Predictions of watertable depth and soil salinity levels for land capability assessment using site indicator species

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Running title: Predicting saltland capability using indicator species

Abstract

Salt-affected land varies spatially and seasonally in terms of soil salinity and depth to the watertable. This paper asks whether native and naturalised species growing on saltland can be used as ‘indicators’ of saltland capability. The percentage cover of native and naturalised species was recorded in the spring of 2004 and 2005 across saltland transects on three sites in Western Australia. The presence of these plants was related to average soil salinity (EC_e) at depth (25 - 50 cm) and depth to the watertable in spring. Eight naturalised species occurred with 40% or greater cover on the sites. Species preferences varied, with some such as samphire (*Halosarcia pergranulata*) and puccinellia (*Puccinellia ciliata*), only occurring in shallow watertables (less than 0.7 m deep) and EC_e values of greater than 16 dS/m. Others such as capeweed and ryegrass were dominant where watertables were deeper (greater than 1.3 m) and salinity levels lower (ECe values of 2–8 dS/m and 4–16 dS/m respectively). Our data suggests that some of the species recorded can be used as indicators of saltland capability and further, can predict the most productive species to sow in that area. Other species were not found to be good indicators as they displayed more opportunistic habitat requirements.

Keywords: dryland salinity, wheatbelt, native and naturalised species, production potential

Introduction

Secondary salinity in Australia is caused by the mobilisation of salts stored deep in the soil profile as a result of a rise in the watertable due to the clearance of native perennial vegetation and their replacement by annual crops and pastures which use less water (Ghassemi *et al.* 1995). This has resulted in a loss of productivity over large areas of agricultural land. In 2000 it was estimated that nearly 5.7 million hectares (Mha) were at risk of dryland salinity as a result of shallow watertables, with this being expected to increase to 17 Mha by 2050 (National Land and Water Resources Audit 2001). However, in Western Australia, rainfall in the Northern and Eastern Agricultural Regions has fallen since 2000, and these estimates are now being revised downwards (George *et al.* 2008).

One of the clear interventions that farmers with salt affected land can make to improve the value and productivity of their saltland is to plant halophyte-based pastures incorporating saltbushes (*Atriplex* L. sp.), puccinellia (*Puccinellia ciliata* Bor) and tall wheatgrass (*Thinopyrum ponticum* (Podp.) Barkworth & D. R. Dewey)) (Barrett-Lennard *et al.* 2003; Bennett *et al.* 2009; Jenkins *et al.* 2010; Barrett-Lennard *et al.* 2013). However, such pastures often fail because the plants are placed into inappropriate parts of the landscape (Nulsen 1981; Thomas *et al.* 2009; Jenkins *et al.* 2010; Barrett-Lennard *et al.* 2013). It has been hypothesized that one of the principal reasons for this failure is that plant zonation on saltland is actually affected by a range of stresses including salinity and waterlogging (Barrett-Lennard 2002, 2003; Barrett-Lennard *et al.* 2003; Bennett *et al.* 2009). Attempts have been made to summarise the best location for current pasture options for saltland in terms of both salinity and waterlogging using a salinity/ waterlogging matrix of ten key indicator species (Bennett *et al.* 2009). However, limited quantitative data were available to make these assessments and no attempt was made to quantify the levels of salinity and waterlogging used in this key.

The interaction between salinity and waterlogging is important, particularly where there are shallow watertables (Barrett-Lennard *et al.* 2003; Bennett *et al.* 2009). Experiments with sea barley grass (Malik *et al.* 2009), and puccinellia and tall wheatgrass (Jenkins *et al.* 2010) have shown that under non-waterlogged conditions tolerance to salinity is greater than under the combined effects of waterlogging and salinity. Those species that are not adapted to waterlogging, such as tall wheatgrass (Jenkins *et al.* 2010) and some accessions of sea barley grass (Malik *et al.* 2009), showed decreased growth compared to under saline conditions alone. Tall wheatgrass showed a 50% decrease in shoot dry matter at 300 mM NaCl (Jenkins *et al.* 2010) and sea barley grass by up to 42% at 200 mM NaCl (Malik *et al.* 2009) when grown under waterlogged conditions.

The interaction of salinity and waterlogging has also been shown to be critical during germination of tall wheatgrass and puccinellia (Zhang *et al.* 2005). Tall wheatgrass germination rates decreased by 83% (cv. ‘Tyrell’) and 92% (cv/ ‘Dundas’) under waterlogged saline conditions (153.8 mM NaCl), compared to germination at 153.8 mM NaCl alone, and pucinnellia (cv. ‘Menemen’) decreased by 61% under the same conditions (Zhang *et al.* 2005). An interaction between salinity and waterlogging was also found in a study looking at survival and best growth of perennial species on a salinity/waterlogging gradient. Rhodes grass (*Chloris gayana* Kunth), saltwater couch (*Paspalum vaginatum* Sw.) and samphire (*Tecticornia* Hook. f. sp.) all showed best growth with a watertable at 0.8 – 1.1 m in summer, but Rhodes grass showed best growth at 3.5 – 5.5 dS/m, saltwater couch at 5.3 – 8.9 dS/m and samphire at >24 dS/m (Barrett-Lennard *et al.* 2013).

One of the problems of using measurements of salinity and depth to watertable (as a predictor for when plant roots are affected by waterlogged soils) to assess saltland capability is that these two stresses are not easy to measure by farmers, and can vary considerably both spatially and temporally across the landscape (Setter and Waters 2003; Bennett *et al.* 2009). On saltland in Western Australia, watertable depths are closest to the surface in winter following winter rains and soil salinity levels are lowest at this time as a result of the leaching of salt from the soil surface (Smith 1962). Watertables start to fall in spring as rainfall decreases and soil salinity levels rise due to the effects of capillarity as a result of evaporation of water from the soil surface, reaching a maximum during summer and autumn. Soil salinity shows a similar degree of temporal variation with large variations at the soil surface across a few metres (Barrett-Lennard *et al.* 2008a; Barrett-Lennard *et al.* 2013). Importantly, temporal variation in soil salinity decreases with increasing depth in the soil profile so it may be more diagnostic of the ability of saltland to grow perennial species by measuring subsoil rather than surface soil salinity (Smith 1962; Bennett *et al.* 2009).

