School of Environmental Biology

REVEGETATION OF SALT-AFFECTED LAND AFTER MINING: GERMINATION AND ESTABLISHMENT OF HALOPHYTES

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ABSTRACT

Gold and nickel mining are a common land use in the semiarid Eastern Goldfields region of Western Australia. A frequent outcome of mining activity is highly saline landforms that result from the widespread use of hypersaline (> 50 g L^{-1} NaCl) groundwater for mineral processing and hydraulic tailings reclamation, and from saline horizons in soils, subsoils and mullock. Under State government legislation, all mined land must be rehabilitated to a stable and sustainable landform at the completion of mining activities.

There was little land rehabilitation carried out in the mining industry until the mid-1980s. At that time, legislation was introduced and, in due course, guidelines were issued on recommended approaches to rehabilitation. Today, rehabilitation of disturbed areas is usually integrated into the mining program and has become the rule rather than the exception. There has, however, been limited innovation in recent years and the established methods are not suitable for every land rehabilitation scenario, especially those where very high salinity is an important factor. The aims of this thesis were to make a contribution towards a better understanding of the ecology of halophytes suitable for use in revegetation and the likely physical requirements for their sustainable establishment on post-mining landforms.

In terms of germination, many of the halophytes currently used for rehabilitation of saline substrates are well suited in that they are able to germinate in solutions of up to 20 g L^{-1} NaCl. Furthermore, when higher salinities are encountered, seed dormancy is induced until salinity is reduced to a level at which germination can occur. There were differences observed between germination of annual and perennial chenopods that reflected their successional roles where annual chenopods tend to have a higher salt tolerance and germinate more rapidly. I developed a tolerance index to enable different germination responses to be readily compared. Values for the tolerance index ranged from 5.7 to 25.3 for the halophytic species compared with a value of 0.2 for the glycophytic *Secale cereale*. Values for saltbushes (*Atriplex*) and bluebushes (*Maireana*) ranged from 6.5 to 9.8 while values for samphires (*Halosarcia*) were higher (10.7-17.4).

Germination and early growth of taxa in the succulent genus, *Halosarcia,* were also studied. Though a member of the Chenopodiaceae, with a number of species occurring commonly throughout the region, *Halosarcia* spp. are not widely used in land rehabilitation. This is in part attributable to the poor level of knowledge of germination and growth characteristics compared with saltbushes and bluebushes, many of which are widely used. Two species studied, *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa*, are more salt-tolerant for germination than some other chenopods more widely used. Furthermore, in terms of their early growth, each taxon continued to grow in salinities up to 40 g L^{-1} NaCl, although root production and mass were reduced at that concentration. Another taxon, *H. pergranulata* subsp. *pergranulata*, was found to have a partial physical dormancy attributable to the testa, a phenomenon rare among halophytes. Dormancy was alleviated by scarification but was most effective where this occurred near the micropyle.

Field trials were conducted to assess methods of rehabilitating severely salt-affected surfaces ($EC_e > 50$ dS m^{-1}). In the initial trial, a number of surface treatments, including ripping, rock mulching and mounding, were shown to reduce soil EC_e in loam soils over a long period of time (seven years) compared with the control. In a subsequent trial, the use of good quality waste water, in conjunction with ponding banks, strongly promoted the establishment of vegetation by supplementing soil moisture and enhancing soil P although a reduction in soil EC_e was not observed. The depth and duration of ponding influenced the species that established and the cover achieved. Methods by which a soil cover could be established over hypersaline tailings surfaces were also investigated. The absence of a capillary break layer resulted in severe salinisation ($EC_e > 100$ dS m^{-1}) of a non-saline clay loam soil cover and likely severe difficulties in establishing and maintaining vegetation on the cover. Two types of capillary break layer, a synthetic membrane and a layer of coarse iron fayalite granules (nickel slag), were both effective at preventing the capillary rise of salts into the soil cover.

The physical and biological characteristics of the shores of Lake Lefroy, a large salt lake in the Eastern Goldfields region, were analysed using multivariate techniques.

Physical characteristics were strongly influenced by the orientation of the shores in relation to the predominant winds, and by depth to the saline groundwater table. Plant species were distributed in zones across the lake shores with small changes in elevation resulting in substantial changes in species distributions. Those plant species occurring at the lowest elevations (Zone I), including *Halosarcia* spp., exhibited a very high tolerance of saline soil and groundwater through an ability to accumulate Na^+ and Cl^- and make the necessary osmotic adjustments, and a capacity to tolerance high groundwater levels. Under certain conditions, the lake shore environment could be a useful model for a rehabilitated landform.

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1.0 INTRODUCTION

1.1 Mining in the Eastern Goldfields of Western Australia

The Eastern Goldfields region of Western Australia lies about 500 km east of Perth (Figure 1.1). The region has no formal boundaries but it is generally considered to lie east of Southern Cross and the Yilgarn region, north of Norseman, south of Leonora and Laverton in the Northern Goldfields, and west of the Nullarbor Plain. The area is best known for its gold mining, centred on the city of Kalgoorlie-Boulder, but it also supports nickel mining and a pastoral industry. The semiarid climate prevents the production of cultivated crops or other more intensive agricultural activities.

