA2, SA and Victoria for cross-site analysis. Analytical methods to be employed include spatial analysis, ANOVA, multivariate analysis and AMMI. To supplement the datasets, where required, geospatial analysis will be used to generate site-wide estimate maps of salinity and waterlogging across the seasons and years of the SGSL project.

5. Scientific publications

- Review on ecology of saltland pastures.
- Discussion paper on diagnosing saltland capability
- Use of Producer Network Site data to validate the salinity/ waterlogging/ soil texture matrix. An abstract will be submitted to the International Salinity Conference in February 2007 for a forum paper.
- Cross-site analysis of SGSL Research sites. An abstract will be submitted to the International Salinity Conference in February 2007 for a journal paper.

Human resource issues:

Megan Ryan has been on maternity leave from January 2006 until February 2007.

Sarita Bennett has been on maternity leave from August 2006 to end November 2006.

A casual research scientist (Sommer Jenkins) was appointed at the beginning of October to assist Sarita Bennett in obtaining queries from the Producer Network and Research Site Databases.

Section 3: Acknowledgements

Thanks for Sommer Jenkins for on-going work on the Producer Network Database.

Section 4: Appendices

Appendix 1. Plant ecological zonation and productivity in saltland pastures: a review.

Appendix 2. From principles to practicalities – diagnosing the capability of land affected by salinity and waterlogging.

Appendix 1

Plant ecological zonation and productivity in saltland pastures: a review

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Introduction

Saline landscapes have large variations in soils and hydrology, and occur in diverse climatic regions. Saline soils are found in arid deserts, near inland and coastal marshes, and in areas affected by rising water-tables (see Barrett-Lennard 1986; Ghassemi *et al.* 1995), and occupy about 7% of the world's land area (Dudal and Purnell 1986). Although all continents in the world have some inland agricultural areas with increasing salinisation, Australia has the largest overall area (Rengasamy 2006) caused by clearance of the native perennial vegetation and though irrigation which has changed the equilibrium of the watertable (Hatton *et al.* 2003). Clearance, irrigation and the introduction of annual pastures and crops have resulted in an increase in the amount of recharge through reduced evapotranspiration compared with natural systems (Hatton and Nulsen 1999). As groundwaters rise, salts in the soil profile are brought to the surface in the discharge zones of the landscape (Rengasamy 2006). Our interest in the ecology of saltland arises primarily as a response to Australia's developing problem of dryland salinity; 5.66 Mha are regarded as being at high risk of salinity now and the area at risk is expected to increase to ~17 Mha by the year 2050 (National Land and Water Resources Audit, 2001). Western Australia has the greatest area of land affected by secondary salinity, with 1.0-1.2 Mha currently severely salinised and 2.8 to 4.4 Mha land with a high risk of developing secondary salinity (Anon. 2003). In addition to dryland salinity movement of sodium through the soil profiles has resulted in over 60% of soils in the agricultural areas of Australia becoming sodic (Rengasamy 2006). Sodic subsoils restrict the leaching of salts and prevent the transmission of water through the profile which has led to the accumulation of salts in the subsoils (root zone layers) in amounts which are detrimental to plant roots (Rengasamy 2002). In the dryland cropping areas of southern Australia water stored in the subsoil is critical for crop production. ECe ranges of 4 to 16 dS/m are common in subsoil salinity, and although not high, are sufficient to cause an increasing osmotic effect as the soil dries due to evapotranspiration. A reduction in water uptake by plants through low osmotic potential from subsoil salinity causes a reduction in their ability to survive and produce (Rengasamy 2002).

Primary salinity exists where soils are salt-affected as a result of the natural long-term accumulation of salts, for example the gradual accumulation of products of weathering, or due to the one-time submergence of the soil under the sea (Ghassemi *et al.* 1995). It is part of the Australian landscape, reflecting the development of the landscape over time. Salt deposition is mainly oceanic salt carried inland from wind and rain. In a healthy catchment salt is leached slowly downward and stored below the root zone of the native vegetation. Secondary salinity is caused by the mobilization of stored salt in the soil profile by extra water – either through irrigation or land clearance. The extra water raises the watertable or increases the water stored in confined aquifers bringing water close to the soil surface. Evaporation of this water leaves salts behind and results in the salinisation of the landscape (Ghassemi *et al.* 1995).

Soils subject to salinity are also often constrained by waterlogging because of shallow watertables or reduced infiltration of surface water due to soil sodicity (Barrett-Lennard 2003; Barrett-Lennard *et al.* 2003) and therefore there is a need to breed not only for tolerant to saline soils, but also to waterlogging tolerance. Setter and Waters (2003) found large genetic diversity for waterlogging tolerance at the seedling stage in most temperate cereals. Cereals have been bred to a narrow genetic base, and it can therefore be assumed that breeding for salt and waterlogging tolerance in saltland pasture species would benefit from very high genetic diversity for waterlogging tolerance, assuming that it is under similar genetic control to cereals.

The review can be broken down into three main sections; the main ecological drivers of saline landscapes – salinity, waterlogging and inundation, with particular reference to ecological zonation in natural salt marshes and agricultural landscapes; the salinity/ waterlogging matrix for agricultural pasture species, and its importance in relations to plant germination, establishment, performance and nutritive value; and a land capability assessment that combines all the above factors and provides a practical method of quantifying the state of the soil for productive saltland pastures.

Salinity, waterlogging and inundation as key ecological drivers of vegetation in saline areas

Saline landscapes differ from other environments in that; a) they are variously subjected to the stresses of salinity, waterlogging and/or inundation, and b) their ecological and agricultural potential (i.e. their capability) depends on the severity of these factors (Barrett-Lennard *et al.* 2003).

Each of these stresses has the capacity to compromise plant growth and survival. Their interaction therefore, creates a range of niches for highly specialised plants, leading to clear ecological zonation depending on each species' tolerance and adaptation to waterlogging, salinity, inundation and the interactions between these stresses. Salinity decreases the availability of water to plants ("osmotic effect") and has direct adverse effects on metabolism through "specific ion" effects (Greenway and Munns 1980). Waterlogging decreases the availability of oxygen to roots due to the rapid consumption of soil oxygen by roots and micro-organisms, the low solubility of oxygen in water and the low diffusivity of oxygen in water-filled pores (Armstrong 1979). Poor aeration causes roots to suffer energy deficiency as adenosine triphosphate (ATP) production is reduced (Gibbs and Greenway 2003). Air-filled porosity of soils is generally considered to be limiting when it is 10% or less (Setter and Waters 2003). For each 1% decrease in air-filled porosity of surface soil below this threshold, average wheat yields have been reported to be decreased by 0.29 t/ha (McDonald and Gardner 1987). For most species waterlogging under saline conditions impairs sodium and/or chloride exclusion. For example, averaged over 24 plant species, waterlogging (hypoxia) caused a 228% increase in sodium concentrations and a 135% increase in chloride concentrations in sampled shoot tissues (Barrett-Lennard 2003). In turn, the increased salt uptake to the shoots impairs plant growth and survival (Barrett-Lennard 1986; Barrett-Lennard *et al.* 2003). Inundation covers shoots with water, decreasing gaseous exchange between leaves and the atmosphere (Voesenek *et al.* 2006).

Ecological zonations of plants due to salinity and waterlogging are well documented in salt marshes. For example;

a) on a semiarid Mediterranean salt marsh in south-east Spain Alvarez Rogel, Ortiz Silla and Alcaraz Ariza (2001) reported that two chenopod shrubs *Arthrocnemum macrostachyum* and *Sarcocornia fruticosa* dominated in the most saline areas, another chenopod, *Limonium cossonianum*, occupied an intermediate zone in respect to salinity and *Suaeda vera*, a shrubby chenopod that does not persist below the high spring tide mark, occupied the top of the slope;

b) on an mediterranean-climate estuarine wetland in California, Callaway et al. (1990) studied the seasonal variation in salinity at four different vegetation zones ranging from the low marsh zone with high salinity all year, to the hypersaline salt flat zone, to the transition zone with hypersalinity in summer and low salinity in winter, and to the non-flooded grassland with low levels of salinity all year. Winter annuals dominated in the transition zone as they are able to survive the dry, hypersaline conditions of summer as seeds;

c) on a New England salt marsh, where the conspicuous zonation consists of dominant cordgrass, *Spartina alterniflora*, communities at the lowest tidal elevations, salt marsh hay, *Spartina patens*, at the mean high tide mark, and black rush, *Juncus gerardi* at the terrestrial edge of the marsh (Levine *et al.* 1998). All of these species are clonal perennials, spreading almost exclusively by vegetative growth;

d) on an Alaskan salt marsh (Snow and Vince 1984; Vince and Snow 1984). The most seaward mudflat zone consisted primarily of sea arrow-grass, *Triglochin maritimum*, and the perennial grass *Puccinellia phryganodes*. Neither were observed to flower and appeared to spread vegetatively. A second mudflat zone was sparsely occupied by another perennial grass, *Puccinellia nutkaensis*. The mudflat zone was replaced by a dense sedge meadow of *Carex ramenskii*, followed by *Carex lyngbyaei*, which in turn was replaced by *Carex pluriflora* on the landward side. River bank levees and other slightly elevated areas were more floristically diverse and were covered in a range of grasses and forbs. The main species were the grasses *Poa eminens* and *Festuca rubra*, followed by the forb *Potentilla egedii*.

Ecological zonation has also been documented from inland saline lakes in semi-arid Western Australia (Barrett 2006) and the desert south-west of North America (Bush 2006; Parker 1991). However, studies have tended to concentrate solely on salt as the factor affecting plant growth and survival or have looked only at the effects of waterlogging. Few studies considering all affecting and interacting factors have been investigated (Bush 2006), yet it is known that plant zonation in salt marshes is influenced by temporal and spatial edaphic gradients, both of which must be considered if plant-soil relationships in saline soils are to be fully understood (Alvarez Rogel *et al.* 2001).

The interacting factors influencing plant zonation are further confounded by spatial and temporal variations of soil moisture and salinity (Teakle and Burvill 1938). In saline areas with a mediterranean climate, this is particularly important, as the lowest soil salinity concentrations are not always those areas furthest from the coast (Callaway *et al.* 1990; Penning and Callaway 1992). In these environments upper marsh soils are typically euryhaline with rainfall periods leaching salts to deeper soil horizons and periods of drought resulting in salt being brought to the surface due to evapotranspiration (Callaway *et al.* 1990). Seasonal variations in salinity levels are thus important in some zones of the salt marsh (Alvarez Rogel *et al.* 2001). The survival of perennials in these euryhaline zones is partially dependent on their ability to tolerate the conditions of hypersalinity present in summer and autumn (Callaway *et al.* 1990). In temperate climate salt marshes subjected to frequent inundation, but not to the high summer temperatures of more mediterranean climates, salinity levels appear to determine the seaward limit of a species distribution, depending on that species salt tolerance, whereas the low saline distributional limit is determined by a species competitive ability (Levine *et al.* 1998; Snow and Vince 1984). The abrupt boundaries that often exist between marsh vegetation zones can be attributed to biotic factors, such as competition, as edaphic factors tend to change gradually across a marsh (Penning and Callaway 1992). Snow and Vince (1984) also suggest that it is the species with the broadest range in tolerance to saline conditions that are restricted to the most saline sites as these species have lower competitive abilities in terms of shoot to root ratio and in their allocation of biomass to sexual reproduction. Reproduction is predominantly vegetative with a high proportion of biomass allocated to roots. These broad range species are thus displaced at low salinity sites as they are poorly adapted to holding space compared to the other grass species and sedges included in the study. The relative salt tolerance of halophytic species has been shown to be a significant factor in determining their success in competition with glycophytes or less salt tolerant halophytes in saline conditions (Ungar 1998) and halophytes have been reported to be more competitive under saline conditions than under non-saline conditions (Kenkel *et al.* 1991).

Levine et al. (1998), following his study on perennial grasses and *Juncus* species in a New England salt marsh, hypothesised that the lower competitive ability of the species in the high salinity zones of the marsh is due to competition for nutrients, and subsequently showed that nutrient application in the form of nitrogen changed the competitive ability of the species in the salt marsh with those species that were less competitive becoming more dominant following nitrogen application. A further study on the competitive ability of New England perennial salt marsh plants (*Spartina patens*, *S. alterniflora*, *Juncus gerardi* and *Distichlis spicata*) under nutrient (60 g NPK) application (Emery *et al.* 2001) concluded that the stress tolerant plants were consistently the best competitors with increased nutrient availability and that an increase in nutrient availability can lead to dramatic changes in the distributions of salt marsh plants. Competition was found to be primarily below ground under ambient marsh conditions, but was above ground at high nutrient availability (Emery *et al.* 2001)

Few studies have been conducted on ecological zonation occurring on saltland pastures. Examples include mixed stands of puccinellia and tall wheatgrass. Both species appear to have similar levels of salt tolerance (50% decrease in growth at 25 – 28 dS/m, Marcar 1987), but tall wheatgrass is less waterlogging tolerant and has a deeper root system when in drained soils. Tall wheatgrass is therefore typically found slightly higher in the landscape, with puccinellia occupying the lower areas (McCarthy 1992; Phelan 2004). Jenkins (2007) in a study on the zonation of puccinellia and tall wheatgrass in the landscape suggests that although the two species have similar salt tolerance under drained conditions, the combined effect of saline and waterlogged conditions reduces the competitive ability of tall wheatgrass resulting in a predominance of puccinellia in these saline waterlogged areas. The author (Jenkins 2007) also suggests that puccinellia contains physiological attributes which further enhance its ability to dominate under conditions of combined salinity and waterlogging.

In agricultural landscapes of southern Australia, inundation due to flooding is infrequent, however, as watertables rise as a result of land clearance and the sowing of annual crops which fail to use all the annual rainfall, inundation is expected to increase in both frequency and duration (Bowman and Ruprecht 2000). The effects of inundation are likely to be more damaging to plants than the effects of waterlogging, but there has been little research in this area to date. This urgently needs to be addressed. There have been few studies on the effect of inundation on the survival and performance of plant species in saline pastures. An opportunistic study on inundation of *A. amnicola* on the banks of the Kabul River in Pakistan showed that taller plants (more than 1 m high) had a greater chance of surviving than shorter plants (less than 0.6 m high) during flood events (Barrett-Lennard 2002), as they were able to avoid total immersion. Therefore our current knowledge must be taken from studies of salt marshes. Work by Bertness (1991b) on the zonation of *Spartina* species in a New England salt marsh found that tolerance to inundation and competition between species were affecting the zonation of the two species. Tiller heights of *S. alterniflora* were three times greater in the low marsh, compared to those near the interface between high and low marsh, although total above ground biomass at the seaward edge was one fifth of that at the interface. *S. alterniflora* can persist in both the high and low marsh in the absence of competition (Bertness 1991b), but was unable to outcompete *S. patens* in the high marsh under competition, although it took up to three years before *S. alterniflora* disappeared from transplanted plots. By contrast, *S. patens* was able to survive in the high marsh, but not in the low marsh. Bertness (1991b) suggest that this is because *S. patens* is unable to oxygenate its roots in anoxic soils as it does not possess aerenchyma tissue which promote root oxygenation.

Riversides subject to frequent flooding can also be used as models in determining plant zonation, response and survival to inundation. Blom et al. (1994) studied the responses and survival of early to late successional riverside species to inundation. Early successional species such as *Chenopodium rubrium* showed ecological strategies associated with fast turn over; during the short inundation-free period between successive floods this species completed its lifecycle, producing seeds to survive the next period of flooding. Plants from the late successional zones exhibit highly competitive strategies growing in dense clumps and tended to be perennial whereas plants from the mid-successional zones survived by adopting opportunistic strategies; during periods of flooding these plants maintain large amounts of root and shoot biomass and when the flooded conditions subside respond with rapid growth. However, these mid-successional species are unable to cope with flooding more frequently than once a growing season (Blom *et al.* 1994).