One approach to saltland capability assessment may be to use the plants that naturally grow on saltland ("the indicator species") as surrogates for the measurement of soil salinity and waterlogging. Plant species have been used as indicators of saline soils in Western Australia (Malcolm 1986), Queensland (Bui and Henderson 2003) and Victoria, Australia (Matters and Bozon 1995), and as indicators of soil type (including determining the location of saline areas) in Saudi Arabia (Boër 1996). Piernik (2003) also used the location of halophytic species in a naturally saline area of Poland to determine soil salinity. She found that few species could be used independently to predict soil salinity, but that the use of plant communities was more successful.

This paper focuses on the use of indicator plants that grow naturally on saltland to predict the salinity and depth to watertable of saltland in the wheatbelt of Western Australia. It is important to clarify here that depth to watertable is being used as a predictor for when plant roots are affected by waterlogged soils, rather than when water is visible on the soil surface (inundation). Our hypothesis is that there are relationships between the presence of such indicators, and soil salinity and depth to the watertable, and that these associations can be used to diagnose the capability of these sites.

Materials and methods

Site description

Three transect sites were used for the study and were located in Western Australia (WA) at Meckering (31.6367° S, 116.9572° E), Pingaring (32.9280° S, 118.8082° E) and Wubin (32.5772° S, 117.5548° E) (Figure 1). Rainfall over the study period showed a typical mediterranean pattern with rainfall over the winter months ranging from 121 to 169 mm and over the summer months from 2 to 62 mm, although in subsequent years summer rainfall has been greater. All three sites were on a sand over clay duplex soil with the depth to clay decreasing at the lower end of the study area. For further details on the soil and nutritional profiles of the three study sites see Barrett-Lennard *et al*. (2013). The study area at each transect site was a 50 m by 50 m grid set up on a salinity/ waterlogging gradient (Figure 1, insert). The grid was divided into 10 rows, each 5 m wide, running perpendicular to the salinity/ waterlogging gradient, with five replicates of 5 m wide columns set-up along the gradient, each separated by 5m. This resulted in a total of 50, 5 m by 5 m quadrats or cells at each study area.

INSERT FIGURE 1 HERE

Surface soil salinity (depth 0 to 25cm) and sub-soil salinity to depth (25 to 50 cm) was recorded on four occasions (November 2003, June 2004, June 2005 and September/ October 2005) across each site using an EM38 in both the horizontal and vertical position (EC_{av} and EC_{ah}) and these values were converted to average electrical conductivity of the saturation paste extract (EC_e) values using calibrations derived from soil sampled at 7 to 14 holes per site at depths of 0-25 cm and 25-50 cm on the day of sampling. For further details on the calibration calculations see Barrett-Lennard *et al*. (2013). Surface soil salinity is highly variable both spatially and temporally, with the variation decreasing with depth (Smith 1962). Therefore averaged soil salinity measurements at depth were used to give an approximation of soil salinity at depth across the seasons.

Watertable depth was recorded at nine bores located across each of the WA research sites, and results were interpolated across the study areas using the Krige function of geospatial analysis within Genstat v.10 (Lawes Agricultural Trust 2007). The watertable depth used for all analysis was an averaged spring watertable depth, averaged from approximately monthly readings between September and November inclusive. This time frame was used as this is the time period when most of the indicator species would be actively growing. Most indicator species are annuals and are therefore not present, other than as seeds in the soil, over the summer.

Percentage cover of native and naturalised species occurring in each transect 'cell' was recorded annually by estimating the occurrence of the dominant species in each transect 'cell'. Species whose percentage cover was less than 5 % were not recorded as it was felt that these species were at the limit of their ecological niche and therefore would not be good indicators of soil salinity and watertable depth. Surveys were undertaken in September in 2004 and in 2005 at the three transect sites in WA, although no survey was taken at Meckering in 2005 as the site was too wet for access.

Statistical analysis

Genstat v.10 (Lawes Agricultural Trust 2007) was used for all analysis within the study.

An irregular grid (REML) spatial analysis was conducted on the indicator species recorded at 40% or more cover in any of the transect 'cells' at the three sites, with species recorded, year and site all as fixed levels within the analysis. Row and column position were both taken to be random levels in the analysis. Watertable depth showed a normal distribution, however soil salinity level was not normal and so was transformed using a logarithmic transformation prior to the spatial analysis.

A hierarchical cluster analysis was used to identify the main occurrence of each indicator species within a salinity/ waterlogging matrix. It was calculated at three percentage cover limits; 25% and greater than cover in a cell, 40% and greater cover in a cell and 55% and greater cover in a cell, generating three salinity/ waterlogging matrices based on the main cluster of each species following the cluster analysis. The Euclidean distance was used to form the similarity matrix and the group average method was used for the final cluster analysis (Manly 1994).

Results

The results of the spatial analysis on the three transect sites showed that there were significant differences in both soil salinity and watertable depths between species recorded and between sites (Table 1). The Wald Statistic value was greater for both species and site in relation to depth to watertable, compared to sub-soil salinity. It was also greater for the interaction of species x site and species x year, although the difference was less.