As earthmoving and ore processing technologies have improved over the years, low grade and high tonnage gold ore deposits have become more economically viable. Modern earthmoving equipment can shift ore and waste rock more efficiently and carbon-in-pulp (CIP) gold processing technology usually ensures good recoveries of gold from ore. As a result, very few underground operations remain and the trend is towards the creation of large open pits and correspondingly large waste rock dumps and tailings storage facilities. This manner of mining can have localized but severe environmental impacts. Left untended, the areas disturbed are unlikely to ever revegetate naturally. There are examples of mining waste from Roman times that are still poorly vegetated (Johnson and Lewis, 1995). Natural processes can play an important role in the restoration of mined land, but when the nature of land disturbance is severe, it is often necessary to ameliorate extreme soil conditions and introduce suitable plant species (Bradshaw, 1997).

Until the mid-1980s, there was little mined land rehabilitation undertaken in the Eastern Goldfields and no legislative framework requiring it. In 1985, a Work Party on Conservation and Rehabilitation in the Mining Industry reported on the gold mining industry (Work Party, 1985). It found the gold mining industry to be "significantly behind other segments of the mining industry with respect to environmental management". A number of

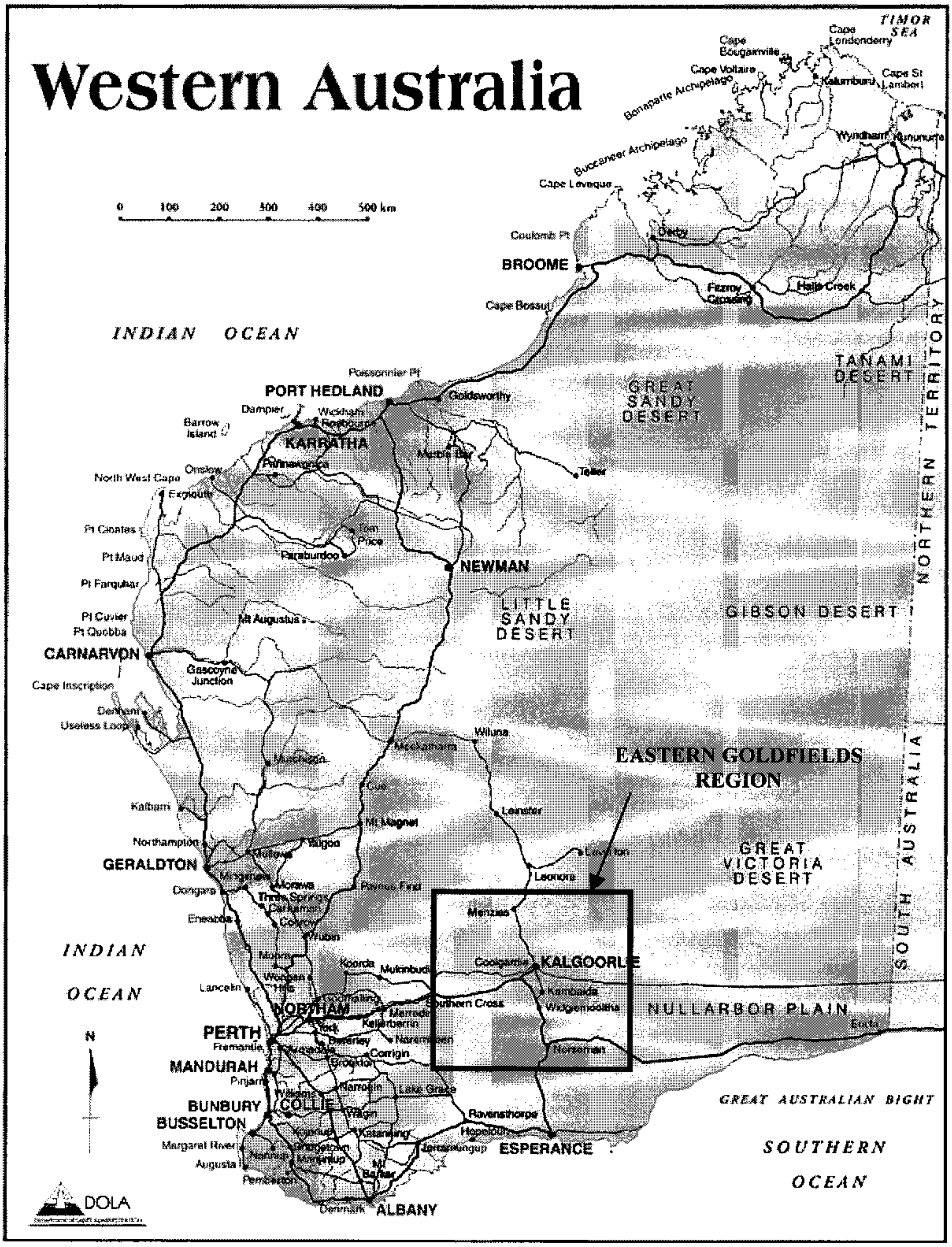

Figure 1.1: Location of Eastern Goldfields region of Western Australia.

recommendations were made, with the most significant of these relating to the development of an "environmental management unit" within the Western Australian Department of Mines and the requirement for tenement holders "to submit written environmental proposals" prior to "any significant surface disturbance". Special mention was made of the environmental problems faced by the Kalgoorlie-Boulder area.