A study by Blom et al. (1990) on the zonation of *Rumex* species along river foreland found that long-lived polycarpic perennials occupy the higher elevation zones that are rarely flooded in summer, short-lived polycarpic perennials occupy the infrequently flooded transitional zone and annual, biennial and short-lived monocarpic perennial species occupy the zone that is frequently flooded and commonly waterlogged. Those species that are frequently flooded showed greater aerenchyma development in roots with an associated increase in root porosity and length, resulting in continued aeration of the roots (Voesenek *et al.* 2006). Shoot elongation is a response to ethylene production during periods of inundation (Blom *et al.* 1990), however flooding intolerant species have been found to show inhibited growth during periods of complete submergence as a result of inhibited ethylene diffusion to the atmosphere.

Blom et al. (1990) also found that reproduction methods of flooding tolerant species indicate the species method of tolerance. For example, *Rumex maritimus* is able to survive long periods of waterlogging and periods of complete submergence by surviving as vegetative plants. If flowering has commenced when flooding occurs then abortion of the flowers resulted. In contrast *Chenopodium rubrum* attempts to flower and set seed in the short periods between flooding events. *C. rubrum* does not tolerate prolonged flooding events, and even prolonged waterlogging appeared to be a threat to survival. The survival strategy of *C. rubrum* is to produce large numbers of seed between flooding or waterlogging events (Blom *et al.* 1990). Blom et al. (1990) suggest that the use of indicator species such as *Rumex* and *Chenopodium* are essential in understanding the mechanisms used to survive and adapt to different waterlogging and inundation regimes that occur as a result of flooding events. It is important to understand that there are different life-history strategies used to adapt to flooding that are dependent on the perenniality of the species under study.

A further study on the competitive ability of high marsh perennials *Distichlis spicata*, *S. patens* and *Juncus gerardi* (Bertness 1991a) found that *J. gerardi* was the most competitive, followed by *S. patens*. However, *J. gerardi* was not tolerant of high levels of salinity and in situations with elevated salinities (25 to 33 g/kg), such as in bare ground patches, *J. gerardi* showed signs of severe water stress. Bertness (1991a; 1991b) therefore concluded that there is a strong inverse relationship between colonisation ability and competitive ability in marsh plants; this supports the theory of Grime (1979) that there is an inverse relationship between competitive ability and the ability of plants to tolerate abiotic stress.

Matching plants to sites

Ecological zonation on saltland arises from the interaction of a number of factors, such as salinity, waterlogging, inundation and soil texture, combined with spatial and temporal variation across a site. To rehabilitate and develop productive pasture systems on saltland environments plants need to be targeted to the conditions in which they are best suited. Determining the characteristics of the landscape is a key factor in deciding which plants should be planted where. The use of native indicator species may be very valuable in placing the 'right plant' into the 'right place' (Loch *et al.* 2003), and the best indicators for the development of a sustainable and productive saltland pasture are to mimic the ecosystems of natural saltland systems. Although secondary salinity in agricultural areas is present in all continents of the world, it is increasing fastest in Australia (Rengasamy 2006). For this reason southern Australia, and in particular studies in Western Australia, will be used as case studies in developing our understanding of the importance of siting, germination, establishment and performance of saltland pasture species for the rehabilitation and sustainable production of saltland pastures in agricultural areas with increasing secondary salinity.

Land in valley floors in the eastern wheatbelt of Western Australia are subject to high levels of salinity and waterlogging and follow a similar pattern of plant zonation to relatively undisturbed saline lakes in eastern Western Australia. These saline lakes can therefore be used as models in the rehabilitation of degraded saline lands (Barrett-Lennard *et al.* 2005a). For example, a transect taken from the waters edge (the most salt-affected and waterlogged area) of a saline lake in southern Australia, to areas that are marginally influenced by salinity and waterlogging further up the slope, found that areas with severe inundation will be bare as a result of their extreme salinity and susceptibility to inundation. Slightly further up the slope (0.1 to 0.2 m) the zone will be dominated by self-sown samphire (*Halosarcia* spp.), a group of highly salt and waterlogging species. Soils subjected to inundation are often clayey at the surface and of low productive potential. However, colonization by samphire species will stabilise the sites and decrease erosion (Barrett-Lennard *et al.* 2005a). Populations of samphire (*Halosarcia pergranulata*) growing on playas of mudlfats in Western Australia are subjected to months of waterlogging and in some cases complete submergence. Pedersen et al. (2006) attributed the tolerance of samphire to these stresses to their ability of their basal woody stems to photosynthesise O2 and that this O_2 production is an important source of O_2 for the roots.

The zonation described above needs to be considered when establishing degraded saltland pastures. If plants are sown into an area in which they are not well suited then their germination, establishment and performance will be at best poor and they are unlikely to survive. For example, if saltbush is sown into the 'samphire zone' at the high salinity, high waterlogging end of a site it is unlikely to survive. However, temporal and spatial variation in salinity and waterlogging levels across a site can mean that determining the 'correct' zone in which to plant a species is very difficult. The next section of the paper will expand on our understanding of the preferred zonation of different saltland pasture species.

The interaction between salinity and waterlogging is complex and not fully understood, although waterlogging usually reduces a plants ability to tolerate saline conditions (Barrett-Lennard 2003). The effects of waterlogging or salinity alone have been reported extensively, however, there is less information available on the interactive effects of the two combined, a condition that occurs frequently in the field in southern Australia (Lu *et al.* 2004). A study of the effects of waterlogging and salinity on soils near two saline lakes in Western Australia found that salinity electrical conductivity (EC) values increased with waterlogging, reaching a peak after 14 days of waterlogging and that the increase was lowest in sandy soils with low initial $EC_{1:5}$ values (0.02 dS/m (Lu *et al.* 2004). Our limited current knowledge on the interaction of salinity and waterlogging suggests that improvements in plant growth can be obtained with modest drainage or lowering of the watertable (10-20 cm) (Barrett-Lennard 2003). This level is sufficient to alleviate the effect of waterlogging, but not to reduce soil salinity.

Barley and wheat are both relatively sensitive to waterlogging (McDonald *et al.* 2001), yet in combination with salinity the effect on growth rate is even greater. For example Barrett-Lennard (1986) showed that after 14 days of waterlogging at 0.5 mM NaCl dry shoot weights of barley were reduced 5% compared to a non-waterlogged control, yet dry shoot weights were reduced by 23% at 70 and 125 mM NaCl compared to aerated plants under the same salt treatment. In a second example, saline (100 mM NaCl) hypoxic conditions reduced growth by 13 to 89% in eight wheat cultivars compared to 100 mM NaCl or hypoxia alone (Akhtar *et al.* 1994).

Quantification of salinity and waterlogging in the landscape

Measurement of salinity

Soil salinity is most often recorded as electrical conductivity and can be measured as either $EC_{1:5}$ or ECe. $EC_{1:5}$ (w/v) is measured by mixing one part by weight (g) air-dried soil to five parts by volume (ml) of distilled water, which is agitated and then allowed to settle (Anon. 2005). Soil texture affects the value of the $EC_{1:5}$ as sand particles do not hold as much salt from the soil water as clay particles will do. Therefore a sandy soil will result in a lower $EC_{1:5}$ reading than a clay soil even though the soil water (which is the part affecting the plant roots) is the same (Anon. 2005). Conversion factors for $EC_{1:5}$ to ECe are given in Anon. (2005), for example an $EC_{1:5}$ of 1 dS/m in a sandy soil is equivalent to an ECe of 15 dS/m, whereas the same ECe from a heavy clay soil would have been recorded as $EC_{1:5}$ 2.5 dS/m. Due to soil/ salt interactions, $EC_{1:5}$ readings also tend to underestimate the true value of soil salinity, particularly sandy soils (Department of Natural Resources Queensland 1997) and therefore to get a more accurate measure of salinity that is independent of the soil type $EC_{1:5}$ readings are converted to ECe (Anon. 2005). Measuring ECe can be time-consuming and therefore expensive. However it is the most reliable and widely accepted measure of comparing salinity concentrations between soil types, and is the 'international standard' (ref. Soils Handbook).

It is important to note that soil water salinity levels can increase as a result of two processes; a decrease in soil water through drainage or evapotranspiration, and/ or an increase in the amount of salt in the soil (ref.). When the salinity level of the soil is measured it is conducted using a standardized amount of water. Therefore the reported soil salinity is not the same as the level of salinity plant roots might be experiencing in the ground. There is a further differential experienced by plants growing in saline soils, between the bulk soil salinity and the salinity of the soil surrounding the roots, as transpiration by plants results in a mass flow of water and salt to the roots markedly altering the salt concentration at the root-soil interface (Sinha and Singh 1976). Net accumulation of salt around the roots occurs as a result of water uptake and simultaneous net 'exclusion'. Salt accumulation around the roots is greater in areas with high evaporative demand, such as arid and semi-arid areas (Sinha and Singh 1974) and has been observed in glycophytic crops such as corn (Sinha and Singh 1974) and wheat (Sinha and Singh 1976) and in halophytic species such as saltbush (Barrett-Lennard and Malcolm 1999) and puccinellia (Zhang *et al.* 2005b).

One of the most important aspects of salt-affected sites is that the salt concentrations vary considerably between seasons, years, depth and across a site. This variability results in a mosaic of conditions that suits plants from mildly saline-tolerant non-halophytes through to highly salt tolerant halophytes across the site (Rogers *et al.* 2005). Variations of up to an order of magnitude have been recorded in the concentration of chloride on a soil dry weight basis within one square metre (Teakle and Burvill 1938). Over what depth? expand

Comparisons of salinity classes across southern Australia

A summary of the Australian state salinity classifications are given in Table 2. However, there are complications even trying to draw up the simple table shown, as salinity is measured in different units, i.e. ECe (WA and SA) and $EC_{1:5}$ (Victoria and MDBC), and using different numbers of classes. Even within Victoria there are two classifications with three classes in the published 'Spotting Soil Salinity' guide (Matters and Bozon 1995) and five classes in the classification used by the Landscape Systems, Spatial Sciences section of the Department of Primary Industries, Victoria (R. Clark, Pers. Comm.). To further complicate the comparison of salinity classifications, the FAO/ UN classification (Dudal and Purnell 1986) uses measures of exchangeable sodium percentage (ESP) to define the severity of saline soils. The state salinity classifications in Australia do not include ESP in descriptions of soil salinity classes, despite its use in the most recent Australian soil classification (Isbell 1998; Rengasamy 2006).

Table 2. Salinity classes from some Australian state classifications, converted to dS/m (ECe) for a loam soil. A comparison is also provided with the UN salinity classification.

Salinity classes	**WA**[1]	**SA**[2]	**Vic**[3*]	**MDBC**[4*]	**FAO/ UN**[5]
Lowest salinity class	Non-saline <2	Non-saline 0-2	-	Not affected 0	Sodic phase ESP 6-15 in upper 1.0 m
	Slightly 2-4	Low 2-4	Low <6	Slightly 2-4	Solonetz ESP >15 in upper 0.4 m
	Moderately 4-8	Moderate 4-8	Moderate 6-14	Moderate 6-14	Saline phase 4-15 in upper 1.0 m
	Very 8-16	High 8-16	-	-	-
Highest salinity class	Extremely >16	Severe >16	Severe 14-35	Severely >14	Solonchak > 15 in upper 0.75 – 1.25 m

* calculated from published $EC_{1:5}$ values, assuming a loam soil type to allow for comparisons between published classes used in the different states.
[1]WA (Anon. 2005)
[2]SA (Henschke and Herrmann 2005)
[3]Vic. (Matters and Bozon 1995)
[4]NSW (Anon. 2002), adapted from (Allen 1996)
[5]FAO/UN (Dudal and Purnell 1986), ESP = exchangeable sodium percentage (%)

A second type of classification is also provided by Martin and Metcalf (1998) based on loss of productivity of land in relation to degree of salinity and presence of salt tolerant vegetation. However, no absolute salinity measurements were given (see Table 3).

Table 3. Classes of salt-affected land in southern Australia (from Martin and Metcalfe 1998)

Class	Description
Not at risk	Land not susceptible to salinity, regardless of land use or management
Stable	Land susceptible to salinity, but unlikely to become saline under the current land use or management
At risk	Land susceptible to salinity and likely to become saline under the current land use of management
Slightly affected (<10% decrease in productivity)	Land with reduced productivity from non-salt tolerant plants, some salt tolerant plants present, seasonally or permanently shallow watertable and some small bare areas
Moderately affected (10-50% decrease in productivity)	Land showing a significant loss in non-salt tolerant plants, salt tolerant plants common seasonally or permanently shallow watertable, bare areas up to 5m² in size, some erosion present
Severely affected (>50% decrease in productivity)	Land showing an absence of non-salt tolerant plants, permanently shallow watertable, large bare areas which are often badly eroded.

Measurement of waterlogging

SWE_{30} is the sum of excess water above a soil depth of 30 cm. It is an index developed by Sieben (1964) to integrate the depth of the watertable and the duration of waterlogging at particular depths (in this case 30 cm or above), and therefore allows an assessment of waterlogging intensity. Although the SEW_{30} is a quantitative measure of interpreting the adverse effect of waterlogging on crop yields it has serious limitations (McFarlane *et al.* 1989) and includes a number of assumptions. These are discussed below.

- The SEW_{30} assumes that crop yield is negatively affected when the watertable rises to within 30 cm of the soil surface. It has been correlated to wheat and oat yields with intermittent waterlogging in duplex soils in Western Australia (Cox 1988), but there has been no work to determine if 30 cm is the best depth for the index, of if better correlations with effects on plant yields can be obtained from SEW_{20} or SEW $_{10}$ for instance (Setter and Waters 2003). Also, is the index true for other crops, annual pasture grasses and legumes, shrubby saltland pasture plants etc. Further work is required on other crop and pasture species to determine if 30 cm is the best depth to use in the index.

- The index also assumes that the adverse effect of waterlogging on plants follows a linear increase in relation to an increase in the watertable above 30 cm, and as the number of days of waterlogging (duration) increases. The relationship in this index allows comparisons to be made across treatments and field situations, for example a five day waterlogging treatment at the soil surface and a 15 day waterlogging treatment at a soil depth of 20 cm both have an SEW_{30} of 150 cm days (Malik *et al.* 2001). The comparison between treatments or field sites is useful, but is it accurate? Are the effects of waterlogging for five days on the surface and for 15 days at 20 cm really comparable?

- That recovery of plant growth is linear in relation to previous level of waterlogging. However, Malik et al. (2001) found that plant biomass after 14 days recovery was no longer proportionally affected by the previous level of waterlogging, with plants subjected to waterlogging at the soil surface and at 100 mm below the soil surface having a similar mass. Malik et al. (2001) suggest that the reduced rate of recovery after waterlogging compared to a continuously drained treatment is due to a smaller capacity for assimilation in these two treatments as a result of fewer photosynthetically active leaves being available at the end of the waterlogging treatment and due to a slow recovery of rate of photosynthesis.

- Even very short waterlogging events can result in a severe reduction in the growth of crops depending on their growth stage. A three day waterlogging treatment resulted in no visible adverse effects on wheat shoots during the waterlogging, but after a 25 day recovery phase the plants more closely resembled plants under continuous waterlogging, than those that had been grown in continusously drained soils (Malik *et al.* 2002). The severity of the effect of waterlogging appears to vary depending on the growth stage of the plant; the wheat in the study by Malik et al. (2002) was at the vegetative stage, whereas a study by Meyer and Barrs (1988) on waterlogging of wheat at the stem elongation stage found no adverse effect of short-term waterlogging (96 h) on final grain yield. The relationship of SEW_{30} to crop damage will therefore vary depending on the growth stage of the crop when subjected to waterlogging.