INSERT TABLE 1 HERE

Figure 2 shows the location of four of the indicator species recorded across the three sites. The species presented have four different locations across the salinity/ waterlogging matrix, although it is accepted that the results are strongly focussed across the watertables that were recorded across the three sites. The salinity of the sub-soil measurements were transformed using a logarithmic scale to normalise the data, and are presented in Figure 2 on the same scale. This has the effect of separating the location of the species occurring at the lower sub-soil salinities on the figure, but can give the impression that species that occur at high to extreme sub-soil salinities, such as samphire for example, occur over a narrow sub-soil salinity range (Figure 2b). In fact samphire was recorded over a range of 24 to 80 dS/m sub-soil salinity. The salinity classes (non-saline, low-, moderate-, high-, severe- and extreme salinity) described in this paper are based on those of Barrett-Lennard *et al.* (2008b). For ease of reference these have been reproduced in Table 2. The non-saline, and low-, moderate-, and high-salinity classes are identical to those used by Rogers *et al*. (2005), except that high salinity now has an upper EC_e limit. Two further classes have been added to the table, severe and extreme, which increases the applicability and specificity of the classification for Western Australian conditions.

INSERT FIGURE 2 HERE

INSERT TABLE 2 HERE

The mean and standard error of each species' position in the landscape, at 40% or greater cover, in relation to watertable depth and salinity of the sub-soil (25-50 cm), are shown in Table 3. Samphire showed little overlap with other species, only occurring in cells with a shallow watertable and extreme soil salinity levels (Figure 2b). Puccinellia was also only recorded in cells with shallow watertables and high to extreme soil salinity levels. Rat's tail fescue (*Vulpia myuros* (L.) C.C. Gmel.) and curly ryegrass (*Parapholis incurva* (L.) C.E. Hubb.) were both recorded only in cells with a shallow watertable of less than 1.2 m, but differed in their salinity requirements; rat's tail fescue occurring at low salinity levels (2 – 4 dS/m and curly ryegrass at high to severe salinity levels (8 – 32 dS/m). Capeweed (*Arctotheca calendula* (L.) Levyns), slender iceplant (*Mesembryanthemum nodiflorum* L.) and annual ryegrass (*Lolium rigidum* L.) were recorded at the highest frequencies in cells with the deepest watertables (Figure 2a, c and d). However, soil salinity levels are clearly differentiated between these later three species, with capeweed recorded most frequently in cells with low to moderate soil salinity levels, annual ryegrass at low to high soil salinity levels and cotula (*Cotula coronopifolia* L.) and slender iceplant (Figure 2c) recorded at the highest frequencies in cells with severe soil salinity levels.

INSERT TABLE 3 HERE

Figure 3 shows the results of the cluster analysis to identify each species' preferred location in the landscape in relation to depth to watertable during spring, and subsoil salinity. The preferred location was determined by the inclusion of a 'cell' in the main cluster at the 80% similarity level. 'Cells' included in the cluster analysis and presented in Figure 3a were those where the nominated species occurred at 25% or greater cover within the 'cell'. 'Cells' included in Figure 3b were those where the nominated species occurred at 40% or greater cover, and those in Figure 3c where the nominated species occurred at 55% or greater cover. The 'cells' within the main cluster are included in the 'preferred area' for each species shown on each figure in Figure 3, highlighting the range of watertable depths and soil salinities that each species is able to tolerate. The exact ranges of each of the species for both ECe and depth to watertable at the three percentage covers (25, 40 and 55%) are shown in Table 4. As the percentage cover of each species increases in the cluster analysis the 'preferred area' for each species becomes more specific. Where 25% cover or greater is used (Figure 3a) there is a large degree of overlap of the different indicator species. In Figure 3c where 55% cover or greater has been used to generate the species locations in the landscape there are large gaps where there is no species cover. However, at 40% or greater cover of a species, the graph of the main clusters of each species at the 80% similarity level provides a potentially useful map of the species preferred location in the landscape (Figure 3b). On this graph (Figure 3b) and in Table 4 it would appear that both capeweed and annual ryegrass are not very specific in their requirements or preference for watertable depth or salinity.

INSERT FIGURE 3 HERE

INSERT TABLE 4 HERE

Discussion

The present work has shown that the occurrence of native and naturalised indicator species with 40% or greater cover is highly specific for subsoil salinity (2–80 dS/m) and depth to watertable in spring (0.5–2.7 m) in Western Australia, and has the potential to be used as a saltland capability assessment matrix. The study contained a selection of species which are indicative of highly saline conditions (greater than 8 dS/m); samphire, puccinellia, curly ryegrass, cotula and ice plant, and also species that indicate where the watertable is less than 1 m deep; samphire, puccinellia and rat's tail fescue. We can therefore accept the hypothesis that there is a relationship between indicator species, and depth to the watertable and sub-soil salinity. However, it is important to note that our work suggests that the saltland capability assessment matrix cannot be usefully determined using just the presence of indicator species; the species should be dominant in the landscape and occurring at 40% or greater cover within a particular location.

Using the results of the cluster analysis with the 40% or greater cover of indicator species in a 'preferred location' (Figure 3b) and the 95% confidence intervals for best growth (determined from the largest 10% of plants) of the perennial legumes, grasses and halophytes presented in Barrett-Lennard *et al.* (2013) and Jenkins *et al.* (2010) we can update and add figures to the axes of the salinity/ waterlogging matrix in Bennett *et al.* (2009). The updated matrix is shown in Figure 4 where the best growth of Rhodes grass, saltwater couch, lucerne, bluebush, saltbush, samphire (Barrett-Lennard *et al.* 2013), tall wheatgrass and puccinellia (Jenkins *et al.* 2010) is laid over the indicator species preferred location at 40% or greater cover, after re-calculating watertable depths to average depth in spring, rather than the average depth over spring and summer, which is used in their papers. This combined graph (Figure 4) can be used as the basis for a saltland capability assessment matrix.