Following the adoption of the majority of the Work Party's recommendations, rapid advances were made in environmental management. In 1988, the Western Australian Department of Mines released rehabilitation guidelines (Western Australian Department of Mines, 1988) to assist miners and these were followed by the findings of two three-year research programs into waste dump rehabilitation (Fletcher *et al.*, 1989; Jennings *et al.*, 1993). By the 1990s, some mines had developed integrated environmental management programs that dealt not only with rehabilitation but also with other environmental issues such as dust, noise and sulphur dioxide emissions (Howard *et al.*, 1991). In 1994, the Minerals Environment Liaison Committee (MELC) reviewed the progress made by the gold mining industry since the release of the original recommendations by the Work Party (Minerals Environment Liaison Committee, 1994). While considerable progress had been made, the management and rehabilitation of hypersaline tailings facilities were singled out as problem areas.

In recent years, a system of performance bonds has been introduced whereby the operating company issues a bank guarantee to cover the cost of rehabilitation should the company default on the work (Department of Minerals and Energy, 1998). The bond can be retired upon completion of rehabilitation to the satisfaction of the Department. By the late 1990s, however, few of these have been wholly retired although partial retirement commonly occurs. The reasons for this are numerous but include:

- the slow rate of succession of rehabilitated areas due to the semiarid climate;
- a lack of clear milestones and completion criteria to recognize such progress; and
- widespread difficulties with saline and other ‘hostile’ materials.

It is the latter issue of revegetation of saline materials with which this thesis is concerned.

1.2 Sources and impact of salinity

1.2.1 Overview

Gold and nickel mining in the Eastern Goldfields lead to the creation or extension of saline land surfaces in a number of ways. While the extent of the affected areas is very small in comparison with salt-affected lands resulting from land clearing and agriculture in Western Australian (Malcolm, 1983), legislation under which the mining industry operates requires a high standard of environmental management and land rehabilitation (Department of Minerals and Energy, 1996a). Furthermore, successful rehabilitation of salt-affected areas in the Eastern Goldfields can be made more difficult by the semiarid to arid climate. The latter ensures that once areas of a minesite become saline they are likely to remain so under normal rain-fed conditions and without substantial earthworks and amelioration.

The principal source of salt in mined landforms in the Eastern Goldfields is soil or substrate contamination through the use of hypersaline groundwater (>50 g L^{-1} total dissolved solids). This water is used for the processing of gold ore, reclamation and reprocessing of tailings, or as a result of open pit dewatering. Its use is due to the increased volume of gold production since the early 1980s that required a corresponding increase in the volume of water needed for processing. Fresh water had been supplied to Kalgoorlie-Boulder since 1902 via the Goldfields Water Scheme which brought water from dams near Perth, 500 km to the west (Blainey, 1993). This source, however, had become very expensive and water could not be supplied in the necessary quantities. Attention turned to local groundwater resources that were substantial but often hypersaline. Modern CIP technology is compatible with hypersaline water and groundwater has become the main source of process water.

The demand for groundwater in and around Kalgoorlie-Boulder increased rapidly from 1.2×10^6 kL in 1984 (BHP and AGC, 1988) to around 15×10^6 kL in 1990 (Commander *et al.*, 1991) and 26.5×10^6 kL in 1996 (Ion, 1998). The quality of groundwater is extremely variable. Sources of potable, brackish and saline (10-50 g L^{-1} TDS) water exist but are relatively few. Table 1.1 shows some typical groundwater resources and their quality and Figure 1.2 compares typical groundwater quality to some other water standards.

Table 1.1: Concentration of total dissolved solids (TDS) in some groundwater resources used by the mining industry in the Eastern Goldfields (from Turner *et al.*, 1993).

Source	TDS (g L^{-1})
Pancontinental	28.5-170.7
Newcrest	49-104.1
Poseidon Kaltails	99.3-130.7
Kalgoorlie Consolidated Gold Mines	164.1-213.1