- SEW30 does not consider temperature – expand – the duration of the waterlogging event will vary depending on the surrounding air temperature as warmer temperatures will result in greater evapotranspiration from the soil surface than in colder climates (refs???).

- Waterlogging of the soil is temporarily very variable. It does not increase to a set depth from the soil surface, stay there for a nominated duration and then recede, but varies temporarily in relation to rainfall events, soil surface evapotranspiration and localized plant water use. This can clearly be seen in Fig. 1 which shows the measurement of depth to watertable from the soil surface using a hydrograph. The SEW_{30} is the grey shaded part of the graph above the 30 cm soil depth. Sampling to calculate SEW30 should therefore be conducted frequently during the cropping season.

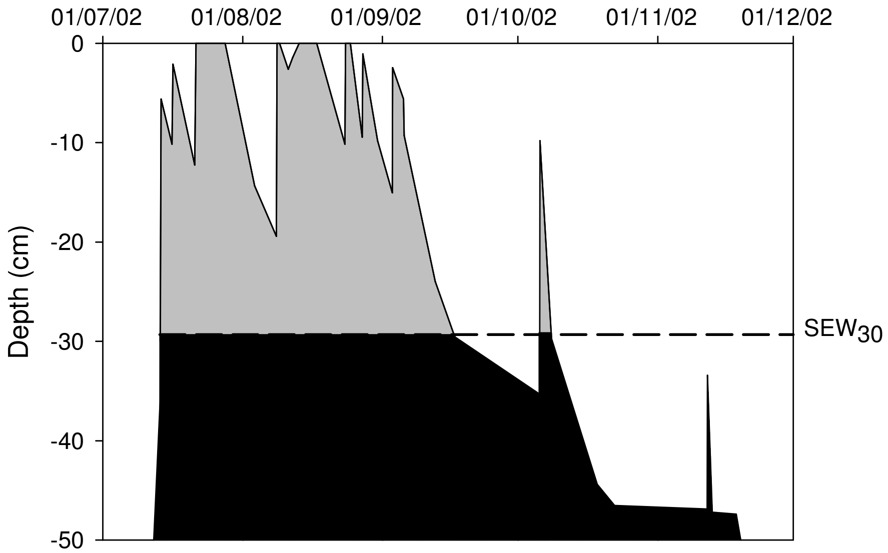

Fig. 1. Hydrograph showing variation in depth to watertable over time at a site at Narrogin, Western Australia, from McFarlane, Barrett-Lennard and Setter (1989). Grey shaded area is SEW_{30}.

• Further temporal variation in the effect of waterlogging occurs between seasons and between sites (McFarlane *et al.* 1989; Setter and Waters 2003). For example studies in Western Australia at a number of sites and years (McFarlane *et al.* 1989) found that at Mount Barker in 1984 oat yields were not affected by waterlogging until the SEW_{30} exceeded 500 cm days, yet at Yornaning in 1987 both oat and spring wheat yields decreased by 520 to 550 kg/ha with every 100 cm days with no initial threshold, and at Narrogin in 1985 spring wheat yields decreased by about 56 kg/ha per 100 cm days again with no threshold. The authors (McFarlane *et al.* 1989) concluded that variations could be the result of different cultivars, soils and/ or environmental conditions.

• Waterlogging varies spatially across a paddock and therefore the effect of waterlogging on crop yield will also vary spatially across the paddock. This is shown in Setter and Waters (2003) where several hundred piezometers were installed across a paddock and the level of the watertable recorded daily or weekly. The resulting values were used to produce SEW_{30} waterlogging intensity maps. Setter (2000) found that in duplex soils the duration and timing of waterlogging may vary by up to 400-fold over a distance of only 50m, even where there was no observable difference in the surface topography.

An alternative measure of waterlogging is therefore required that accounts for the other interacting factors which affect plant growth, such as …..? Suggestions? Indicator species?.

Watertable drawdown

The rooting depth of different saltland pasture species is important not only in relation to tolerance to waterlogging, but also in relation to drought avoidence over summer. For example, river saltbush (*Atriplex amnicola*) has a root depth of around 0.5 m (Galloway and Davidson 1993), whereas old man saltbush (*Atriplex nummularia*) has a root depth of up to 3.5 m (Jones and Hodgkinson 1969). A mixed sowing of these species across a paddock will achieve the most sustained drawdown of watertables, with river saltbush persisting in areas with shallower watertables (1.0 – 1.5 m) and old man saltbush persisting in areas with deeper watertables (1.5 – 2.5 m) (Barrett-Lennard and Galloway 1996). The planting of mixtures of saltland species is important because spatial variations in watertable depth may not be apparent at the time of sowing and can not be accurately predicted into the future. A successful saltland pasture can therefore only be achieved by planting a mixture of species to cover the range of salt and waterlogging niches found within a paddock.

Revegetation by saltbush may play an important role in lowering watertables and therefore reducing the impact of combined waterlogging/ saline conditions. Results have been reported from a number of farms in Western Australia where the watertable has been reduced sufficiently for an understorey of annual legumes to be sown in combination with the saltbush (Barrett-Lennard 2002; Barrett-Lennard and Galloway 1996). However, these studies are based on few or single bores with no replication. There is therefore a clear need for better documented and replicated evidence of groundwater draw-down by stands of saltbush. A summary of reported results are given below, along with the number of bores measured during the study;

1. Michael Lloyd (a farmer in the Pingaring region of Western Australia) established a good stand of mixed saltbush species on a saline duplex soil with a watertable of 0.5 – 2.0 m in April 1998 (average annual rainfall 354 mm, 1998: 331 mm). By the end of the second year the watertable had been reduced by about 0.5 m compared with an adjacent non-revegetated site and was able to sustain an understorey of the relatively salt-sensitive balansa clover (Barrett-Lennard 2002). Based on comparisons of single bores at each site.
2. A mixed stand of saltbush was established at Kellerberrin in the North Stirlings area of Western Australia on a sandy-textured site with a summer watertable of only 1.2 m in September 1989 (Average annual rainfall 334 mm). Five years later the summer watertable had been drawn down to 2.5 m, a self-sown understorey of subterranean clover (*Trifolium subterraneum*) had developed and the saltbush appeared to be severely moisture deficient (Barrett-Lennard and Galloway 1996). Based on measurements from a single bore. A previous study at the same site (Greenwood and Beresford 1980) found that over summer saltbush plantations may evapotranspire about 250 mm of groundwater.

Temporal and spatial variation of salinity and waterlogging

The spatial and temporal variation that occurs across landscapes has been discussed earlier in relation to salt marshes with similar levels of variation occurring in agricultural landscapes and even within a paddock (Teakle and Burvill 1938). Quantifying levels of salinity and waterlogging is therefore problematic.

Temporally, waterlogging is known to increase over the winter months and to decrease over the summer months (McFarlane *et al.* 1989), but when is the best time to record it, how often should it be measured? Which time of year is the most stressful to the plant – winter when plants are subject to waterlogging and possibly periods of inundation, or summer when plants are subject to drought? Similar variation has been recorded in levels of salinity with levels falling over winter due to leaching by winter rains and rising again in spring and summer due to evapotranspiration (Smith 1962).

Spatial variation is also important with differences in elevation and texture resulting in micro-variation in levels of salinity and waterlogging across a paddock. This is highlighted by a study on the botanical diversity of two saline ecosystems in Western Australia (Norman *et al.* 2003) which was found to be much higher than is typical of non-saline paddocks. The site with the higher salinity and greater degree of waterlogging contained 31 plant species and the less saline site 24 species. The high diversity in these two saline ecosystems was attributed to the niche differentiation due to spatial variation in salinity and waterlogging that occurs across the two sites.

Other factors affecting the impact of salinity and waterlogging

Soil texture

Soil texture affects the impact of the stress of salinity and waterlogging. For example, a little clay is important in increasing plant establishment and production, but it soon becomes a limiting factor above ??% as it increases the effect of waterlogging as the air-filled porosity decreases, therefore increasing hypoxia for roots (refs). Hypoxia decreases root survival and the uptake of nutrients. Although there have been suggestions that soil texture may affect the growth of saltbush species through effects on soil aeration (ref), the case at present does not seem strong or well researched. In duplex soils, Davidson et al. (1996) found no effect of depth to clay (ranging from 10 to 70 cm) on the growth of *Atriplex amnicola*. However, a more detailed investigation at the same site (Galloway and Davidson 1993) revealed depth to clay was significant on a micro-scale (2 – 10 m), indicating high spatial variability within the individual 'plots' of the study area. As soil salinity levels increase, the interaction of soil salinity and hypoxia due to poor soil aeration results in the complete cessation of root growth (Galloway and Davidson 1993). Barson et al. (1994) predicted using the PLANTGRO model that soil texture will have a moderate to severe limitation (rated 4 - 5 on a rating of 0 - 9, where 9 represents rapid death of the plant) on the growth of *A. amnicola*, with moderate limitations (3 – 4) also predicted for *A. canescens*, *A. lentiformis* and *A.*

undulata. *A. nummularia* was the only species in which soil texture was not a limiting factor. The authors (Barson *et al.* 1994) do not state how soil texture is defined or measured, but state that it affects the ability of the plant roots to lengthen. Other major assumptions are made during the generation of the model that limit the validity of the final predictions, namely;

1. The plant files for each species were chosen from sets of alternative notional environmental relationships for the factors used in PLANTGRO, rather than being developed from data collected at a number of field sites where saltbush species have been grown;
2. *A. amnicola* was used as a reference species to assist in developing the environmental responses for the lesser known *Atriplex* species. Therefore it is unknown if the predictions from PLANTGRO accurately reflect the environmental response of the lesser known *Atriplex* species or if they mimic those of *A. amnicola*;
3. Data from only 4 sites were used to determine which environmental factors were likely to be limiting the growth of the different saltbush species, even though Barson et al. (1994) state that 14 sites were available.
4. The fit of the predicted model using four sites, to the observed responses from 14 sites, is not great for either summer water deficit or soil aeration. The authors (Barson *et al.* 1994) state that more water is likely to be available over summer than has been accounted for in the model due to selected sites being in valley floors and that this could have been built into the model. They also state that the model could not differentiate three of the species, *A. nummularia*, *A. lentiformis* and *A. undulata*, in their response to soil aeration as the three species have similar levels of drought tolerance using the PLANTGRO variables. However, they do not specify the link between soil aeration and drought tolerance, nor how drought tolerance is calculated within the PLANTGRO model.

Climate

The effect of climate, both rainfall and temperature, are further factors that need to be taken into consideration when deciding on the optimum species to plant on saltland pastures. For example, Barrett-Lennard and Galloway (1996) related the growth of *Atriplex amnicola* to ‘average annual temperatures’. In a 3-point correlation (based on plant growth at two locations in Western Australia and one in Pakistan) they noted that there did not appear to be much growth at average annual temperatures below 15^{o}C. More recent studies as part of the Sustainable Grazing on Saline Lands initiative suggest that there is a linear relationship between shoot growth in both *A. amnicola* and *A. nummularia* to thermal time (calculated on an hourly basis). The critical temperature threshold below which growth does not occur has been estimated at 8–9^{o}C (Barrett-Lennard, Pers. Comm.).

Matching plants to sites: The salinity/ waterlogging matrix

The complexity of the interactions between salinity, waterlogging and inundation makes it difficult for those wishing to re-establish plants on saltland. To assist, simple matrices have been developed to improve the targeting of plant species to locations on saltland. Figure 2 gives an example of such a matrix for Australia. Each species has been given a place in the matrix denoted by a circle. This does not indicate the limits to survival of that species; rather it indicates the zone in the saline-waterlogged landscape where that species is presumed to have its greatest competitive advantage. For example, samphire can grow at low and high salt levels (Short and Colmer 1999), but presumably is a poor competitor at lower salinity with other plants. In winter-dominant rainfall areas with an annual rainfall of 300-400 mm, duplex and gradational soils of lower levels of salinity and waterlogging are highly suited to the growth of saltland pastures (saltbush (*Atriplex* species) and small-leaf bluebush (*Maireana brevifolia*)) combined with annual understorey species and have moderate productive potential for grazing (Barrett-Lennard 2003). In higher rainfall areas (400-500mm) perennial-annual combinations may also be useful, but perennial species will be the shrubs *Acacia saligna* and saltbush species and perennial grasses will be puccinellia (*Puccinellia ciliata*) and tall wheat grass (*Thinopyrum ponticum*) (Barrett-Lennard and Holt 1999; Phelan 2004). Sandplain seeps dominate areas with high productive potential where the main stress is waterlogging. These soils will grow trees and plants with lower levels of tolerance to salinity and waterlogging such as the pasture plants balansa clover (*Trifolium michelianum*), kikuyu (*Pennisetum clandestinum*) and Rhodes grass (*Chloris gayana*) (Barrett-Lennard 2003). The basis for ascribing the locations for the species in the matrix is given in Table 1. It should be stressed that apart from a number of unpublished ecological observations, these comparative competitive effects have not been confirmed, especially under controlled conditions of salinity and waterlogging.

The matrix shown in Fig. 2 identifies the position of plants occurring at different levels of salinity and waterlogging in a landscape. However, it does not account for a number of other interacting factors such as; effect of soil texture, inundation, grazing tolerance, management. The effects of the majority of these interacting factors are largely unknown, so research in these areas are required.

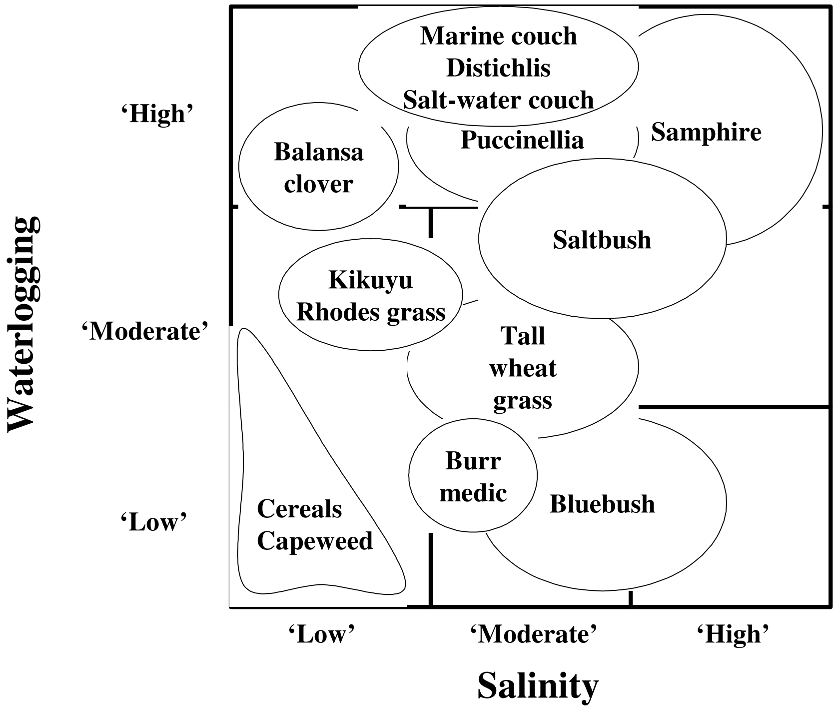

Fig. 2. Major ecological niches for some selected plants on saline and waterlogged land in Australia (Barrett-Lennard *et al.* 2003). Species are: balansa clover (*Trifolium michelianum*), burr medic (*Medicago polymorpha*), bluebush (*Maireana brevifolia*), cereals (*Triticum aestivum*, *Hordeum vulgare*), distichlis (*Distichlis spicata*), kikuyu (*Pennisetum clandestinum*), marine couch (*Sporobolus virginicus*), puccinellia (*Puccinellia ciliata*), rhodes grass (*Chloris gayana*), saltbush (*Atriplex* sp.), salt-water couch (*Paspalum vaginatum*), samphire (*Halosarcia* sp.) and tall wheatgrass (*Thinopyrum ponticum*).