INSERT FIGURE 4 HERE

We suggest that at EC_e levels of less than 8 dS/m the technique used in this paper is not as accurate as at higher ECs because the principle indicators, capeweed and annual ryegrass, also occur widely on non-saline soils and are therefore not very diagnostic (Western Australian Herbarium 1988). These species should therefore not be used in isolation, and alternative measurements are required for less saline sites (<8 dS/m), in combination with indicator species. The principle extra measurement required is depth to watertable, as at less saline sites there is a wide variation in the productive potential of the sites, depending on the depth to the watertable. Nulsen (1981) found that depth to saline groundwater was the best indicator of the potential of saltland for the growth of barley grass, annual ryegrass, barley and wheat crops. The potential for sowing bluebush, Rhodes grass and saltwater couch into saline sites could all be improved with the combined knowledge of indicator species and depth to watertable (Barrett-Lennard *et al.* 2013). These assessments have potential in that they can be readily conducted by farmers.

One of the key requirements of a saltland capability assessment matrix is to determine land which is;

a) becoming affected by salinity and cropping is becoming more marginal,
b) moderately productive land, that is capable of growing saltbush, bluebush, tall wheatgrass (in Australian states where allowed (Bennett 2009)) and puccinellia, and

c) land of low productive potential, that only supports the growth of highly salt tolerant species such as samphire and naturalised puccinellia.

The indicators included in the study are thus strongest for the prediction of where salt tolerant perennials such as saltbush (indicated by annual ryegrass and slender ice plant) and puccinellia (indicated by cotula and sown, not naturalised puccinellia) would be productive, and also where extremely saline land (identified by the presence of samphire and naturalised puccinellia) should be fenced off and left to revegetate naturally. It is suggested that saltbush should not be sown where samphire and naturalised puccinellia occur as the combination of a shallow watertable and severe to extreme salinities (>16 dS/m) results in plants with a shallow root system that are unable to survive the summer (Barrett-Lennard *et al.* 2013). The nutritive value and production of saltbush also decreases at extreme salinities (400 mMol) (Masters *et al.* 2010).

It is recommended that saltbush is sown where there is a dominance of annual ryegrass, with some slender ice plant and capeweed, and where the depth to watertable is greater than 1.5 m. This land would be determined as moderately productive using the saltland capability analysis. At these locations the productive potential can be increased by using combinations of species (Barrett-Lennard 2000). For example, saltbush with a legume understory, such as balansa clover (*T. michelianum* L.) or burr medic (*M. polymorpha* L.) raises the productive potential by providing high-nutrient plants to supplement the saltbush. In autumn when green feed is in short supply saltbush has been shown to make up to 50% of selected feed (Norman *et al.* 2010). However, during winter and early spring when saltbush growth is reduced, annual pastures have high digestibility and comprise up to 87% of daily feed intake (Norman *et al.* 2010). Thus the combination of the saltbush with the legume understorey provides a productive feed option that extends the availability of green feed during the year and reduces the requirements for supplementary feeding.

In all predictions it is important to read the landscape, avoiding low lying areas, or those areas that are prone to winter waterlogging where saltbush will not persist, and it is suggested that the break of slope is a better location. It is recognised that farmers and their advisors will seldom make assessments on which species to sow where based on indicator species alone, but will also look at the fall of the landscape, range of species available for their location, natural variation in the landscape, indicators of waterlogging, rainfall and local weed knowledge. This would exclude tall wheatgrass from being sown in Victoria as it is a declared noxious weed in this state (Bennett 2009).

The soil salinity levels recorded where the puccinellia and samphire were present in this study were higher than expected. Samphire has been reported to show its best growth at soil salinity levels of 25 – 40 dS/m (Barrett-Lennard *et al.* 2013) and puccinellia has previously been reported to show its best growth at soil salinity levels of 16 - 32 dS/m (Semple *et al.* 2003) and 13 – 24 dS/m in the top 30 cm (Hamilton 1972). It can also withstand periodic flooding under these conditions (Rogers and Bailey 1963). It is suggested that ecotypic adaptation for tolerance to higher salinity levels than is present in the puccinellia cultivar 'Menemen' may have occurred at the Meckering site. Further investigation is required to determine whether this is the case as this may be a potential source of selection material for increasing the salinity tolerance of puccinellia compared to the current cultivar. Note, both Hamilton (1972) and Rogers and Bailey (1963) refer to puccinellia as *P. capillaris* rather than *P. ciliata* due to a misidentification following collection in 1961(Oram 1990).

Further research

The saltland capability analysis described in this paper has a number of short-comings. It is based on only three sites in Western Australia, and it is recognised that none of the sites had any cells that had a deep watertable, but were highly saline (below 0.6 m, 30 to 64 dS/m). There is also a gap in the mid watertable depths (1.5 to 1.8 m) where the three sites did not form a continuous guide. To complete the range of salinities there is a need to sample soils at the very low to normal soils range (0 – 2 dS/m EC_e) to determine the lower limit of some of the more spatially variable species such as capeweed and annual ryegrass, and potentially to pick up some of the annual legumes, which as discussed above, are currently missing. This saltland capability analysis is therefore not able to determine which native or naturalised species occur in these conditions, or which perennial species could be grown there.

There are a number of important saltland and waterlogging tolerant plants that were missing from the three sites included in this study that typically occur in waterlogged and saline conditions. The most prominent of these is sea barleygrass that tends to occur where the watertable is closer to the surface than it was at any of sites included in this study and is an important indicator for saltland capability analysis (Malcolm 1986). In its native environment in western Europe and north Africa it occurs in saline meadows or salt marshes (von Bothmer 1991). Western Australian accessions have been shown to be more waterlogging (McDonald *et al.* 2001; Garthwaite *et al.* 2003) and salinity (Garthwaite *et al.* 2005) tolerant than wheat, and also importantly to be more tolerant to the combined stresses of salinity and waterlogging (Malik *et al.* 2009). Phalaris (*Phalaris aquatic* L.) is also absent from the study. This is an important pasture species in the eastern states of Australia where it has been shown to be tolerant to salinity levels of up to 8 dS/m with occasional waterlogging (Nichols *et al.* 2008b). Under these conditions it is a productive pasture producing 8.5 t/ha in the second year and persisting into the 3rd year of the pasture.