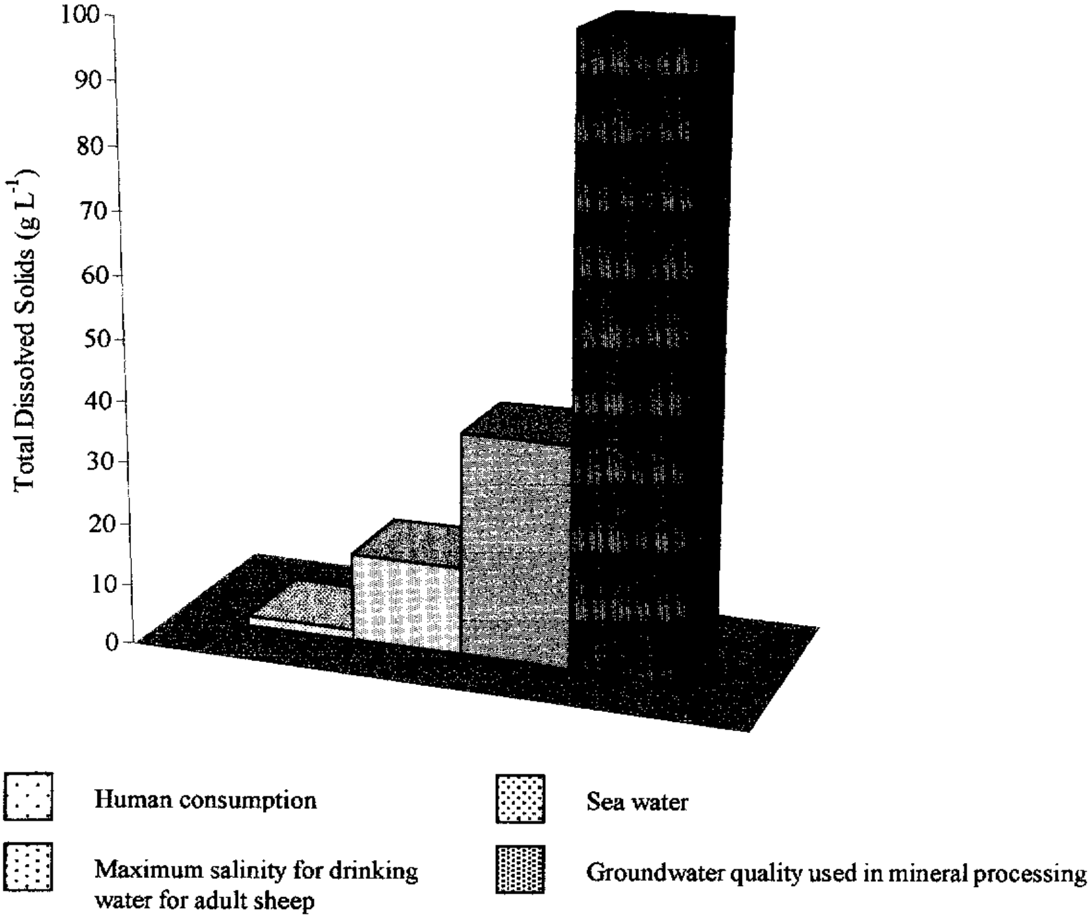

Figure 1.2: Typical groundwater quality used in mineral processing in the Eastern Goldfields (Turner *et al.*, 1993) compared with other common standards and values (Taylor, 1991).

1.2.2 Tailings storage facilities

Given the quantities and quality of groundwater used, millions of tonnes of salt are brought to the surface each year from underground aquifers for eventual storage in surface facilities. The Western Australian Department of Minerals and Energy records showed 61 registered gold or nickel tailings storage facilities in May 1997 with tailings $\geq$ 50,000 ppm TSS (Total Soluble Solids) (J. Ranasooriya, Department of Minerals and Energy WA, pers. comm.). These facilities have a total surface area of over 34 km^2. A further 17 have tailings with salinities of 15,000-50,000 ppm TSS and cover almost 5 km^2.

An Australia-wide survey (Minerals Council of Australia, 1996) recorded nine operations with localised impacts on surrounding vegetation due to seepage of hypersaline water from tailings storage facilities. Losses of hypersaline water from sluice mining operations and tailings dams on pastoral leases have been of concern to some pastoralists (Pringle *et al.*, 1990). While there is some evidence to show that some plants can utilise saline groundwater in limited amounts (Mensforth *et al.*, 1994), relatively sudden rises in saline water tables adversely affect vegetation and result in salinisation of soils with concomitant rehabilitation difficulties. Affected areas often show surface crusting of salts or staining of soils due to the attraction of water vapour to relatively dry soils with crystalline salt.

The need to research the design of tailings storage facilities to aid their rehabilitation and revegetation and possible future reprocessing was recognised some time ago (Mulcahy, 1979) and remains of some concern (Minerals Environment Liaison Committee, 1994). Placement of saline tailings as backfill in underground mining operations has been promoted as an alternative to surface storage (De Souza, 1992) but there are now few instances in the Eastern Goldfields where it can be applied.

1.2.3 Other mining sources

Saline groundwater may escape into the surface environment through facilities other than tailings storages. Groundwater for use in mineral processing is pumped to treatment plants from remote borefields. Spillage of saline water occurs through rupture of pipelines, although most pipelines have systems for prevention or capture of water spillages. The use of saline groundwater for dust suppression is also common practice at many mine sites. Kyle (1989) found that this did not usually result in damage to surrounding soils and vegetation but he urged careful design of on-site drainage and education of mine personnel on the effects of saline water on vegetation. Salt spray from mining activities has been shown to modify invertebrate communities in affected soils (Read, 1996). Hypersaline water has been used to hydraulically reclaim old gold tailings for retreatment (see Chapter 5), resulting in a highly saline land surface. Spillage of saline water from drilling operations is another minor contributor.