The matrix includes both annual and perennial species. Annuals ripen at the end of spring before the salinity of the soils increases as a result of evaporation and the rise of salt to the surface. Annuals also escape the worst salinity stresses as they persist as seeds through the summer, germinate after the early winter rains when top soils have been leached of salt (Carter and Ungar 2003). Perennials, on the other hand, have to survive all extremes; especially the very high salinity levels reached during the drought conditions of summer and therefore must have sufficient salt tolerance for these conditions. Puccinellia is the exception as it behaves more like an annual in avoiding the worst stress by becoming dormant (drought induced dormancy) over summer, re-shooting from tiller bases after the opening rains in autumn (Barrett-Lennard and Holt 1999; Phelan 2004). Given these different life history traits, it is not surprising that tolerances to salinity will vary considerably within mixed stands of perennials and annuals. For example in the annual/ perennial stand in Fig. 3, the river saltbush plants in the background have a 50% decrease in shoot growth at ECw (electrical conductivity of soil water values of about 40 dS/m (calculated from the data of Aslam *et al.* 1986). This is equivalent to an ECe value of 26.6 dS/m assuming a well-drained soil with a leaching fraction of 0.15 to 0.2 (Grattan 2002). In contrast, the sea barleygrass in the foreground has a 50% decrease in shoot growth at ECw values of about 26 dS/m (calculated from the data of Garthwaite *et al.* 2005).

Fig. 3. ???? showing a stand of river saltbush (*A. amnicola*) with sea barleygrass (*H. marinum*) dominating the foreground (Need e.g. with species included in matrix).

The matrix currently includes only a few species for which we have ecological information on salt and waterlogging tolerance. No units are included on the matrix as levels of salinity and waterlogging are extremely variable over the year. Instead the matrix provides an indication of the position of the different saltland pasture species in relation to each other in a waterlogged saline system. Indicator species can be used in a similar manner to provide an estimate of the severity of waterlogging and salinity in an area. However care must be taken as other interacting factors, such as grazing regime, past management history, soil conditions and seasonal influences, contribute to species composition within a particular pasture (Department of Natural Resources Queensland 1997). For example, creeping saltbush (*Atriplex semiblaccata*) is a good indicator of salinity as it occurs on saline and disturbed soils, although it will generally be absent from intensively grazed paddocks (Christiansen 1993). Care must also be taken as many species that occur on saline soils also grow on non-saline soils and it is the absence of species known to have low salinity tolerance, as well as the presence of species known to have salt tolerance, that will provide the indication of severity of salinity at a particular site (Department of Natural Resources Queensland 1997). Table given of salinity indicator species. Do we want to include it?

Land Capability Assessment to go in here

From an agricultural perspective we can conjecture that the highest growth potential will be in those areas which have relatively low levels of salinity with some waterlogging. In arid environments these are the areas which will have the longest growing seasons for annual plants. These are therefore likely to be the areas where other agricultural interventions (such as drainage, fertiliser application etc.) will be most profitable.

Improving conditions for saltland pasture species

A way of potentially increasing the match between saltland pasture species and the site is to modify the site using methods such as raised seed beds, niche seeders or drainage channels. The aim of these is to raise the seedling above the level of waterlogging, encourage the removal of excess water away from the site or leach salts from the soil surface. Both raised seed beds and drainage channels have been developed for sowing species on sites which are prone to waterlogging. However, their success when used on saline sites that are also prone to waterlogging is less well documented (Bakker *et al.* 2006; Bakker *et al.* 2002) . Also the success of site modification is dependent on the site characteristics at each site in question. For example, raised seed beds have been successful in duplex soils where most of the water movement below the surface is lateral, rather than horizontal as the raised seed beds act as small surface drains (Setter and Waters 2003), see Hamilton 2000). However, under saline conditions Bakker et al. (2002) found that soil salinity levels at the edges of the raised beds were higher than in the centre. The difference in salt concentration between the edges and the centre of raised beds is a common feature when irrigating with slightly saline water, however the highest concentration is usually found in the centre as this is where most of the water infiltrates (Malcolm 1983). In a rainfed situation it would be expected that excess water would drain away resulting in a more uniform distribution. However, Bakker et al. (2002) suggest that there is increased evaporation from the edges of raised beds due to the larger exposed surface area which raises soil temperature. Further work on the benefits of using raised seed beds (Bakker *et al.* 2006) found that although raised seed beds increased grain yield on waterlogged sites, raised beds do not reduce the impact of salinity on crop productivity. Despite this Bakker at al. (2006) hypothesised that the use of raised beds may help to leach salts from the root zone and limit capillary rise in spring through increased soil cultivation, thus reducing re-salinisation of the root zone. Preliminary results, however, of sowing saltbush on raised beds suggests that the opposite may be true with salt accumulating around the root zone of the saltbush (Barrett-Lennard and Malcolm 1999).

Niche seeding improves the soil conditions by sowing the seed, along with a covering of vermiculite on a raised M-shaped mound (Ref.). The shape of the mound encourages the leaching of salt from the soil around the seed by rain and the vermiculite acts as a mulch retaining moisture around the seed, reducing evaporation from the seedbed, and thus reducing the upward movement of salt (Barrett-Lennard *et al.* 1991). The raising of the seedbed above the level of the surrounding soil also reduces the incidence of waterlogging. However, there are limitations to the success of niche seeding and it has not been successful in areas with high salinity, heavy clays or a shallow sand layer (less than 10 cm) over clay, waterlogged soils (Barrett-Lennard *et al.* 1991). Furthermore, high weed competition and lack of insect control reduce success of establishment of saltbush species from seed.

A number of different types of drainage channels have been to designed to manage waterlogging, such as reverse seepage interceptor, conventional seepage interceptor and spoon (v-shaped) drains (Cox and McFarlane 1995; Cox *et al.* 1994). A diagram of a reverse seepage interceptor drain is shown in Fig. 4 and highlights the movement of water over the surface and through the profile in relation to the direction of the downward slope. A study by Cox and McFarlane (1995) found that on average installation of drains reduced the incidence of waterlogging on the downstream side by 68% in the wettest season of the study, despite large soil variability between transects which influenced waterlogging intensity (measured by SEW_{30}). However, for management of salinity and waterlogging they are best combined with other management practises such as ….. (Department of Natural Resources Queensland 1997).

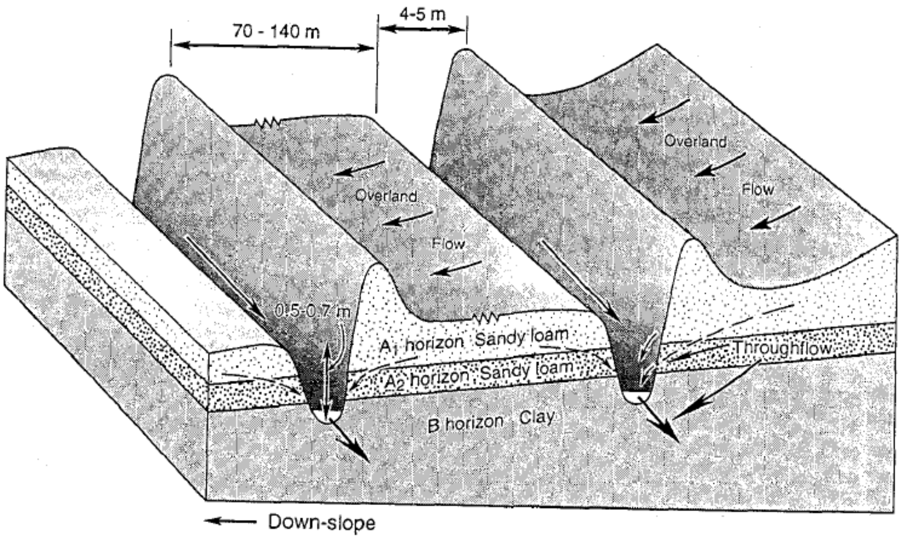

Fig. 4. A reverse seepage interceptor drain (from Cox *et al.* 1994)

<u>Questions arising under matching plants to sites:</u>

a) Which plants should be sown where according to known soil conditions – level of soil salinity, depth, seasonal variation and salinity of groundwater, soil texture, soil pH, soil density, frequency and duration of inundation, and duration and intensity of summer drought?

b) Is it possible to develop an array of indicator plant associations that are related to salinity and waterlogging to help with site characterisation?

c) What is the minimum composite of soil conditions required to reliably recommend plants for sites? Which conditions are most important to measure? How often and when should these be measured?

Germination and seedling establishment

There is a small window of opportunity for seed germination and successful establishment in saline environments with germination occurring during periods of reduced soil salinity, usually following rainfall events (Ungar 1982). Both glycophytes and halophytes are salt sensitive at germination and early establishment (Flowers *et al.* 1986; Ungar 1978; 1982) and adequate rainfall is essential for germination in semi-arid and arid environments (Kigel 1995). For example, the germinability of puccinellia decreased with increasing concentrations of NaCl (Myers and Couper 1989), with germination reduced to 50% that of distilled water at an osmotic potential of -0.55 MPa (convert to ECe). Germination was also affected by temperature with maximum germination occurring at 24/17° C diurnal range and being completely inhibited at constant temperatures above 33° C (Myers and Couper 1989). Rate of germination was not affected by level of salinity, but by increasing or decreasing temperatures away from the 24/17° C diurnal range (Myers and Couper 1989).

Puccinellia has a low germination rate even under non-saline conditions. Zhang et al. (2005a) recorded a germination rate of only 40% for puccinellia cv. Menemen after 8 days with no NaCl treatment. The rate of germination decreased until no germination was recorded at 461.5 mM/L NaCl and only 2% at 359 mM/L NaCl. Tall wheatgrass cv. Tyrell by comparison achieved nearly 100% germination by day 8 under no NaCl, and even at 153.8 mM/L NaCl achieved 95% germination after 10 days (Zhang *et al.* 2005a). At levels of NaCl above 154 mM/L the germination rate started to decrease until at 461.5 mM/L NaCl only 8% of the seeds germinated. In general the mean time to germination increased linearly in both puccinellia and tall wheatgrass as NaCl concentration increased (Zhang *et al.* 2005a), although it is interesting to note that in puccinellia pre-treatment of the seed with NaCl increased germination rates by up to 3.5 times (205 mM/L NaCl). Tall wheatgrass is often reported to be less salt tolerant than puccinellia which contradicts the results of Zhang et al (2005a) presented above. However, the rate of germination of tall wheat grass rapidly falls under waterlogged and salt stressed conditions. For example at 153.8 mM/L NaCl germination rates of 18 and 94% were recorded for puccinellia cv. Menemen and tall wheatgrass cv. Tyrell respectively, while under waterlogging at the same level of NaCl they were 7 and 15.7% respectively (Zhang *et al.* 2005a) showing the increased impact on germination of combined waterlogging and salt stress compared to salt stress alone.

Mangrove species also require salinities of less than saltwater to germinate, with germination occurring during the wet season when high rainfall and groundwater seepage lower salinities to levels suitable for establishment and rapid seedling growth (Ball 1998; Ball and Pidsley 1988). In mangrove species with viviparous seedlings, NaCl concentrations of the propagule are maintained at relatively low levels compared with the parent plant (Pannier 1962). By the time of abscission from the parent plant the sensitivity of the propagules to salt has decreased, thus allowing germination and early growth to occur on the parent plant whilst the propagule is most sensitive to salt stress with later establishment occurring once the seedling has developed some tolerance to salt stress (Smith and Snedaker 1995).

The transition from germination to seedling establishment is perhaps the most critical phase in the success of plants in saline conditions (Osmond *et al.* 1980). The availability of low salinity conditions for up to three days at 21°/28°C diurnal range was found to increase the rate of true leaf development and therefore salt tolerance in *Atriplex lentiformis* (Malcolm *et al.* 2003). The authors (Malcolm *et al.* 2003) suggest that as field temperatures in Western Australia are much lower than this, that low salinity conditions would be required for at least two weeks for successful establishment to occur in the field. Samphire needs about a week of low salt during germination and then behaves as true halophyte if salt levels are increased (English 2004). (Also look at Greg Barrett's PhD Thesis). *H. pergranulata* subsp. *pergranulata* showed a high percentage of survival in 10 day old seedling subjected to increasing levels of NaCl (English *et al.* 2002). A study on the mudflats and dunes surrounding a saline lake in the goldfields of Western Australia recorded germination of three species of *Halosarcia* (*H. indica* subsp. *bidens*, *H. doleiformis* and *H. pergranulata* subsp. *pergranulata*) on moist soil following a drop in lake levels after spring rain. $EC_{1:5}$ levels at this time were only 2 dS/m in the dunes and 10 dS/m in the mudflat soils (English *et al.* 2002).

The narrow window of opportunity in which saltland pastures species can be successfully established as seed has led to the development of the planting of seedlings of some saltland pasture species to increase success. For example, direct seeding of saltbush, puccinellia and tall wheat grass was a complete failure, three years in a row at Anameka Farms, Tammin, Western Australia and a decision was made that heavy clay soils do not suit direct seeding. Planting seedlings led to success with a good survival rate and grazing was possible after one year (York and York 2004). A comparison by Barrett-Lennard et al. (1991) of niche seeding versus direct planting of nursery-raised seedlings of saltbush found that nursery-raised seedlings were less susceptible to the effects of salinity, waterlogging, dry and/ or cold weather and insect attack. Competition by weeds for light and water was also reduced as the planter blades removed most of the weeds. Planting nursery-raised seedlings is relatively costly compared with direct seeding and therefore there is a need to increase the success of establishment following niche seeding. Barrett-Lennard et al. (1991) suggest that niche seeding is suitable for sandy textured and sand over clay duplex soils where the sandy A horizon is more than 10 cm deep. Malcolm et al. (2003) found that certain ecotypes of river saltbush showed a propensity to volunteer or self-sow which is not common in saltbush. Two volunteering accessions have subsequently been identified 'Rivermor' and 'Meeberrie' (E. Barrett-Lennard, Pers. Comm.). Malcolm et al. (2003) suggest that direct seeding using seed from selections of such ecotypes should increase the rate of success of establishment.

The use of mixtures in saltland pastures is advocated by Barrett-Lennard and Ewing (1998) who suggested that the mix of perennial and annual species should be a 'functional mimic' of the original ecosystem with perennial species being responsible for lowering the watertable, reducing surface soil salinity and reducing wind and water erosion, whereas the annual species would be responsible for the production of fodder for grazing animals. The choice of which species to include would vary depending on climate, levels of soil salinity and waterlogging, and the number of years the farmer was prepared to forego grazing to establish the perennial component of the system (Barrett-Lennard and Ewing 1998). Management of the system would be essential and include factors such as grazing control and plant nutrition through fertiliser applications. Many of the perennial saltland species have small seeds and develop small seedlings that have little initial vigour (compared to annuals?? Ref). These are subject to competition from larger seeded annual species. For example, the field establishment of river saltbush has been shown to be strongly improved by the removal of competing grasses by hand and herbicide application (Vlahos 1997). How therefore should we establish saltland perennials with annuals in such a way that the perennials establish but the pasture is a true mixture? One means of doing this may be to use alley farming techniques, in which the perennials are sown in one or more rows physically separated from bays of annuals. This kind of planting (suggested by Barrett-Lennard *et al.* 2005b) would enable the use of otherwise mutually exclusive herbicide strategies.

Weed management is very important during the establishment of perennials on saltland pastures as most of the first year is spent developing the root system (Vlahos 1997). Competing weeds can therefore easily out-compete perennial seedlings in the first year of establishment (Phelan 2004). Grazing is also an issue with perennials benefiting from no grazing during the establishment year; puccinellia will not withstand grazing in the first year and can be only lightly grazed in the second year (Barrett-Lennard and Holt 1999).