However in areas with excessive waterlogging and a summer EC_e of greater than 30 dS/m it does not persist beyond the first year (Nichols *et al.* 2008b). Southwell (1999) suggested that although it is not a recognised salt tolerant pasture species they usually include it in shotgun mixes on saltland as, due to the natural variation across the saltland, there are always some areas where it will persist and be a productive component of the pasture. The current saltland capability analysis should therefore be expanded to include sites in the eastern states of Australia to determine the position of phalaris in the landscape. However, it is also recognised that across southern Australia it is a weed risk, with the risk in New South Wales being higher than in the other states, with specific guidelines being given on where in the landscape it can be sown (FFI CRC 2011).

Other important naturalised species that were present at the sites in this study, but at too low numbers to be included in the analysis were the annual legumes; balansa clover (*Trifolium michelianum* Savi), woolly clover (*Trifolium tomentosum* L.) and burr medic (*Medicago polymorpha* L.). Balansa clover is highly productive in waterlogged environments, but only at low salinities whereas burr medic is highly productive at moderate salinities, but not when combined with waterlogged conditions (Nichols *et al.* 2008a). Woolly clover is a naturalised species that is thought to indicate areas that could be sown to more productive salinity tolerant annual legumes (Anon. 2006). It can tolerate periods of inundation of up to 34 days (Gibberd and Cocks 1997) and is reasonably salt tolerant, with dry matter production not decreasing significantly at 80 mol NaCl/m^3 (Rogers *et al.* 1997). Other less prominent species missing from the analysis were; buckshorn plantain (*Plantago coronopus* L.), which shows moderate salinity and waterlogging tolerance; salt sand spurrey (*Spurgularia marina* (L.) Griseb.), which has a high salt tolerance, but is not waterlogging tolerant; and spiny rush (*Juncus acutus* L.), which can withstand long periods of inundation but only where salinity levels are less than that of sea water (Anon. 2006).

It is recognised that the lack of important species, such as sea barley grass, may have led to some bias in the analysis due to the choice of site, particularly as all the sites were characterised by a sandy duplex soil, which increases the availability of the water to the plants compared to soil types with a higher clay content (Ayars *et al.* 2006). It is therefore suggested that in order to draw more robust conclusions regarding the effectiveness of predictor species in indicating watertable depth and soil salinity level, there is a requirement to increase the number of sites, to sample across the complete range of soil salinities and water table depths and to expand the saltland capability analysis across to southern and eastern Australia.

Conclusions

Zonation in native and naturalised indicator species is a reflection of soil salinity and depth to watertable. Their presence in saline landscapes has the potential to assist in locating the best performing saltland pasture species on saltland of various capabilities. Most of the species recorded have either a wide tolerance to soil salinity or to watertable depth, but when more than one species is present, accurate identification of the potential soil salinity and watertable depth increases. The use of indicator species is thus a powerful tool to be used in combination with depth to watertable to predict saltland capability and thus potential production of salt-affected land.

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Figure headings

Figure 1. Location of the three transect sites in Western Australia. Insert: diagram of the transect layout at each site. The arrow shows the direction of increasing soil salinity and decreasing depth to the watertable.

Figure 2. Percentage cover of a) capeweed, b) samphire, c) iceplant and d) annual rygrass in transect ‘cells’ across three transect trials in Western Australia. Sub-soil salinity measurements along the x-axes have been transformed using a logarithmic scale to normalise the data. ■ = 55% or more cover, ▨ = 40 - 55% cover, □ =25 - 39% of cover, ◇ = 1 - 24% cover, + = not present.

Figure 3. Position of indicator species in the landscape in relation to depth to watertable, as a measure of waterlogging tolerance, and soil salinity. Location of each species is based on the results of cluster analysis, using the main cluster as the species preferred location. Species cover at; a) 25% and greater cover in a ‘cell’ included in the analysis, b) 40% and greater cover in a ‘cell’ included in the analysis, and c) 55% and greater cover in a ‘cell’ included in the analysis. Sub-soil salinity measurements along the x-axes have been transformed using a logarithmic scale to normalise the data. —— Rat’s tail fescue, ······ capeweed, — · ryegrass, —— samphire, - - - puccinellia, — · – curly ryegrass, - - - cotula, — — ice plant

Figure 4. Position of indicator species in the landscape in relation to depth to watertable, as a measure of waterlogging tolerance and soil salinity overlaid with position of perennial grasses, legumes and shrubs from Barrett-Lennard et al. (2013) and Jenkins et al. (2010)**.** For indicator species, the location of each species is based on the results of cluster analysis using cells with 40% or greater cover of a species, where the main cluster is the species preferred location. For the perennial grasses, legumes and shrubs their location is determined as range where cells containing plants with top 10% of growth were located. —— Rat’s tail fescue, ······ capeweed, — · ryegrass, —— samphire, - - - puccinellia, — · – curly ryegrass, - - - cotula, — — ice plant

Table 1. Wald Statistic results from the irregular grid spatial analysis of watertable depth and salinity levels of the recorded native and naturalised species on three WA research sites. Wald statistics (Chi-squared probabilities) significant to 0.05 or greater are shown in bold.