1.3.4 Natural sources

The salt in groundwater, and in soil profiles, originates from marine sediments and gradual accumulation of salt deposited in rainfall. Minor amounts of salts are deposited each year from dust precipitated in rainfall and as dry fallout. Kalgoorlie received an estimated 20.3 kg ha^{-1} of sea salt (calculated from the chloride content of sea water, 55.05%) in 1973 (Hingston and Gailitis, 1976). The source of this salt is mainly marine aerosols but includes redistributed salts from salt lakes. The hypersalinity of groundwaters is due to their having been affected by evaporation in salt lake systems at some time in the past (Turner *et al.*, 1993).

Although the occurrence of salt in soil horizons and regolith (see Fig. 1.3 for an example), saline waste rock and overburden is widespread, it can usually be managed if it is identified during the mining process. It can then be incorporated within waste rock dumps and away from outer surfaces. In addition to the above, some minesites will have naturally saline areas if they occur on or around a salt lake and disturbed areas with a naturally shallow saline water table may become more saline.

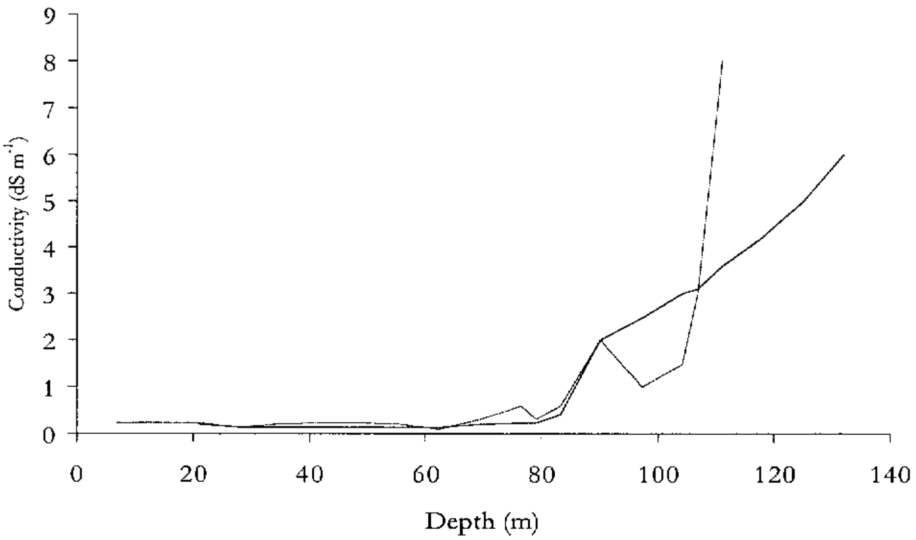

Figure 1.3: Profiles of interstitial salt in cuttings from two drill holes through an ore body (adapted from Department of Minerals and Energy, 1996a).

1.3 Thesis objectives

1.3.1 Overview

The rehabilitation of salt-affected land is an issue of major importance around the world (Malcolm, 1989; Le Houèrou, 1992). In most cases, the degradation is a consequence of activities associated with agriculture or grazing. By comparison, the contribution to land salinisation as a result of mining is very minor, but it can lead to significant localised impacts. It is important to rehabilitate such land during or soon after mining to reduce the need for ongoing management of that land. Unsuccessful or ineffective rehabilitation can lead to costly remedial works, lengthy post-closure monitoring phases and, in some cases, adverse effects on adjacent land.

In the Eastern Goldfields, the outcome of studies by Fletcher *et al.* (1989) and Jennings *et al.*

(1993), and guidelines issued by the Department of Minerals and Energy (Department of Minerals and Energy, 1996a), have formed the basis for rehabilitation of mined land. Development of rehabilitation technology, however, has slowed in recent years (Cannon, 1996) and the established rehabilitation 'recipes' cannot be applied to every rehabilitation scenario (Barrett, 1994). My study sought to refine existing, and initiate further, approaches to the rehabilitation of saline land after mining. It did not examine approaches to rehabilitation where significant earthworks and engineering designs are deemed necessary but focused on two key areas as outlined below and in Fig. 1.4.

1.3.2 Ecophysiology of halophytes

For many taxa, the germination stage is highly significant in determining a species' ability to establish and survive. While seeds of halophytes may survive under saline conditions, germination may not occur until salinity is reduced (Ungar, 1995). Halophytic taxa within the Chenopodiaceae are widely used for land rehabilitation in the Eastern Goldfields, usually by direct seeding (Fletcher *et al.*, 1989). While many of these have been assessed for salt tolerance at germination (eg. Fletcher *et al.*, 1989; Osborne *et al.*, 1993), few studies have attempted to rank or otherwise classify germination responses within a typical seed mix and draw inferences from these responses. This is undertaken in Chapter 2.