Prob. With late breaks of season as low salinity levels are associated with cold air and in particular soil temperatures. An earlier break warmer soil and air temperatures promote rapid germination and early growth.

Allen (1994 and 1996) for Victoria.

Questions arising under establishment:

a. To what level and for what time period does salinity have to decrease for germination and establishment to occur in halophytes and glycophytes, does this vary with temperature and what is the relationship?

b. What proportion of the failure of saltland plantings can be attributed to inappropriate husbandry/ nutrition/ pest and weed control (site preparation, fertiliser application, insecticides etc.)? Can these factors be prioritised and can we ameliorate them?

c. Is planting a mixture of species the best approach to dealing with the heterogeneity of saline areas? How many species are required and if too narrow a suite is sown is this only suitable for a typical ‘average’ site and not allow for extremes in salinity and waterlogging?

d. Competition can eliminate some species during establishment. It is recognised that having mixtures of saltland species is desirable for improving nutritive value and for filling all available niches within a spatially variable paddock. What is the best method of attaining the desired mixture of saltland species? Should species be sown together, apart or in sequence?

Performance

(Am wondering if this section and nutritive value and grazing sections should be combined. There is a lot of material that would fit into both.)

(Need to develop background paragraph to this section. This whole section still needs a lot of work and little time has been spent on it so far.)

(What level of productivity have been achieved so far from various saltland pastures (t/ha and DSE/ha)).

(Need to check and read, add information from references listed in Table 2? At end of review.)

With reference to the relationship between shoot volume and biomass, there are now a number of published relationships. Barrett-Lennard and Malcolm (1995) and Davidson, Galloway and Lazerescu (1993) calculate shoot volume as $\frac{1}{6} \times \prod \times D1 \times D2 \times H$ (where D1 is the widest diameter of the shoot canopy, D2 is the diameter of the shoot canopy perpendicular to D1 and H is the height of the canopy). Between them, these authors have reported relationships for river saltbush between shoot volume and leaf biomass from 9 different data sets.[1] It is interesting how variable these relationships are (in Barrett-Lennard and Malcolm (1995), slopes of lines of best fit vary from ~0.3 to 0.5 kg of leaf per cubic metre of shoot volume[1]). Presumably these differences in slope (ie. plant leafiness) are mainly due to seasonal differences (soil moisture) in the months prior to harvest. [NB. This can be checked as weather station data should be available for all these studies.]

Can saltbush be used as a form of 'plant-based drainage' as suggested by Barrett-Lennard *et al.* (2005b)? Barrett-Lennard and Galloway (1996) found that there is little growth of river saltbush where the average annual temperature is below 15°C, (earlier Pers. Comm. 8 or 9°C) with the best growth occurring

[1] The data from Barrett-Lennard and Malcolm (1995) were for 18-28 month old river saltbush plants tabulated below:

Location	**Correlation between shoot volume (m^3 - x-axis) and leaf dry weight (kg - y-axis)**	r^2
Esperance	y = 0.497x + 0.223 (n = 23)	0.61
Katanning	y = 0.475x + 0.084 (n = 21)	0.67
Merredin	y = 0.442x + 0.452 (n = 18)	0.56
Tammin	y = 0.291x + 0.552 (n = 12)	0.64
Jacup	y = 0.275x + 0.594 (n = 11)	0.77
Kamballup	y = 0.393x + 0.497 (n = 11)	0.93
Denbarker	y = 0.459x + 0.385 (n = 10)	0.50
Gairdner	y = 0.345x + 1.449 (n = 10)	0.34

over summer. There is a pressing need to establish quantitative relationships between key growth drivers and transpiration if stands of halophytes are to be used as a form of 'plant-based drainage'. A study by Barrett-Lennard *et al.* (1998) suggests that transpiration by trees is reduced under clay soils as the clays reduce the rate of water flow to the tree roots. However they stipulate that these results can not be confirmed and that further work is required.

Melilotus alba has also been suggested as a potential forage pasture species that would help to fill the autumn feed gap (Thompson *et al.* 2001) as it has been recorded as producing up to 10 t/ha dry matter in experimental plots on land with salinity levels varying from 1-5 dS/m, with 70% of the dry matter production occurring between December and the end of February. This high level of dry matter production compared to only 2 t/ha from Persian, balansa and strawberry (*Trifolum fragiferum*) clovers on the same site. *M. alba* has a high nutritive value (75-80% digestibility, however, it does contain some anti-nutritional factors, such as Coumarin, which may affect sheep health (Thompson *et al.* 2001).

Production from tall wheat grass pastures sown in mixtures with balansa clover (*Trifolium michelianum*) and Persian clover (*T. resupinatum*) found that production ranged from 1 to 10 t/ha compared to unimproved pasture plots where production varied between 2 and 5 t/ha (McCaskill and Bennetts 2004). Pasture growth was found to be negatively correlated with both ECe (explaining 95% of the variation) and wetness (a measure of degree of waterlogging) and the authors (McCaskill and Bennetts 2004) suggest that tall wheat grass should not be sown where the Ece level exceeds 25 dS/m. The interaction between salinity and waterlogging is recognised, but is not analysed or discussed.

A demonstration plot of a range of different pastures legumes at Yealering, Western Australia found that there was a large difference in tolerance to both salt and waterlogging and that selections from wild accessions of some species should rapidly lead to cultivars with improved tolerance of both stresses (P. Nichols (DAFWA), Pers. Comm.).

<u>Benefits of applying fertilisers to saltland pastures</u>

Puccinellia is highly responsive to nitrogen application in late winter (Barrett-Lennard and Holt 1999) resulting in an increased growth and number of tillers, improved long term survival, and better feed quality and seed production. The application of urea (100 kg/ha) and superphosphate (75 kg/ha) to puccinellia pastures has been reported to increase pasture mass and sheep liveweight gain by about 8% compared to unimproved and superphosphate-only improved puccinellia pastures in the first year of application (Fenton *et al.* 2004). The increase in pasture growth has been estimated to support 13 DSE/ha over the grazing period, and increase of nearly three times that of the improved puccinellia pasture with no fertiliser application (Edwards *et al.* 2004). Further benefits recorded were the maintenance of pasture mass over late spring/ early summer when feed availability was declining in other treatments and in the subsequent grazing year when the extra feed is used over late summer/ autumn (Fenton *et al.* 2004).

Further benefits have been recorded by adding balansa clover to the pasture rather than urea in both pasture biomass and liveweight gain (Hebart *et al.* 2006), although questions have been raised on the long-term persistence of balansa clover in a moderately saline environment. See McCarthy.

<u>Questions arising under performance:</u>

a) Can plant performance, rather than survival, be related to site conditions? How many soil condition criteria are required and can they be estimated visually?

b) Is plant performance and water use affected by soil texture?

c) There is a benchmark yield for wheat and annual pastures related to annual rainfall (ref.). A similar benchmark does not exist for saltland pasture species. Is it therefore possible to generate one, so that growers know under what conditions saltland pastures can be economically grown, which species or mixture will give them the best economic return, and how their production compares to an 'ideal' maximum?

d) Sites can evolve for a number of reasons including; changed management increases available niches, water-tables are drawn down by plants, soils become less salt-affected or moisture deficient, pioneer plants increase their proliferation, original plants die and new ones are not recruited. For the long-term value of saltland pastures it is important to determine whether production increases, decreases or remains stable with time? What amendments can be made to avoid decline and does grazing change the balance? Also do saltland pastures become more or less saline or waterlogged over time?

Nutritive value and grazing

(This section is saltbush dominant at the moment. Need to expand to include work on other saltland pasture species such as Pucci and TWG. Questions also need to be expanded to include other species.)

(Need section on effect of fertiliser on saltland pastures – Pucci, balansa and burr medic, but also halophytic shrubs (very little). Also what are nutrient deficiency levels of halophytic shrubs, is there a critical concentration. This isn't known and needs to be highlighted in review.)

Grazing saltland pastures has the potential to provide valuable feed reserves during summer/ autumn when dry matter availability of annual pastures is at its lowest (Kelly 2002). The autumn feed gap is normally covered by feeding supplements of grain and hay. However, farms with saltland pastures have the opportunity to be more profitable as they are able to fill the autumn feed gap with a feed resource grown on the farm and to sell the reserved grain and hay (O'Connell and Young 2002; Phelan 2004). Thompson et al. (2002) concluded that sheep grazing saltland pastures at a site in south-west Victoria during summer/ autumn were heavier during pregnancy and at shearing in July, and produced better quality wool than sheep grazed under 'normal' conditions on non-saline land.

Halophytes are of value to grazing animals because they often contain high nitrogen concentrations (values of more than 2% dry weight are common – (Barrett-Lennard *et al.* 2003) which may be converted into protein in the rumen (given sufficient energy). At least part of this nitrogen may be in the form of the small molecular weight amino acid glycinebetaine (which plays a key role in halophyte osmotic adjustment – Storey *et al.* 1977) and nitrates (Norman *et al.* 2004b). Halophytes also tend to accumulate high concentrations of salt in their leaves (for saltbush, ash concentrations of 20–30% in dry leaves are common – (Barrett-Lennard *et al.* 2003). These high salt loads are likely to restrict the intake of saltbush to below 1 kg/head/day for sheep (Masters *et al.* 2005b), and this may restrict liveweight gain or even cause liveweight loss when saltbushes are the major component of the diet. Masters et al. (2005b) suggest that even if halophytic shrubs such as saltbush and bluebush only make up 25 to 30% of the total diet sheep, production will be depressed, and with more that 30% it is unlikely that sheep would be able to consume sufficient quantities of digestible organic matter to grow. Plants growing in saline areas also tend to accumulate other secondary compounds, such as oxalates, coumarins and tannins, which can adversely affect palatability, feed intake and animal health (Masters *et al.* 2005a).

A study conducted on the nutritive value of four species of halophytic shrubs collected from five saline environments in Western Australia (Tiong *et al.* 2004) found that *Atriplex nummularia* and bluebush (*Maireana brevifolia*) had the highest digestibility and crude protein content respectively and were therefore preferable to *A. amnicola* and *A. undulata* for providing summer/ autumn forage. However, it is unknown from the report the age of the leaves that were sampled for the study. Nutritive value studies usually analyse new fully expanded leaves on a plant (ref?). However in saltbush the leaves continue to expand until they senesce and drop off the plant (Barrett-Lennard, Pers Comm.). Therefore a protocol is required on when to sample leaves for nutritive analysis in halophytic shrubs for species where the leaves do not stop expanding.

The key to the productive use of halophytic forages therefore appears to be to mix the feed with other less salty and complementary sources of fodder, such as hay (Warren *et al.* 1990), perennial grasses (Warren and Casson 1992) or annual legumes such as balansa clover and burr medic (Craig 2002; Phelan 2004). Moderate levels of liveweight gain (40 to 90 g/ day) have been reported in 15-month old ewes fed tall wheat grass (*Thinopyron ponticum*) and melilotus (*Melilotus alba*) over spring and summer (Thompson *et al.* 2001). In a number of pen and field trials, feeding sheep a 50:50 mixture of saltbush leaf and roughage led to doubling of feed intake, increased digestibility and liveweight gain of about 70 g/day compared to feeding saltbush or hay alone (Warren *et al.* 1990). There is also the opportunity of increasing the nutritive value of the saltbush through selection and breeding as stands are still mainly established from wild sources of seed. Grazing trials on old man saltbush and river saltbush recorded greater liveweight gain over 50 days on sheep fed old man saltbush compared to river saltbush (Barrett-Lennard *et al.* 2005b; Norman *et al.* 2004a). The main difference between the two species was feed quality with the old man saltbush having lower acid detergent fibre and neutral detergent fibre (Norman *et al.* 2004a).

A study comparing the preference of sheep for two saltbush species; old man saltbush (*A. nummularia*) and river saltbush (*A. amnicola*) (Norman *et al.* 2004b) found that sheep preferentially grazed river saltbush, but the authors (Norman *et al.* 2004b) could not relate the preference to compositional characteristics, such as digestibility of dry and organic matter, crude protein and percentage ash, oxalates and nitrates of the two species. Other factors therefore influenced preference. It has since been suggested that under continuous grazing wavyleaf saltbush is slowly removed from the pasture due to preferential grazing, resulting in no recovery from grazing and subsequent death (H. Norman & E. Barrett-Lennard, Pers. Comm). When sheep are given a choice of diets with a range of sodium chloride concentrations and energy concentration, the availability of low salt alternative species will allow the sheep select for a mixed diet and therefore to increase intake and growth compared to being fed an exclusive high salt diet (Thomas *et al.* 2006). Even on highly saline sites there will be a choice of species available to sheep to graze, and these will vary in salt and ion composition, digestible energy and crude protein (Masters *et al.* 2006).

Differential grazing pressure on component species of a pasture leads to the debilitation of some species by grazing at high stocking rates and the subsequent change in vegetation composition (Norton 1986). Comparison of set-stocking versus rotational grazing found that set-stocking eliminated susceptible species such as wavy-leaf saltbush and encouraged weeds cover (refs). A higher stocking rate can be achieved if rotational grazing is performed as it forces the animals to eat a more equal mix of the feed on offer (Phelan 2004). Continuous browsing of saltbush encourages the development of woody branches, thus reducing palatability, whereas heavy rotational grazing leads to increased production of palatable new growth with a lower salt concentration in the leaves (Masters *et al.* 2001; Schultz 1996). A study by Wilmot and Norman (2006) also found that saltbush biomass did not increase if the plants were left ungrazed during autumn due to leaf drop during autumn and spring. It is important to note that most of data on which stocking rate – animal production models have been based are from short-term trials, yet the interaction between plant regeneration and competitive ability with stocking rate increased the longer the heavy grazing pressure is imposed (Norton 1986). The influence of climate is rarely accounted for, yet may be an important factor in determining the interactions of species with and without grazing (Norton 1986). For example in grazing management studies of rangelands in south-west Utah containing *Atriplex confertifolia*, *Artemisia spinescens* and *Ceratoides lanata*, Norton (1978) concluded that the proportion of *C. lanata* was not influenced by grazing, that *A. confertifolia* increased under grazing and that *A. spinescens* increased when grazing was removed, the later two species working in a complimentary fashion replacing each other depending on whether grazing was included or excluded from the rangeland.

However, further statistical analysis on the data (Norton 1986) found that the relationships were more complex than originally thought and that the climate during the study period may be important. However measurements were not taken frequently enough to confirm the effect of climate.

Wool growth and fibre diameter are both depressed in sheep fed diets high in sodium, however the amount of wool produced per kg of organic matter intake increased (Masters *et al.* 2005b). Sheep grazed on improved pastures of puccinellia with superphosphate and either urea or balansa clover showed an increase in clean fleece weight and wool yield (Abraham *et al.* 2006) and increased staple strength (Edwards *et al.* 2004). A mixed pasture with Puccinellia and balansa clover also showed a significant increase in fibre diameter, which is undesirable. However, it is suggested that increasing the stocking rate of these productive pastures will reduce the amount and diameter of wool from individual animals (Abraham *et al.* 2006). The digestibility of Puccinellia has been calculated to range from 46% before the break of season to 65% in June, with the digestible crude protein varying between 2.5% (dry stalk only) and 18% over the same time period (Morris 2001). From these studies it is estimated that the feed value of puccinellia is at its best between June and October.