	Watertable depth (m)			EC_e (dS/m)		
Fixed terms	Wald statistic	d.f.	Chi (pr)	Wald statistic	d.f.	Chi (pr)
Species	18108.41	7	**<0.001**	1785.17	7	**<0.001**
Site	33059.57	2	**<0.001**	1028.53	2	**<0.001**
Year	657.04	1	**<0.001**	1.96	1	0.161
Species x Site	233.42	6	**<0.001**	199.92	6	**<0.001**
Species x Year	124.49	4	**<0.001**	36.86	4	**<0.001**
Site x Year	722.25	2	**<0.001**	0.07	1	0.785
Species x Site x Year	2.08	2	0.353	1.35	2	0.509

Table 2. Suggested Australian classification system for categorisation of soil salinity (Barrett-Lennard *et al.* 2008b). The non-saline, and low-, moderate-, and high-salinity categories are identical to those used by Rogers *et al.* (2005), except that high salinity now has an upper EC_e limit

Suggested term	EC_e range (dS/m)	$EC_{1:5}$ range (based on conversions of George and Wren 1985)			Typical plants affected
		For sands	For loams	For clays	
Non-saline	0–2	0–0.14	0–0.18	0–0.25	–
Low salinity	2–4	0.15–0.28	0.19–0.36	0.26–0.50	Beans[1]
Moderate salinity	4–8	0.29–0.57	0.37–0.72	0.51–1.00	Barley[2]
High salinity	8–16	0.58–1.14	0.73–1.45	1.01–2.00	River saltbush[3]; saltwater couch[4]
Severe salinity	16–32	1.15–2.28	1.46–2.90	2.01–4.00	Puccinellia[5]
Extreme salinity	> 32	> 2.29	> 2.91	> 4.01	Samphire[6]

References for effects on plants:

[1] Beans (*Phaseolus vulgaris*) – 50% decrease in grain yield at EC_e 4 dS/m (Steppuhn *et al.* 2005)

[2] Dryland barley (*Hordeum vulgare*) – 50% decrease in grain yield decreased at EC_e 8 dS/m (Steppuhn *et al.* 2005)

[3] River saltbush (*Atriplex amnicola*) – good survival at average EC_e values up to 12 dS/m (Barrett-Lennard *et al.* 2008a)

[4] Saltwater couch (*Paspalum vaginatum*) – good survival at average EC_e values up to 12 dS/m (Barrett-Lennard *et al.* 2008a)

[5] Puccinellia (*Puccinellia ciliata*) – can occur at EC_e values around 33 dS/m (Barrett-Lennard *et al.* 2008a)

[6] Samphire (*Halosarcia* spp.) – good survival at average EC_e values of 40 dS/m(Barrett-Lennard *et al.* 2008a); can survive at EC_e up to 105 dS/m (English 2004)

Table 3. Salinity (EC_b) and watertable depths where species occur at 40% or greater cover across the three sites. Multiple comparisons (depicted as suffix letters ‘a’ to ‘f’) show the significant differences between species at P<0.05 in relation to the standard errors of differences of means (watertable depth = 0.2766. EC_e = 3.498). EC_e values have been back transformed from the logarithmic transformation used for the Wald analysis.

Watertable depth (m)			EC_e (dS/m)		
	Mean*	St. error		Mean*	St. error
Samphire	-0.56*a*	0.008	Rat’s tail fescue	1.25*a*	0.339
Puccinellia	-0.60*a*	0.009	Capeweed	4.86*b*	0.420
Rat’s tail fescue	-0.89*b*	0.018	Annual ryegrass	9.82*c*	0.911
Curly ryegrass	-0.92*b*	0.057	Cotula	11.42*c*	1.51
Cotula	-1.12*b*	0.071	Curly ryegrass	15.70*d*	2.554
Capeweed	-1.51*c*	0.063	Iceplant	18.08*d*	1.41
Iceplant	-1.80*d*	0.089	Puccinellia	32.65*e*	2.56
Annual ryegrass	-1.98*d*	0.086	Samphire	70.94*f*	5.32

*Different suffix letters indicate significant differences between species at P<0.05.

Table 4. Salinity and watertable depth ranges of the main cluster following cluster analysis where species occur at 40% or greater cover across the three sites. ECe values have been back transformed from the logarithmic transformation used for the Wald analysis.

	Ece (dS/m)			Depth to watertable (m)		
Species	25%	40%	55%	25%	40%	55%
Capeweed	1.1 - 31.6	2.4 - 16.7	2.4 - 10.1	0.7 - 2.5	0.7 - 2.5	0.7 - 2.5
Annual ryegrass	2.3 - 37.0	2.7 - 17.0	8.5 - 17.0	0.7 - 2.5	1.0 - 2.5	2.1 - 2.4
Rat's tail fescue	2.9 - 5.7	2.9 - 4.1	2.9 - 4.1	0.8 - 0.9	0.8 - 0.9	0.8 - 0.9
Cotula	3.4 - 42.2	10.3 - 22.6	14.8 - 22.6	0.6 - 1.3	0.6 - 1.3	0.6 - 1.2
Iceplant	10.9 - 37.0	20.3 - 37.0	23.3 - 37.0	0.9 - 2.4	1.2 - 2.2	2.0 - 2.2
Curly ryegrass	14.8 - 67.7	23.1 - 31.6	-	0.6 - 1.1	0.9 - 1.1	-
Puccinellia	18.8 - 60.7	18.8 - 37.0	23.6 - 37.0	0.5 - 0.6	0.5 - 0.6	0.5 - 0.6
Samphire	22.3 - 81.6	52.0 - 81.6	52.0 - 81.6	0.5 - 1.0	0.5 - 0.6	0.5 - 0.6