Although usage of chenopod seeds is widespread, it has been largely based on *Atriplex* and *Maireana* species, and other chenopods are rarely used (eg. Barrett and Jennings, 1994). The reason for this is twofold. Firstly, there is an existing body of knowledge on the establishment and growth of *Atriplex* and *Maireana* spp. for rehabilitation of degraded pastoral and agricultural areas (eg. Malcolm, 1989). Both genera contain many taxa that are suitable for grazing and forage production. In contrast, knowledge of the seed biology of other chenopods of limited or no forage value is poor. Secondly, many mining operations are encouraged to use palatable species so that these areas can be used for grazing when rehabilitation was complete.

Subsequently, however, there has been interest in establishing other chenopods (Barrett, 1994). This includes non-palatable taxa from the genus *Halosarcia* that comprises leafless

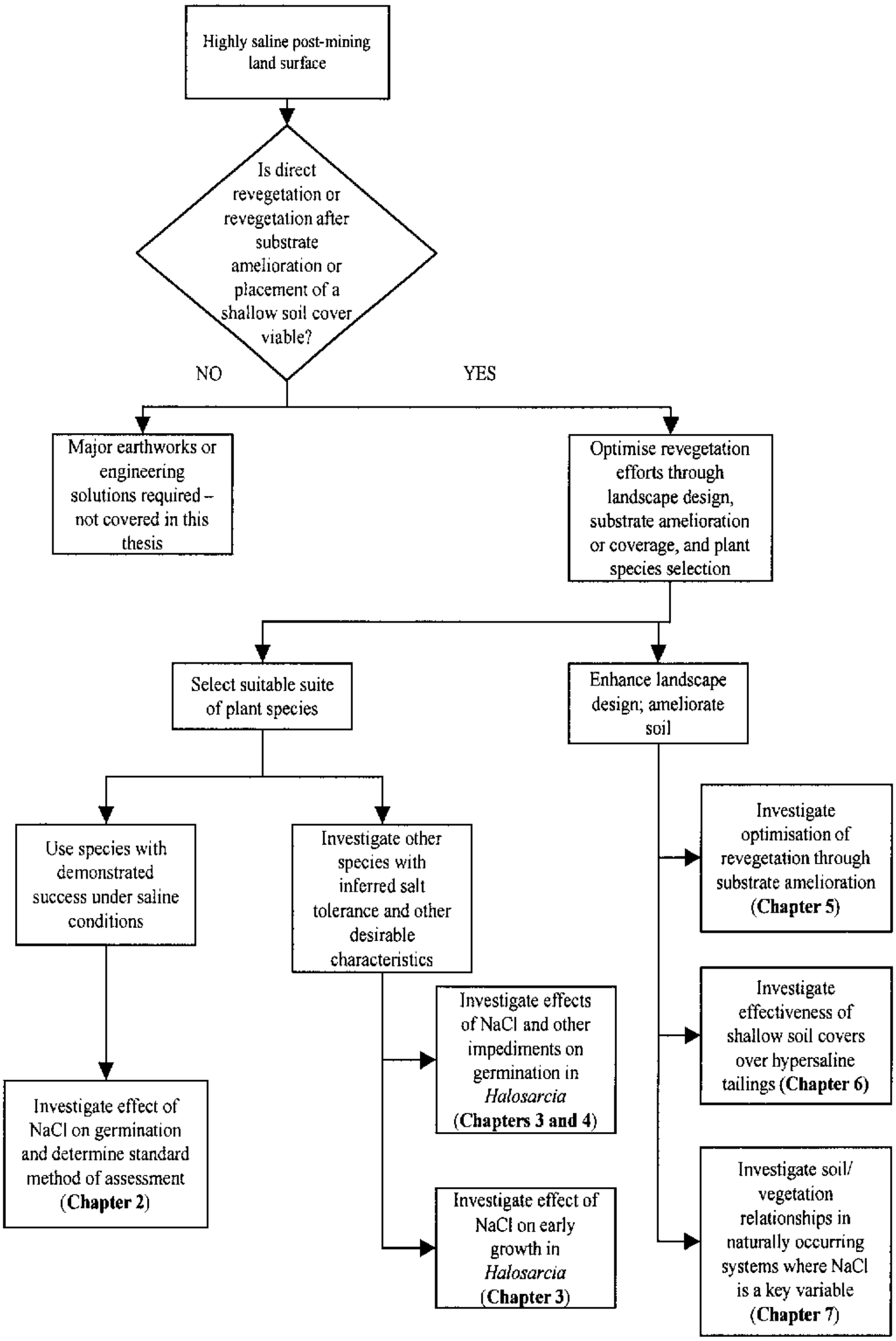

Figure 1.4: Outline of approach towards studies undertaken within this thesis.

succulent shrubs. *Halosarcia* spp. tend to occur naturally in more saline soils than other chenopods. Interest in *Halosarcia* has developed because the existing suite of chenopods was not adapted to some rehabilitation scenarios, for example, areas of very high salinity or where waterlogging occurred. Furthermore, the use of palatable taxa only on rehabilitated landforms placed them at some risk of overgrazing and trampling of newly formed soil surfaces. This could result in unacceptable levels of disturbance and erosion and the possibility of requiring expensive remedial work. Finally, the addition of other taxa to seed mixes would potentially result in greater species diversity and greater resistance to environmental perturbations. Chapters 3 and 4 examine aspects of germination and early growth in *Halosarcia*.