A review on the effect of herbivory on saltland marshes can be used to indicate the response of saltland pasture plants to grazing (Ungar 1998). For example, heavy grazing on saltland marshes eliminates sensitive species and can result in either a dense covering of grass species or in bare patches that allow annuals and other low marsh species to invade high marsh communities. Intermediate levels of grazing by sheep, cattle and horses promotes the highest species richness and heterogeneity (Ungar 1998). Bakker (1985) found that species richness in the mid- and upper marsh in the Netherland increased by 13 species under grazing, compared to mowing (nine species) and untreated salt marshes (2 species) over a ten year period from 1971 to 1981. In shrubland communities on saline soils in Western Australia grazing increased the density of some species such as *Eremophila maculata* and *E. delisseri* and decreased the density of others, namely; *Atriplex vesicaria*, *Aizoon quadrifidum* and *Maireana pyramidata* (Hacker 1987).

<u>Questions arising under nutritive value and grazing:</u>

a) When is the best time to graze saltbush to maintain saltbush persistence and growth?

b) What is the nutritive value and persistence of saltbush under rotational grazing compared to set-stocking?

c) What is the best time and how frequently should puccinellia and tall wheat grass be grazed to obtain maximum nutritive value from the pasture and stop the pasture going rank?

d) What is the optimal time saltland pastures should be left to establish before they can be grazed?

Concluding comments

Saline soils occupy an increasing proportion of the world's surface area. If we observe the key drivers of natural saline ecosystems we have the chance to produce stable and productive functional mimics of these in degraded landscapes. This paper provides a review of the ecology of natural saltland systems and how the knowledge gained on the zonation of species in these saltland systems can be extrapolated to agricultural saltland systems using the salinity/ waterlogging matrix and finally develops further the concepts of the salinity/ waterlogging matrix to develop a practical land capability assessment that can be used by landholders to plan successful and productive saltland pastures.

The hypothesis of the salinity/ waterlogging matrix is that if plant species are planted together they will separate themselves into certain places in the landscape in relation to each species tolerance to salinity and/ or waterlogging and to competition from the other species. There is an urgent need for this hypothesis to be tested both in the field and under controlled conditions; the ecological transplant studies of Bertness (1991b) need to be conducted using agricultural species in an agricultural saline landscape and controlled salinity and waterlogging pot experiments are required to determine the competitive advantage of different species under certain conditions.

The land capability assessment has been developed using data available in the literature. There is an urgent need for the assessment to be tested using long-term transect trials to determine if predictions of which species or mix of species should be sown to develop successful and productive pastures are accurate.

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Table 1. Survival of saltland pasture and other indicator species under salinity, waterlogging and the combined environmental stresses, as reported by various authors. Information from this table was used to develop the salinity/ waterlogging matrix in Figure 1.

Species	**Salinity**	**Waterlogging**	**Combined**	**Reference**
Wheat and Barley	50% decrease in yield at ECe 13 dS/m (wheat) and ECe 18 dS/m (barley)		Low yields at ECe 3-6 dS/m and moderate waterlogging	(Barrett-Lennard *et al.* 1999; Maas 1986)
Black-seeded samphire (*H. pergranulata* subsp. *pergranulata*)	Optimal growth at 10-200 mol m^{-3} NaCl, survived to 800 mol $m^{-3.}$ Survived at EC values in soil water of 200-300 dS/m		Waterlogging had little effect on growth at 80 dS/m	(English *et al.* 1999; 2001; Short and Colmer 1999)
Saltbush *(Atriplex lentiformis* & *A. nummularia*)			Survived irrigation with sea water (55 dS/m)	(Watson *et al.* 1987)
River saltbush *(A. amnicola*)	10% increase in shoot weight at 5 dS/m, 50% decrease at 40 dS/m, still alive at 75 dS/m		Survived brief water-logging at 40 dS/m	(Barrett-Lennard 2002; Galloway and Davidson 1993)
Saltbush (*Atriplex* sp.)	Grew well at salinity levels of 25 dS/m			(Barrett-Lennard *et al.* 2003)
Small-leaf bluebush (*Maireana brevifolia*)	Grew in soil water EC values of 60 dS/m	Did not survive prolonged water-logging		(Malcolm 1963; Malcolm and Swaan 1989)
Puccinellia (*Puccinellia ciliata*) & tall wheat grass (*Thinopyrum ponticum*)	Survives ECe 40 dS/m; best growth at 16-32 dS/m. 50 % decrease in growth at about 25 – 28 dS/m in drained conditions	Puccinellia is highly tolerant of waterlogging and can withstand periods of partial waterlogging. Tall wheat grass is less tolerant that puccinellia		(Marcar 1987; Rogers and Bailey 1963; Semple *et al.* 2003)
Kikuyu (*Pennisetum clandestinum*) & Rhodes grass (*Chloris gayana*)	50% decrease in yield at ECe values of 21 (Kikuyu) and 23 dS/m (Rhodes) under drained conditions.		In winter waterlogged soils, best growth at 12 to 20 dS/m	(Russell 1976; Semple *et al.* 2003)
Balansa clover (*Trifolium michelianum*)	50% decrease in growth at ECe7 dS/m	Highly tolerant of waterlogging, will grow in standing water and forms aerenchyma		(Rogers and Noble 1991)

Notes for Table 1: Puccinellia and tall wheat grass are less tolerant of salinity than saltbush and bluebush, but more tolerant that Kikuyu and Rhodes grass. Puccinellia more tolerant of waterlogging than saltbush, but tall wheat grass is less tolerant than saltbush (Barrett-Lennard *et al.* 2003). Kikuyu and Rhodes grass have a similar level of waterlogging tolerance to saltbush.

Appendix 2

From principles to practicalities – diagnosing the capability of land affected by salinity and waterlogging

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Abstract

This review considers the issue of targeting plants to saline landscapes. A range of recent research has shown that saltland varies in its ability to support plant growth: economic gain is achieved by focusing revegetation into areas of highest capability. The review focuses on two factors that affect capability – salinity and waterlogging. Both salinity and waterlogging are highly temporally and spatially variable. Plant ecological zonation on saltland is a reflection of the ability of plants to integrate and adapt to this variation.

The review has three parts:

4. We summarise the current means by which salinity and waterlogging are measured in Australia.
5. We summarise how salinity and waterlogging affect the "competitive advantage" of plants on saltland in southern Australia.
6. We suggest three criteria by which saltland may be broadly categorised in terms of its capability for economic production. These are: (a) can a plant use the groundwater for growth, (b) is the soil water above the water-table suitable for use, and (c) is oxygen available for root-growth and function.

We conclude that broad land capability assessments may be possible by considering the distribution of rainfall, and by examining the depth, salinity and pH of the groundwater, the soil texture above the water-table and the bulk salinity of the soil as determined by electromagnetic induction using the EM38.

Introduction

Although salinity has adversely affected agriculture for thousands of years, the recognition that salt-affected land can be used for agriculture is quite recent. Initially the focus was on the better use of land that was becoming salinised because of irrigation problems – use of brackish water, use of water with a sodicity hazard and/or the development of shallow water-tables; more recently the focus has moved to "dryland salinity" – land salinised because of rising water-tables associated with the replacement of perennial with annual vegetation (Ghassemi *et al*. 1995).

In Australia, interest in saltland revegetation began in the 1940s and 1950s when tall wheat grass (*Thinopyrum ponticum*), salt water couch (*Paspalum vaginatum*), small leaf bluebush (*Maireana brevifolia*), old man saltbush (*Atriplex nummularia*), and creeping saltbush (*Atriplex semibaccata*) were promoted for saltland revegetation (Teakle and Burville 1945; Smith and Malcolm 1959). The first screening of herbaceous germplasm (69 grasses and forbs) occurred from 1954 to 1959 (Rogers and Bailey, 1963) and resulted in the release of puccinellia (*Puccinellia ciliata*), and subsequent screenings of halophytic shrubs (Malcolm and Clarke 1971; Malcolm and Swaan 1989) resulted in the widespread use of wavy-leaf saltbush (*Atriplex undulata*) and river saltbush (*Atriplex amnicola*).

If anything, the interest in the use of saline land resources has escalated over the last twenty years. Epstein (1985) restated the case for the breeding of salt tolerant crops, there was a renewed focus on the use of saline irrigation water (Rhoades *et al*. 1992), the International Centre for Biosaline Agriculture was established in 1996 (ICBA 2000), and there was a renewed focus on saline agriculture in a range of countries including Pakistan (Qureshi and Barrett-Lennard 1998) and Australia (Barrett-Lennard and Malcolm, 1995; Marcar *et al*. 1995; Powell, 2004; Robins 2004).

Salinity and waterlogging as causal agents in ecological zonation

Ecological zonation on saltland is influenced to a substantial degree by the concentrations of salt in the soil (salinity) and by waterlogging. The influence of salinity is no longer surprising: the term 'halophyte', a plant of saline environments, has been recognised since about 1790 (Flowers *et al.* 1986). However the recognition of the importance of waterlogging as a constraint that affects plant ecological zonation in saline landscapes derives mostly from work conducted since the 1970s (reviewed by Barrett-Lennard 2003; Bennett *et al*., 2007). At the physiological level plants respond to saline soils, primarily by excluding salt at the root surface. Waterlogging causes oxygen deficiency (hypoxia) in soil and this impairs a range of root functions, including the ability of plants to regulate their salt uptake; with increased salt concentrations in the shoots, plant growth and survival can be impaired (reviewed by Barrett-Lennard 2003).

Understanding the principles of ecological zonation on saltland has practical implications for the agricultural use of saltland. It is increasingly recognised that for agricultural systems to be sustainable, they need to operate to a significant degree as 'mimics' of natural systems (Ewel 1999; Hatton and Nulsen 1999). It has been argued that saltland should be regarded as having a range of capabilities based on the severity of salinity and waterlogging (Barrett-Lennard *et al*. 2003). Furthermore, there can be strong economic gains from recognising differences in saltland capability. For example, in the 300–500 mm rainfall zone of southern Australia it has been recognised that the commercial value of saltland is strongly affected by the types of plants that it can grow. Severely affected land that will only grow the most salt and waterlogging tolerant perennial samphire (*Halosarcia* species) has no commercial value and should be protected from grazing and allowed to revegetate naturally (Barrett-Lennard, 2000). However, moderately and mildly affected land can be of economic value. Moderately affected saltland will grow relatively dense (~1,000 stems/ha) stands of saltbush (*Atriplex* species) which can be used for grazing provided that the animals receive a feed (energy) supplement (Masters *et al*. 2006, Norman *et al*. 2007a), and mildly affected land will grow alleys of saltbush with highly productive annual legume under-storey, which can be used for the grazing of growing sheep (Masters *et al*. 2006, Norman *et al*. 2007b; O'Connell *et al*. 2005).

Quantification of salinity and waterlogging in the landscape

Measurement of salinity

A saline soil is one in which the level of electrical conductivity exceeds a certain level such that it impacts on natural and human assets (Rogers *et al*. 2005). This level varies with soil type; for example a red brown earth is defined as being affected by salinity when the $EC_{1:5}$ exceeds 0.3 dS/m (Rengasamy *et al*. 1984). However, one of the most important aspects of salt-affected sites is that the salt concentration varies considerably between seasons, years, depth and across a site. This variability results in a mosaic of conditions that suits plants from mildly saline-tolerant non-halophytes through to highly salt tolerant halophytes (Rogers *et al*. 2005). Variations of up to an order of magnitude have been recorded in the concentration of chloride on a soil dry weight basis over depths and widths of less than 1 meter (Teakle & Burvill, 1938).

Today, soil salinity is commonly determined as the electrical conductivity of the "saturation paste" or the "1:5 extract" (abbreviated as the EC_e and $EC_{1:5}$ respectively).

The EC_e is a laboratory technique and it is more expensive to measure than the $EC_{1:5}$. However, the EC_e is the most reliable and widely accepted measure of comparing salinity concentrations between soil types, and is widely regarded as the 'universal standard'. A saturated soil paste is made by adding distilled water to a ground sample of soil while stirring with a spatula. At saturation, the soil paste glistens as it reflects light, flows slightly when the container is tipped, and slides freely and cleanly off the spatula for all soils but those with a high clay content. The soil saturation extract is prepared by aspirating the water from the saturated soil paste. In contrast, the $EC_{1:5}$ is determined by mixing one part by weight (g) air-dried soil to five parts by volume (mL) of distilled water, which is agitated and then allowed to settle (Anon., 2005).

The relationship between EC_e and $EC_{1:5}$ is affected by soil texture because the saturation percentage is higher for clays than loams and sands (Anon., 2005). George and Wren (1985) have derived the following rule of thumb:

EC_e = (364 * $EC_{1:5}$)/saturation percentage

This gives approximate values for the ratio $EC_e/EC_{1:5}$ of ~8 for clays (saturation percentage ~45%), ~11 for loams (saturation percentage ~32%) and ~14 for sands (saturation percentage ~25%). Because of the lower cost of measurement, many researchers convert $EC_{1:5}$ values to EC_e values using published conversion factors. However, it should be stressed that there are no universally accepted conversion factors across Australia, and an EC_e value calculated in this way should be regarded as an approximation.

It is important to note that salt concentrations in the soil solution are a function of both the salt concentration in the soil, and the moisture concentration in the soil. Salt concentrations in the soil solution can therefore increase because of an increase in the salt concentration in the soil, or because the soil becomes drier through evapotranspiration. The soil drying factor is not considered when salinity is determined as the EC_e or $EC_{1:5}$ – in these instances water is added to the soil to a standard level. Therefore reported soil salinities are not the same as the concentration that the plant roots are experiencing in the ground, although the EC_e comes close – it is the salinity that a plant root would experience in a saturated soil.

Salt concentrations in the soil solution of the rhizosphere can also be affected by the transpiring activity of plants. In saline environments, transpiration results in a mass flow of water and salt through the soil to the root surface (Sinha & Singh, 1976). This is greater in areas with high evaporative demand, such as arid and semi-arid areas (Sinha & Singh, 1974). Net accumulation of salt around the roots also occurs in these areas as the salt concentration of the water increases as it gets closer to the roots as a result of transpiration and subsequent water depletion near the roots (Sinha & Singh, 1976). This has been observed in non-salt tolerant glycophytic crops such as corn (Sinha & Singh, 1974) and wheat (Sinha & Singh, 1976) and in salt tolerant halophytic species such as saltbush (Barrett-Lennard & Malcolm, 1999) and puccinellia (Zhang, Tang & Rengel, 2005). (

(This para still needs some estimations of the extent of the increase from the cited papers.
Also check references by Heupermann and Thorburn)

Comparisons of salinity classes across southern Australia

A summary of the Australian state salinity classifications are given in Table 1. However, there have been complications trying to draw up the simple table shown, as EC_e values are preferred in Western Australia and South Australia, and $EC_{1:5}$ values are preferred by the State of Victoria and the Murray

Darling Basin Commission, and we have had to infer a common soil texture to convert the Victorian and MDBC criteria to EC_e values. Even within Victoria there are two classifications with three classes in the published spotting soil salinity guide (Matters & Bozon, 1995) and five classes in the classification used by the Landscape Systems, Spatial Sciences Section of the Department of Primary Industries (R. Clark, pers. comm.).

Table 1. Salinity classes (converted to EC_e values; dS/m) from state classifications assuming a loam soil. A comparison is also provided with the UN salinity classification.

Salinity classes	**WA**[1]	**SA**[2]	**Vic**[3*]	**MDBC**[4*]	**FAO/ UN**[5]
Lowest salinity class	Non-saline <2	Non-saline 0-2	-	Not affected 0	
↓	Slightly 2-4	Low 2-4	Low <6	Slightly 2-4	
↓	Moderately 4-8	Moderate 4-8	Moderate 6-14	Moderate 6-14	Saline phase 4-15 in upper 1.0 m
↓	Very 8-16	High 8-16	-	-	-
Highest salinity class	Extremely >16	Severe >16	Severe 14-35	Severely >14	Solonchak > 15 in upper 0.75 – 1.25 m

* calculated from published $EC_{1:5}$ values, assuming a loam soil type.