Figure 2

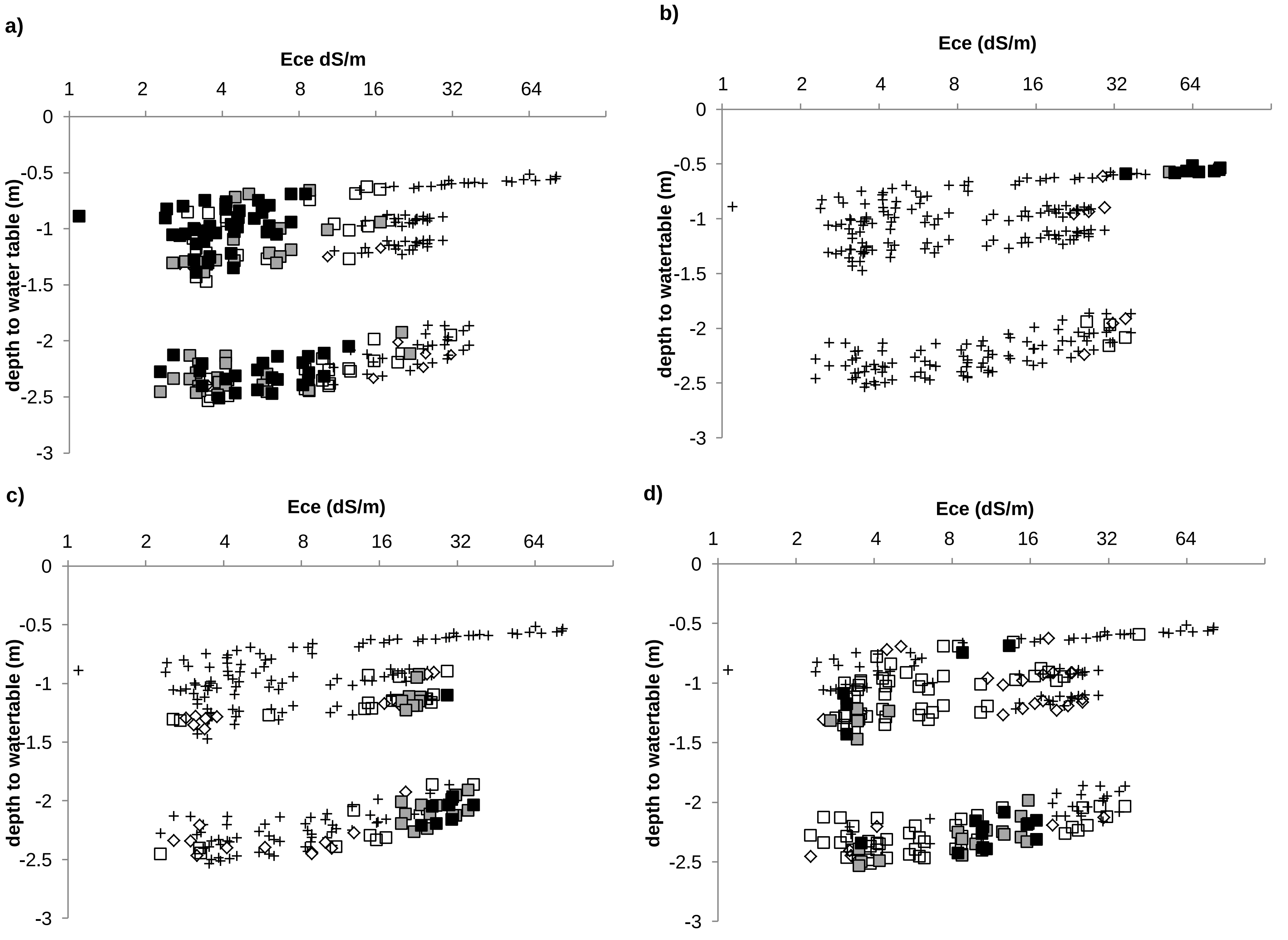

a)
Ece dS/m
1
2
4
8
16
32
64
0
-0.5
-1
-1.5
-2
-2.5
-3
depth to water table (m)
b)
Ece (dS/m)
1
2
4
8
16
32
64
0
-0.5
-1
-1.5
-2
-2.5
-3
depth to watertable (m)
c)
Ece (dS/m)
1
2
4
8
16
32
64
0
-0.5
-1
-1.5
-2
-2.5
-3
depth to watertable (m)
d)
Ece (dS/m)
1
2
4
8
16
32
64
0
-0.5
-1
-1.5
-2
-2.5
-3
depth to watertable (m)