1.3.3 Alternative approaches to rehabilitation

In some instances, established methods of direct seeding are unsuccessful as the soil medium is too saline to permit germination and establishment of even salt-tolerant chenopods under rain-fed conditions. Under these conditions, it is necessary to look at ways of enhancing soil moisture or otherwise ameliorate soil conditions. After examining the effects of surface earthworks, Chapter 5 investigates the effects of ponding good quality waste water on highly saline soils as a possible method that could be adopted for particular problem areas on minesites.

Chapter 6 looks at a 'hostile' substrate, hypersaline mine tailings, for which direct revegetation is unlikely to be successful. Soil covers, with and without capillary breaks to prevent rise of salts from the underlying substrate, were trialled.

Chapter 7 describes research into the distribution of vegetation around the margins of a salt lake and the environmental factors that influence it. An improved understanding of the impact of salinity in natural environments can provide both a basis for the design of alternative post-mining landforms and a profile of the habitat preferences of species of potential use in mine rehabilitation. Some authors (Chalwell, 1996; McKenna, 1996; Sawatsky and Beckstead, 1996) have studied natural landforms as possible analogues for rehabilitated areas and the scope for lake margins to be used in this manner is discussed.

2.0 EFFECT OF NaCl ON GERMINATION OF THE SEEDS OF TEN SPECIES USED IN LAND REHABILITATION IN THE EASTERN GOLDFIELDS OF WESTERN AUSTRALIA

2.1 Introduction

Gold and nickel mining, and sheep grazing, are the predominant land uses in the Eastern Goldfields region of Western Australia. The low mean rainfall of about 250 mm pa prevents the growth of cultivated crops and other agricultural activities. Revegetation after mining is widely carried out (Fletcher *et al.*, 1989). Plants are usually established by direct seeding into contoured furrows in topsoil. Although average rainfall is spread reasonably evenly across the year (Beard, 1978), revegetation work is usually undertaken in autumn when temperatures and evaporation are lower. Most plant species will germinate and establish during the period April to October during which an average of 150 mm of rainfall is received (unpubl. data, Bureau of Meteorology, Kalgoorlie-Boulder Climatic Averages 1939-1996).

Saline horizons in local soils are common. Mining activities, however, can lead to an increase in saline conditions at the surface (Department of Minerals and Energy, 1996a; Barrett, 1994) through the exposure of saline material as overburden or ore from open pit and underground mines, and spillage and seepage of highly saline groundwater used for mineral processing and slurry transport. Saline groundwater, usually containing high levels of NaCl, is used in the absence of any significant fresh or brackish surface water or groundwater reserves (Turner *et al.*, 1993).

For revegetation after mining, locally occurring species tend to be used as they are adapted to the climatic conditions and many are salt-tolerant (Fletcher *et al.*, 1989), especially species from the Chenopodiaceae (*Atriplex* and *Maireana* spp.). Some non-native species are used for particular purposes. An understanding of seed germination is critical to the success of revegetation efforts where temporal and financial constraints dictate that such efforts should be successful in the short term.

For some species at least, germination is the stage in their life cycle during which they are most salt-sensitive (Myers and Couper, 1989). Halophytes are generally more salt-tolerant than glycophytes at germination but all vascular plant species show a delay and a reduction in germination as salt stress is increased (Ungar, 1995). The reduction in germinability may be due to the low osmotic potentials occurring under saline conditions or the toxic effects of the ions. Other factors, including temperature (Khan and Rizvi, 1994; Mikhiel *et al.*, 1992), thermoperiod (Khan and Ungar, 1997), hormones (Khan and Ungar, 1984) and intraspecies variability (Williams, 1960; Philipupillai and Ungar, 1984; Beadle, 1952; Mandák and Pyšek, 1999) may also affect germination under saline conditions, as indeed may differences in the types of salts present (Blank *et al.*, 1994). An important characteristic that distinguishes halophytes from glycophytes, however, is their ability to remain dormant at high salinities and germinate later when the level of salinity is reduced (Ungar, 1995).

I studied the germination response of the seeds of six annual or short-lived perennial species, together with the seeds of three perennial chenopods and a tree species, with a view to identifying salinity levels above which attempts at revegetation are unlikely to succeed. A second aim of the study was to assess the ability of seeds to withstand periods of high soil salinity, such as those that may occur prior to significant winter rains. Thirdly, I developed a means by which different responses between species can be ranked. Limitations of the research and implications for field establishment are discussed.

2.2 Materials and Methods

2.2.1 Species selection and seed pretreatment

Ten plant species were selected comprising three exotic grasses, three annual chenopods, three perennial chenopods and one tree species. Seed collection details and characteristics of each species are given in Table 2.1. The species were selected as each

Table 2.1: Selection of plant species used in mine rehabilitation assessed for germination response to NaCl.