[1] Anon. (2005)
[2] Henschke & Herrmann (2005)
[3] Matters & Bozon (1995)
[4] Anon. (2002), adapted from Allen (1996)
[5] Dudal & Purnell (1986)

A second type of classification is provided by Martin and Metcalf (1998) based on loss of productivity of land in relation to degree of salinity and presence of salt tolerant vegetation. However, no absolute salinity measurements are given with this table (see Table 2). The use of plants as salinity indicators is not new, but allows for a quick and cheap method of determining the level of salinity. This is useful for landholders, who do not have access to the expensive equipment necessary to accurately measure soil salinity within a paddock.

Table 2. Classes of salt-affected land (from Martin & Metcalfe, 1998)

Class	Description
Not at risk	Land not susceptible to salinity, regardless of land use of management
Stable	Land susceptible to salinity, but unlikely to become saline under the current land use of management
At risk	Land susceptible to salinity and likely to become saline under the current land use of management
Slightly affected (<10% decrease in productivity)	Land with reduced productivity from non-salt tolerant plants, some salt tolerant plants present, seasonally or permanently shallow watertable and some small bare areas
Moderately affected (10-50% decrease in productivity)	Land showing a significant loss in non-salt tolerant plant, salt tolerant plants common seasonally or permanently shallow watertable, bare areas up to 5m² in size, some erosion present
Severely affected (>50% decrease in productivity)	Land showing an absence of non-salt tolerant plants, permanently shallow watertable, large bare areas which are often badly eroded.

There is a clear need for an Australia-wide soil salinity classification, that is easy to use, compatible with state classifications and that links soil salinity to plant indicators.

Measurement of waterlogging

(This needs a bit more introduction about hypoxia as the causal effects of waterlogging. Setter and Waters is good on this.)

The SEW_{30} (the sum of excess water above a soil depth of 30 cm), is an index of waterlogging intensity that has been developed by Sieben (1964) to integrate: (a) the height of the watertable above the critical depth of 30 cm, and (b) the duration (in days) that the watertable is above this depth. Its use is based on a number of assumptions discussed below (McFarlane *et al*. 1989).

1. It assumes that plant yield begins to be negatively affected when the watertable rises above the critical depth of 30 cm from the soil surface. The SEW_{30} was developed using cereals, but the 30 cm critical depth constituting the limit for damage in these annual plants is unlikely to apply to perennial plants with deeper roots. Further work is required on a wider range of annual and perennial crop and pasture species to determine how growth is affected by different depths of waterlogging, and what critical depths would be appropriate for this wider range of species.
2. The index also assumes that the adverse effect of waterlogging on plants follows a linear increase in relation to an increase in the watertable above 30 cm and as the number of days of waterlogging (duration) increases. The relationship in this index allows comparisons to be made across treatments and field situations, for example a five day waterlogging treatment at the soil surface and a 15 day waterlogging treatment at a soil depth of 20 cm both have an equal SEW_{30} of 150 cm days (Malik *et al*., 2001). The comparison between treatments or field sites is useful, but is it accurate? Are the effects of waterlogging for five days and for 15 days really comparable, even though the 15 day waterlogging treatment did not reach the soil surface?
3. That recovery of plant growth is linear in relation to previous level of waterlogging. However Malik *et al*. (2001) found that plant biomass after 14 days recovery was no longer proportionally affected by the previous level of waterlogging, with plants subjected to waterlogging at the soil surface and at 100 mm below the soil surface having a similar mass. Malik *et al*. (2001) suggest that the reduced rate of recovery is due to a smaller capacity for assimilation in these two treatments as a result of fewer photosynthetically active leaves being available at the end of the waterlogging treatment and due to a slow recovery of rate of photosynthesis.
4. Even very short waterlogging events can result in a severe reduction in the growth of crops depending on their growth stage. A three day waterlogging treatment resulted in no visible adverse effects on wheat shoots, but after a 25 day recovery phase the plants more closely resembled plants under continuous waterlogging, than those that had been grown in continusously drained soils (Malik *et al*., 2002). The severity of the effect of waterlogging appears to vary depending on the growth stage of the plant; the wheat in the study by Malik *et al*. (2002) was at the vegetative stage, where as a study by Meyer and Barrs (1988) on waterlogging of wheat at the stem elongation stage found no adverse effect on final grain yield. The linear relationship of SEW_{30} to waterlogging will therefore vary depending on the growth stage of the crop when subjected to waterlogging.

5. Waterlogging of the soil is temporarily very variable. It does not increase to a set depth from the soil surface, stay there for a nominated duration and then recede, but varies temporarily in relation to rainfall events, soil temperature, soil surface evapotranspiration and localized plant water use. This can clearly be seen in Figure 1 below which shows the measurement of depth to watertable from the soil surface using a hydrograph. The SEW_{30} is the grey shaded part of the graph above the 30 cm soil depth.

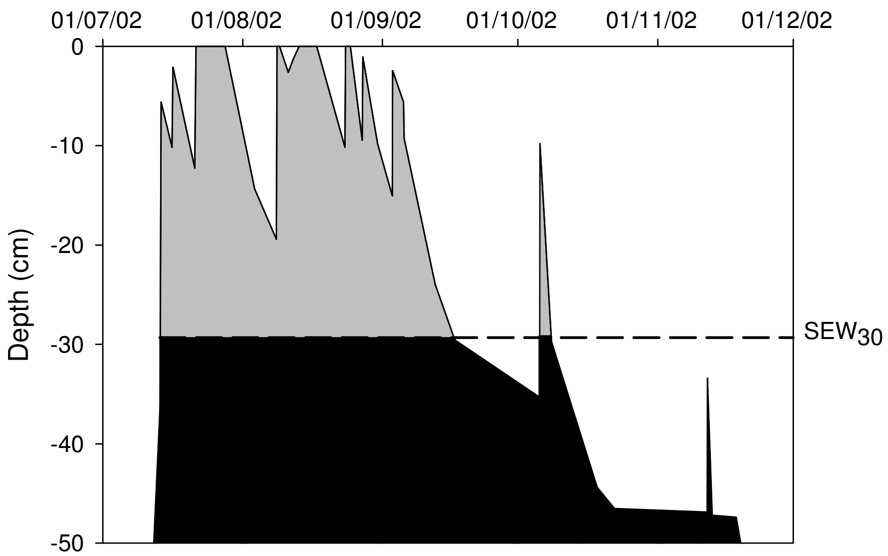

Figure 1. Hydrograph showing variation in depth to watertable over time at a site at Narrogin, Western Australia, from McFarlane, Barrett-Lennard and Setter (1989). Grey shaded area is SEW_{30}.

• Further temporal variation in the effect of waterlogging occurs between seasons and between sites (McFarlane, Barrett-Lennard & Setter, 1989; Setter & Waters, 2003). For example studies in Western Australia at a number of sites and years (McFarlane, Barrett-Lennard & Setter, 1989) found that at Mount Barker in 1984 oat yields were not affected by waterlogging until the SEW_{30} exceeded 500 cm days, yet at Yornaning in 1987 both oat and spring wheat yields decreased by 520 to 550 kg/ha with every 100 cm days with no initial threshold, and at Narrogin in 1985 spring wheat yields decreased by about 56 kg/ha per 100 cm days again with no threshold. The authors (McFarlane, Barrett-Lennard & Setter, 1989) concluded that variations could be the result of different cultivars, soil and/ or environmental conditions.

• Waterlogging varies spatially across a paddock and therefore the effect of waterlogging on crop yield will also vary spatially across the paddock. This is shown in Setter and Waters (2003) where several hundred piezometers were installed across a paddock and the level of the watertable recorded on daily or weekly basis. The resulting values were used to produce SEW_{30} waterlogging intensity maps. Setter (2000) found that in duplex soils the duration and timing of waterlogging may vary by up to 400-fold over a distance of only 50m, and that these differences were sometimes recorded where there was no observable difference in the surface topography.

An alternative measure of waterlogging is therefore required that accounts for the other interacting factors which affect plant growth.

Temporal and spatial variation of salinity and waterlogging

Problems not only exist in the measurement of salinity and waterlogging, but also in the variation of both over time and across small areas. When should levels of soil salinity and waterlogging be measured over the year? Waterlogging is known to increase over the winter months and to decrease over the summer months (McFarlane, Barrett-Lennard & Setter, 1989), but when is the best time to record it, how often should it be measured, and when levels are described in the literature are they referring to summer or winter levels? Which time of year is the most stressful to the plant – winter when they are subject to waterlogging and possibly periods of inundation, or summer when they are subject to drought? Similar variation has been recorded in levels of salinity with levels falling over winter due to leaching by winter rains and rising again in spring and summer due to evapotranspiration (Smith, 1962). The main stress occurs over the summer months when levels of soil salinity are greatest, but knowledge of the levels over the late autumn and winter months are also important as this is when annual species are active, but also when all species are germinating and establishing and the level of salinity at this time can be critical for successful germination and establishment (Ungar, 1978).

Spatial variation in both waterlogging and salinity is as variable as temporal variation with levels varying dramatically within a paddock. For example, Teakle and Burvill (1938) noticed that a badly salt-affected area with no supporting vegetation would be immediately adjacent to a grassed area with low surface salt. Soil salinity is an important factor in determining the growth and establishment of saltland plants, but both the spatial and temporal variation in salinity are affected by the amount of water in the soil (Bush, 2006) leading to difficulties in determining the level of salt in the soil across a site. Therefore how many measurements should be taken across a study area and what is critical level (minimum, maximum, average or range) when making decisions about what species should be sown at a particular site.

(Blom *et al*., 1990) zonation of *Rumex* species along river foreland. Long-lived polycarpic perennials occupy the higher elevation zones that are rarely flooded in summer, short-lived polycarpic perennials occupy the infrequently flooded transitional zone and annual, biennial and short-lived monocarpic perennial species occupy the zone that is frequently flooded and commonly waterlogged. Those species that are frequently flooded showed a root response of aerenchyma development with an associated increase in root porosity and length, resulting in continued aeration of the roots and continued uptake of essential macro-nutrients (Voesenek *et al*., 2006). Increased shoot length is a response to ethylene production during periods of waterlogging (Blom *et al.*, 1990), however flooding intolerant species have been found to show inhibited growth during periods of complete submergence as a result of inhibited ethylene diffusion to the atmosphere. Reproduction methodology varied dramatically between two flooding tolerant species studied. *Rumex maritimus* is able to survive long periods of waterlogging and periods of complete submergence by surviving as vegetative plants. If flowering has commenced when flooding occurs then abortion of the flowers resulted. In contrast *Chenopodium rubrum* attempts to flower and set seed in the short periods between flooding events. It does not tolerate prolonged flooding events, and even prolonged waterlogging appeared to be a threat to survival. Its only survival strategy was to produce large numbers of seed between flooding or waterlogging events (Blom *et al.*, 1990).

Blom *et al*. (1990) suggest that the use of indicator species such as *Rumex* and *Chenopodium* are essential in understanding the mechanisms used to survive and adapt to different waterlogging and inundation regimes that occur as a result of flooding events. It is important to understand that there are different life-history strategies used to adapt to flooding that are dependent on the perenniality of the species under study. (Grazing, even by rabbits, can interfere with survival mechanisms as heavily grazed plants are not able to reproduce and thus depletion of the seedbank occurs).

Populations of samphire (Halosarcia pergranulata) growing on playas of mudlfats in Western Australia are subjected to months of waterlogging and in some cases complete submergence. Pedersen *et al*. (2006) attributed the tolerance of samphire to these stresses to their ability of their basal woody stems to photosynthesise O2 and that this O_2 production is an important source of O_2 for the roots.

Salinity, waterlogging and the "competitive advantage" of plants on saltland

Exploiting the view that ecological zonation in saltland is due primarily to salinity and waterlogging, Barrett-Lennard *et al*. (2003) developed a salinity/waterlogging matrix to explain the relative tolerance of saltland plants, in which the plants that commonly grow on saltland southern Australia were ranked against each other (Figure 2). This matrix was based on an assessment of the literature available at that time (summarised in Appendix). The matrix has proven to be a useful tool in understanding ecological zonation in Australian landscapes and has been cited in several documents seeking to explain plant location in variable landscapes to lay audiences (Powell 2004; Saltland Pastures Situation Statement 2007).

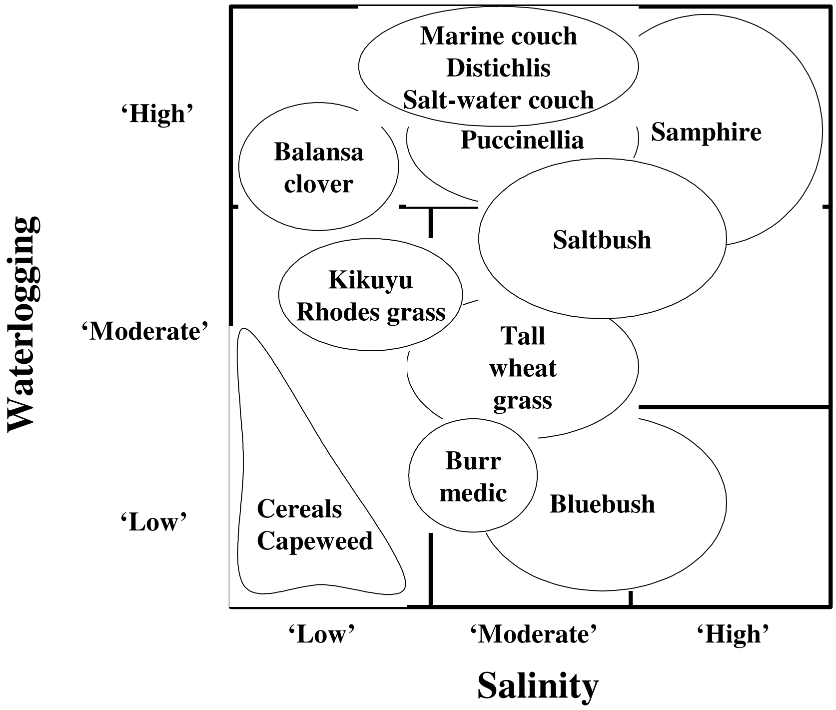

Figure 2 Relative tolerances to salinity and waterlogging of different saltland pasture species from southern Australia (after Barrett-Lennard *et al*., 2003). Species are: balansa clover (*Trifolium michelianum*), burr medic (*Medicago polymorpha*), bluebush (*Maireana brevifolia*), cereals (*Triticum aestivum*, *Hordeum vulgare*, etc), distichlis (*Distichlis spicata*), kikuyu (*Pennisetum clandestinum*), marine couch (*Sporobolus virginicus*), puccinellia (*Puccinellia ciliata*), rhodes grass (*Chloris gayana*), saltbush (*Atriplex* sp.), salt-water couch (*Paspalum vaginatum*), samphire (*Halosarcia* sp.) and tall wheat grass (*Thinopyrum ponticum*).

More recent research has strengthened the case for the matrix. One species (burr medic – *Medicago polymorpha*) has been added to Figure 2 based on recognition that the plant has moderate salt tolerance, but low waterlogging tolerance (M Rogers and T Colmer, unpublished data). Furthermore the relative rankings of puccinellia and tall wheatgrass have been reinforced by the studies of Jenkins (2007) which have shown that the ecological zonation between these two species is based primarily on the exceptional waterlogging tolerance of puccinellia under saline conditions.

While the salinity/waterlogging matrix has strengths, it also has significant limitations.

1. There has been ambiguity regarding what the circles in the matrix symbolise (best growth or survival perhaps). We can state that it was originally felt that the circles in the matrix indicated the likely relative "competitive advantage" of the species in landscapes of different intensities of salinity and waterlogging, but this was never clearly explained (Barrett-Lennard *et al*. 2003). As the matrix was developed primarily based on an understanding of the relative salt and waterlogging tolerance of the species, extrapolation to "competitive advantage" is clearly hypothetical.