Figure 3

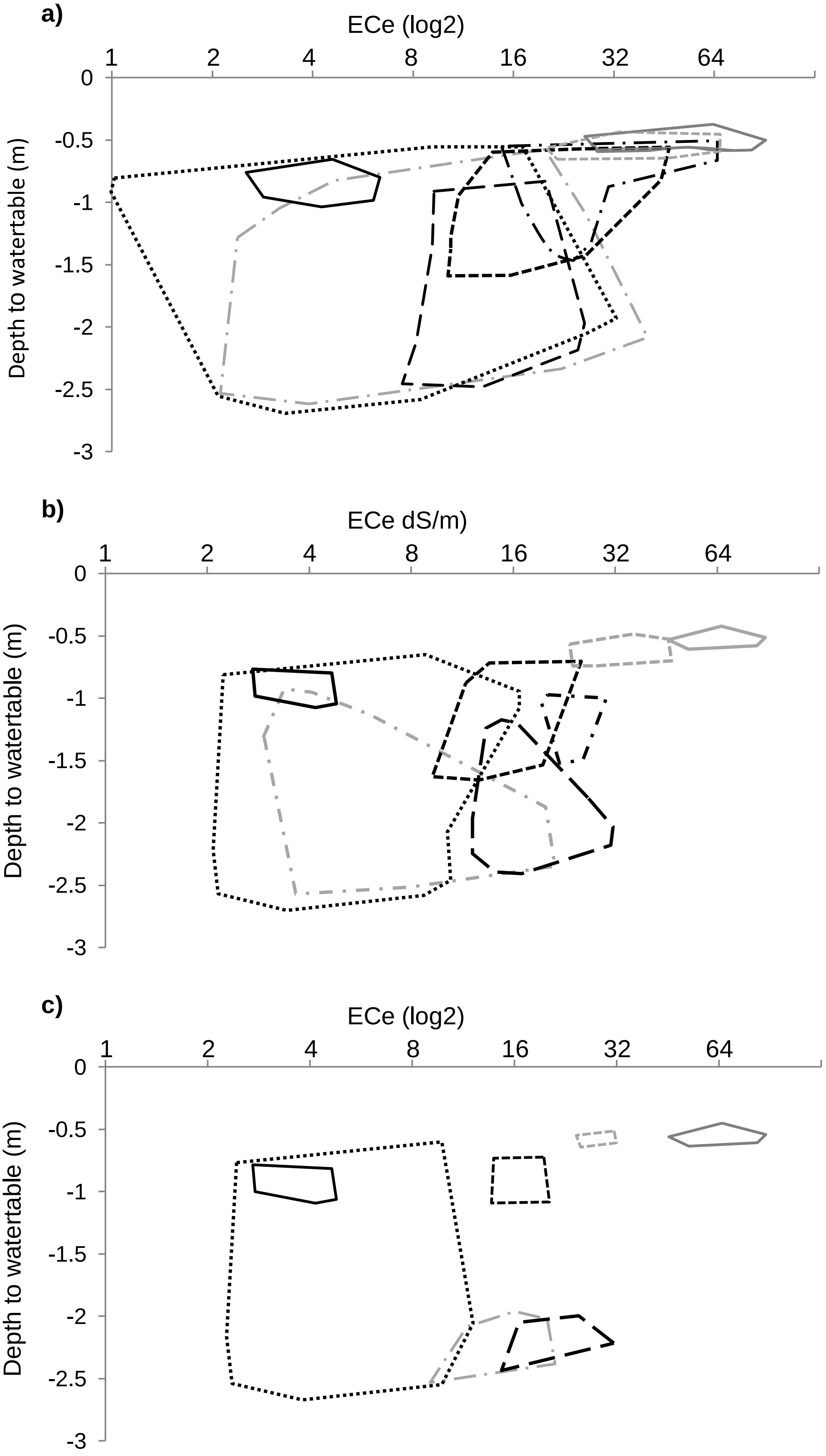
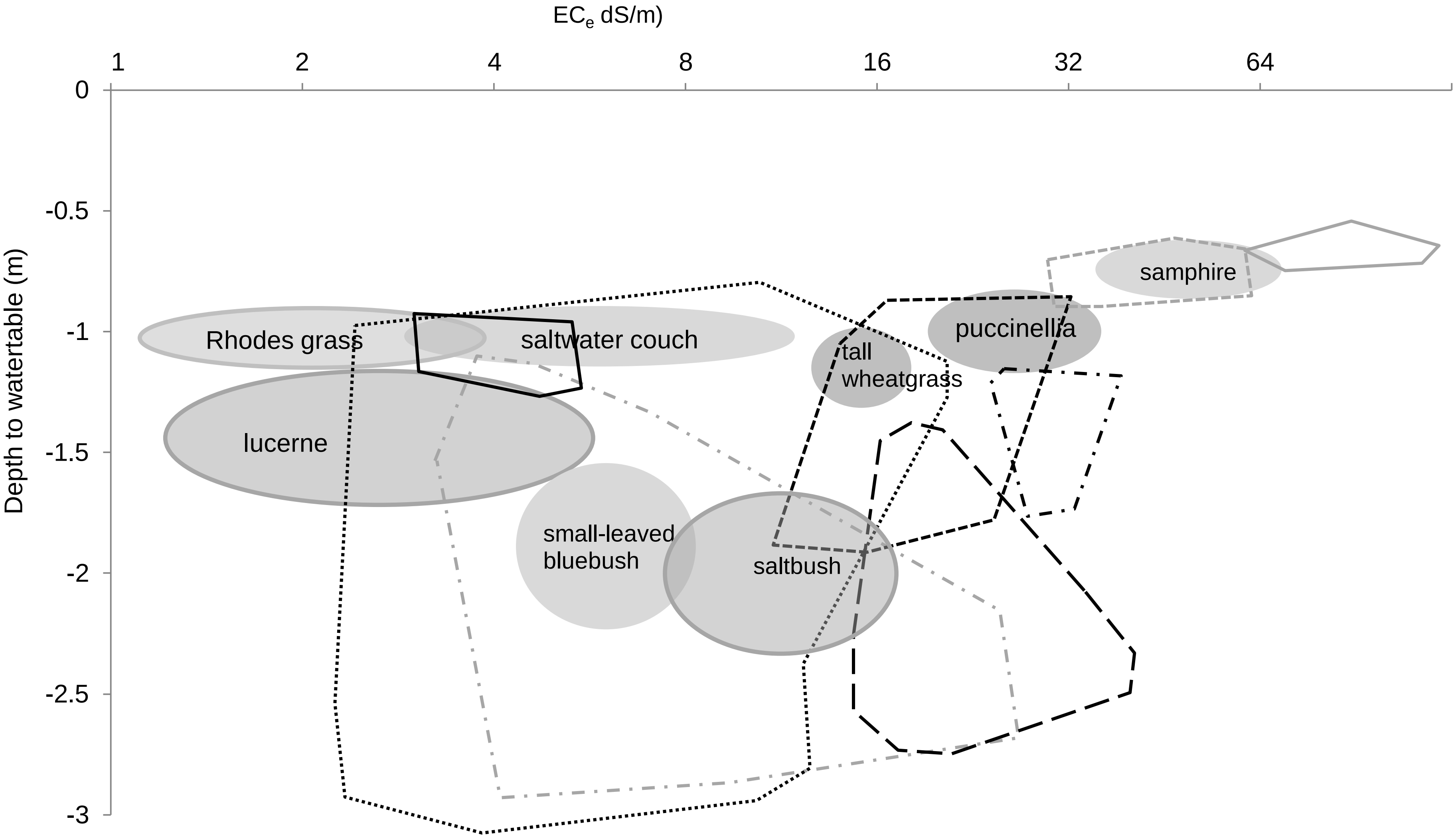

a)
ECe (log2)
1
2
4
8
16
32
64
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth to watertable (m)
b)
ECe dS/m)
1
2
4
8
16
32
64
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth to watertable (m)
c)
ECe (log2)
1
2
4
8
16
32
64
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth to watertable (m)

Figure 4



EC$_e$ dS/m)
1
2
4
8
16
32
64
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth to watertable (m)
samphire
puccinellia
Rhodes grass
saltwater couch
tall wheatgrass
lucerne
small-leaved bluebush
saltbush

1