2. The matrix contains both annual and perennial species with differences in rooting depth. It is not clear over what soil depth "salinity" and "waterlogging" should be assessed but clearly the critical depths would vary between shallow-rooted annuals and deeper rooted perennials.

3. The matrix presents no guidelines for land capability assessment (discussed further below).

Criteria for land capability assessment

Recognising that levels of salinity and waterlogging were hard to integrate into meaningful numbers, the devisers of the matrix did not attach numbers or units to their labels of "low" to "high" salinity and waterlogging. And this was acceptable while the matrix was only used to map the relative competitive advantages of species. However, the limitations to this approach become clear as we move towards diagnosing land capability – quantitative criteria need to be developed by which the land can be categorised. One of the problems with using salinity and waterlogging to explain differences in saltland capability is that these factors are highly variable. Salinity fluctuates seasonally as a result of leaching by rain and salt accumulation at the soil surface through capillarity (Smith and Stoneman, 1970). It is also affected by soil cultivation treatments (Smith 1962), the mulching effects of clumps of annual or perennial plants at the soil surface (Teakle and Burville 1938; Smith 1962, Jenkins 2007), and the accumulation of salt in the root zones of deeper-rooted perennial plants (Heupermann, 1992, Thorburn 1996, Barrett-Lennard and Malcolm, 1999). Waterlogging also varies spatially and temporally in the landscape. Nor is it clear how it should be measured – in terms of changes in concentrations of soil gases like oxygen or through the integration of variable depths to water-table like the Sum of Excess Water (SEW) estimation (Setter and Waters, 2003).

Given these imponderables, how should we proceed with land capability assessment? One approach may be to retain the central tenants of the salinity/waterlogging matrix – that land capability is affected by the levels of these stresses – but to consider land capability in terms of three critical questions: (a) can the plant use the groundwater for growth, (b) is the soil water above the water-table suitable for use, and (c) is oxygen available for root-growth and function. Further comments on these three questions are made below:

Use of groundwater for growth

If the water-table is sufficiently shallow, plants may be able to use the groundwater provided it is not too saline or toxic (eg. too low in pH). A lot of information is now available regarding the ability of a wide range of species to grow on nutrient solutions of different salinities (eg. Maas, 1986; Aronson, 1989). A preliminary matching of plants to sites can therefore be made by comparing this tolerance to groundwater salinity. For example, Figure 3 shows the relationships between growth and solution salinity for samphire (*Halosarcia pergranulata*), saltbush (*Atriplex amnicola*), tall wheatgrass (*Thinopyrum ponticum*) and lucerne (*Medicago sativa*). These plants had 50% decreases in growth at salinities (EC_w values) of about 70, 40, 30 and 10 dS/m respectively. Clearly all species would have been able to grow accessing groundwater with salinities around 10 dS/m, but only the samphire and saltbush would have been able to grow accessing groundwater with salinities around 50 dS/m.

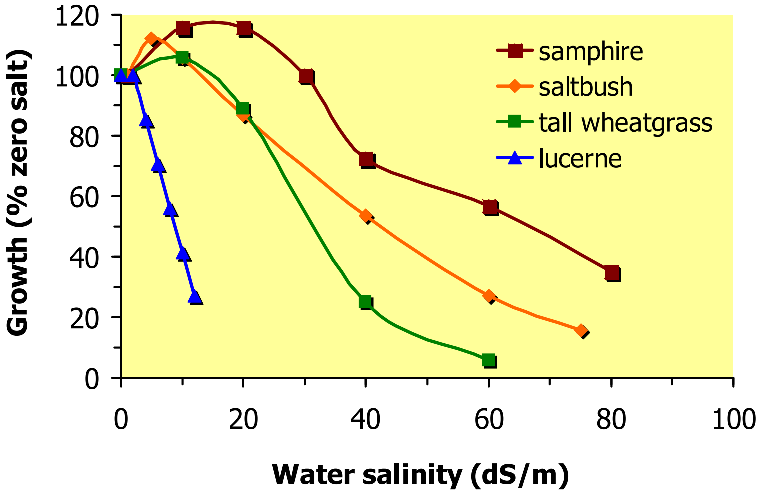

Figure 3. Typical growth responses to increasing salinity for samphire (*Halosarcia pergranulata* – Short and Colmer, 1999), saltbush (*Atriplex amnicola* – Aslam *et al.* 1986), tall wheatgrass (*Thinopyrum ponticum* – Jenkins 2007), and lucerne (*Medicago sativa* – Maas, 1986).

Suitability of the soil water above the water-table for use

This question refers to the salinity of the soil above the water-table and the possibility that there might be lenses of less saline water that the plants may be able to tap into. As such, the question refers primarily to the salinity of the soil above the water-table. How should we handle to issue of seasonal variability in soil salinity? For deeper rooted perennial plants, the most sensible thing may be to ignore the variable soil salinity over the upper 0.2 m of the soil profile and to focus more on the deeper soil profile where salinity varies less. Figure 4 provides an example of the way in which salinity varies mostly at the soil surface. In this experiment, a naturally saline soil near Quairading in Western Australia was either not cultivated or cultivated in the autumn and spring, and the soil salinity was measured to a depth of about 0.6 m at monthly intervals between July and December (Smith 1962). The data show that with both treatments, the bulk of the seasonal variation in soil salinity occurred in the upper 0.2 m of the soil profile, although the seasonal variation with cultivation was less. With both treatments, at 0.3–0.6 m the salinity converged towards a constant value, in this case ~0.6% NaCl (Figure 3).

Plants growing in the soil indicated in Figure 4 can be expected to use the most thermodynamically available water first. If the salinity of the soil solution in the upper 0.2 m of the soil profile was lower than that at depth, then the shallow water would be used for growth. If the salinity of the soil solution in the upper 0.2 m of the soil profile was greater than that at depth, the deeper water would be used for growth. Either way, the salinity of the deeper water would represent the upper salinity limit to which plants were exposed.

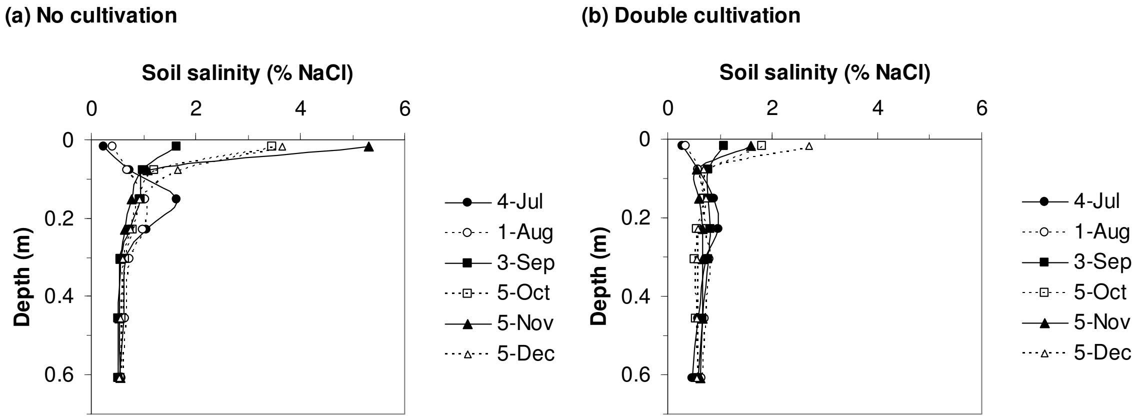

Figure 4. Seasonal changes in salinity (% NaCl) down the soil profile at a site near Quairading WA (after Smith 1962). The site was either: (a) not cultivated, or (b) cultivated in the autumn and the spring. Each point is the geometric mean of 8 measurements.

Availability of oxygen for root-growth and function

This question will be affected both by the depth of the water-table and by factors such as soil texture or soil pore size distribution. In reviewing the literature on soil physical conditions and drainage, Wesseling and van Wijk (1957) concluded that "as a first approximation, one may assume that 10% of volume of airfilled pores is the lowest value at which air can be exchanged in the soil". Soils will be generally below this threshold for at least ~20 cm above the water-table. For example, in a duplex loamy sand over clay soil near Kojonup in Western Australia, Zhang *et al*. (2004) reported air-filled porosities below 10% at 10 cm depth when average water-tables were at depths of ~30 cm. The width of the hypoxic zone unfavourable for root-growth above the water-table is presumably affected by the pore size distribution of the soils. At the extreme, fine textured soils with just a few large pores will be saturated to relatively greater heights above the water-table than fine textured soils (Grable, 1966). However few data are yet available to substantiate this point.

In a way, the EM38 may be the ideal instrument with which to measure soil salinity for perennial plants: it measures the bulk conductivity of the soil to depths of ?? or ?? cm (ref) and its readings are relatively unaffected by whether ECe values are high or low at the soil surface (find reference to see if this is true).

Conclusions

We believe that a method can be developed for determining saltland capability based on the measurement of 5 or 6 parameters. These are: (a) the salinity and pH of the groundwater, (b) the depth of the groundwater, (c) the texture of the soil above the water-table, and (d) the bulk salinity of the soil above the groundwater. The diagnosis could be strengthened by supplementary observations of the types of plants growing on the soil surface.

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Appendix A. Information used to compile salinity/waterlogging matrix (Figure 1)

- Cereals. With waterlogging, barley and wheat grow crown roots that contain aerenchyma – longitudinal air filled channels that allow oxygen to be conducted from shoots to roots (Benjamin and Greenway, 1979; Trought and Drew, 1980). This adaptation enables cereals to tolerate 'low' to 'moderate' waterlogging (McFarlane *et al*., 1989; Setter and Waters, 2003). Under drained conditions, wheat and barley have 50% decreases in yield at EC_e values of 13 and 18 dS/m respectively (Maas, 1986). However, cereals will be susceptible to salinity/waterlogging interactions – low yields are expected with moderate waterlogging at EC_e levels of 3–6 dS/m (cf. Barrett-Lennard *et al*., 1999). Cereals are therefore ranked as tolerant to 'low' salinity.

- Samphire, saltbush and bluebush. Ecological zonation in samphire, saltbush and bluebush is often apparent across gradients of salinity and waterlogging on the fringes of salt lakes and in revegetated saltland (Malcolm and Swaan, 1989). Samphire (*Halosarcia* species) has 'high' tolerance to salt and waterlogging, and survives partial inundation in winter for several months. Young black-seeded samphire (*H. pergranulata*) plants survived with EC values in the soil water of 200–300 dS/m, and waterlogging had little adverse effect on plant growth at 80 dS/m (English *et al*., 1999, 2001). Saltbushes (*Atriplex* species) occur at slightly higher elevations in the landscape than samphire. They survived irrigation with seawater (55 dS/m – Watson *et al*., 1987) and brief waterlogging at 40 dS/m (Galloway and Davidson, 1993), and grew well at EC_e values of 25 dS/m (Barrett-Lennard and Malcolm, 1995, p. 61). Saltbushes are ranked as tolerant to 'moderate' levels of both salinity and waterlogging. Small leaf bluebush (*Maireana brevifolia*) occurs at higher elevations in saline landscapes than saltbushes. It did not withstand prolonged waterlogging (Malcolm and Swaan, 1989), but grew in soil water at EC values of 60 dS/m (Malcolm, 1963). It is ranked as tolerant to similar levels of salinity as saltbushes ('moderate') but 'low' levels of waterlogging.

- Tall wheat grass and puccinellia. When sown together, tall wheat grass (*Thinopyrum ponticum*) and puccinellia (*Puccinellia ciliata*) show strong ecological zonation with puccinellia occurring in more severely affected land than tall wheat grass (McCarthy, 1992). In the field, both species occurred over similar EC_e ranges (5–40 dS/m, Hamilton, 1972) but best growth was at 16–32 dS/m (Semple *et al*., 2003). In sand cultures under drained conditions, these two species had similar growth responses, with a 50% decrease in growth at about 25–28 dS/m (Marcar, 1987). Zonation therefore appears to be due more to differences in waterlogging than salinity tolerance. In keeping with this, *Puccinellia* species are found at the edges of coastal salt marshes in Europe (Armstrong *et al*., 1985; Cooper, 1982), and (in one case) grew *better* under waterlogged than drained conditions at EC values in the range 0–25 dS/m (Stelzer and Läuchli, 1977). In Australia, puccinellia can withstand periods of partial inundation

(Rogers and Bailey, 1963). These grasses are ranked as less tolerant to salinity than the saltbushes and bluebush, but more tolerant than kikuyu and rhodes grass. Puccinellia is more tolerant to waterlogging that saltbush, but tall wheat grass is less tolerant to waterlogging than saltbush.

- Kikuyu and rhodes grass. In pot experiments under drained conditions, kikuyu (*Pennisetum clandestinum*) and rhodes grass (*Chloris gayana*) had a 50% decrease in yield at EC_e values of 21 and 23 dS/m respectively (Russell, 1976). However, on winter-waterlogged field sites, best growth occurred with EC_e values in the range 12–20 dS/m, lower values than for puccinellia and tall wheat grass in the same investigation (Semple *et al*., 2003). These grasses have been ranked as less salt tolerant than tall wheat grass and puccinellia, but between these grasses in waterlogging tolerance.

- Salt water couch, marine couch and distichlis. It is difficult to separate these grasses in the salinity/waterlogging matrix; they have been ranked as having 'high' tolerance to waterlogging, and similar ('moderate') tolerance to salinity as puccinellia and tall wheat grass. Salt water couch (*Paspalum vaginatum*) grew in shallow standing water at lower locations in the landscape than puccinellia (Rogers and Bailey, 1963). In NSW, it gave better cover on two winter-waterlogged sites with EC_e values in the range 16–40 dS/m, than at a non-waterlogged site in this EC_e range (Semple *et al*., 2003). It is tolerant to irrigation with water with EC_w values between 6 and 22 dS/m (Malcolm and Smith, 1971). In glasshouse experiments, 50% decreases in shoot growth occurred at EC_w values between 18 and 29 dS/m, and plants survived EC_w values of 40 dS/m (Dudeck and Peacock, 1985) Notwithstanding this tolerance, we do not see salt water couch growing with samphire. Marine couch (*Sporobolus virginicus*) also grew in standing water, forming aerenchyma in the rhizomes and new adventitious roots from the nodes of inundated stems (Naidoo and Naidoo, 1992). It survived salt concentrations in excess of seawater, but gave better growth at lower salinities (Gallagher, 1979, 1985). At Laidley in southern Queensland, there was more than 90% survival of marine couch in seepage areas with EC_e values of 6–10 dS/m in the upper 20 cm of the soil profile and it was associated with salt water couch (Truong and Roberts, 1992). At Mahasarakam in NE Thailand, it had better survival (75–100%) than distichlis at EC_e values between 20 and 42 dS/m (Yuvaniyama and Arunin, 1991), but this may be a function of the particular genotypes tested. It has been argued that the 'NyPa forage' clone of *Distichlis spicata* is highly tolerant to both salinity and waterlogging (Leake, 1999). Under drained conditions, 'NyPa forage' tolerated electrical conductivities in the root-zone as high as 80 dS/m (145% of the salinity of seawater), although best growth was at less than 20 dS/m. The plant is also known to have exceptionally efficient salt glands in the leaves (Liphschitz and Waisel, 1982). Under waterlogged conditions the plants survived 40 dS/m (73% of salinity of seawater – Leake *et al*., 2001). The roots were able to form aerenchyma.

- Balansa clover. Balansa clover (*Trifolium michelianum*) has hollow stems, forms aerenchyma and will grow in severely waterlogged soil. However, its salinity tolerance is lower than that of cereals (50%

decrease in growth at 7dS/m – Rogers and Noble, 1991). This plant is ranked as having ‘moderate’ to ‘high’ tolerance to waterlogging, but ‘low’ tolerance to salinity.