Species	Seed Source	Date Collected	Characteristics
Atriplex codonocarpa P.G. Wilson (Bell saltbush)	Lakewood, Western Australia (30°48'S, 121°32'E)	December 1993	Annual or short-lived perennial to 0.3 m high; successful coloniser of disturbed land (Mitchell and Wilcox, 1994); seeds heavily in favourable conditions (Rusbridge *et al.*, 1996).
Atriplex holocarpa F.Muell. (Pop saltbush)	Lakewood, Western Australia (30°48'S, 121°32'E)	December 1993	Annual herb commonly 0.15 m high; occurs on lower parts of salt lake margins and saline drainages; can survive in more saline conditions than *Atriplex codonocarpa* (Mitchell and Wilcox, 1994).
Atriplex nummularia Lindley in Mitch. (Old man saltbush)	Kambalda, Western Australia (31°13'S, 121°40'E)	October 1993	Perennial bushy shrub up to 2 m tall; occurs on limestone plains and on lake margins (Mitchell and Wilcox, 1994); initially slow growing but once established forms long-lived shrub layer (Rusbridge *et al.*, 1996).
Atriplex vesicaria Heward ex Benth. (Bladder saltbush)	Kambalda, Western Australia (31°13'S, 121°40'E)	October 1993	Low growing perennial shrub to 0.8 m; prefers alkaline clays and loams on salt lake margins and saline drainages (Mitchell and Wilcox, 1994); widely used in land rehabilitation after mining (Rusbridge *et al.*, 1996).
Casuarina obesa Miq. in Lehm. (Swamp sheoak)	Kambalda, Western Australia (31°13'S, 121°40'E)	October 1993	Tree occurring in brackish or saline situations near salt lakes (Wilson and Johnson, 1989).
Maireana georgei [Diels] P.G.Wilson (Golden bluebush)	Kambalda, Western Australia (31°13'S, 121°40'E)	October 1993	Perennial compact shrub to 0.5 m; occurs on saline alkaline soils in saline shrub communities (Mitchell and Wilcox, 1994); seeds heavily under favourable conditions (Rusbridge *et al.*, 1996).
Maireana pentatropis [Tate] P.G. Wilson (Five winged bluebush)	Lakewood, Western Australia (30°48'S, 121°32'E)	December 1993	Short-lived perennial chenopod; erect shrub to 0.6 m (Pringle and Cranfield, 1995); prefers calcareous soils.
Puccinellia ciliata Bor cv. 'Menemen' (Saltmarsh grass)	Commercial supplier	-	Perennial grass; a pioneer plant for the reclamation of salty land (Paterson, 1992).
Secale cereale L. (Cereal rye)	Commercial supplier	-	An annual grass used to bind disturbed soil (Paterson, 1992); has been used for stabilisation of slopes (Fletcher *et al* 1989).
Thinopyrum elongatum [Host] Beauv. cv. 'Tyrell' (Tall wheatgrass)	Commercial supplier	-	Perennial grass adapted to poorly drained and saline or alkaline soils (Rogers and Bailey, 1963; Paterson, 1992).

is commercially available and has an inferred or demonstrated salt tolerance. All seeds, except for those of the grass species, were collected from the Eastern Goldfields region. In each case, seeds were collected from ~10 individual plants and bulked together. The grasses are not widely used for mine rehabilitation in the Eastern Goldfields due to the low rainfall but are suitable for some applications, especially where soil moisture can be supplemented. The chenopods, however, are common components of seed mixes used in mine rehabilitation (Jennings *et al.*, 1993; Barrett and Jennings, 1994; Rusbridge *et al.*, 1996).

Bracts on the *Atriplex* spp. were removed to improve germinability (Burbidge, 1945; Beadle, 1952). Woody perianths around the seeds of the *Maireana* spp. were removed for the same reason (Osborne *et al.*, 1993). Mechanical means (rubbing between rubber mats, sieving with abrasive materials) were initially used to extract seeds from the bracts and perianths but resulted in damage to seeds. The seeds used here were extracted individually using a scalpel to cut away the surrounding material. Seed weights were obtained by weighing three replicates of 50-100 seeds. The surface of all seeds was sterilized using 1% sodium hypochlorite, then rinsed in deionised water. No other pretreatment was undertaken.

2.2.2 Germination testing

Over the period January-May 1994, seeds were tested for germinability in 90 mm diameter petri dishes with two filter papers (Whatman No. 1) moistened with 5 mL of a NaCl solution. The solutions used were made up with deionised water and contained 0 (control), 5, 10, 20 and 40 g L^{-1} NaCl. The NaCl levels were selected as representative of the range of soil conditions likely to be encountered and within the range in which at least some germination was possible (Ungar, 1995). Five replicates of 30-35 seeds each were used for each treatment. The petri dishes were placed in polyethylene bags to minimise evaporation losses and the consequent concentration of NaCl solutions, and were then transferred to a germination cabinet (Lindner & May Pty Ltd, Windsor, Brisbane) in a randomised block design. The germination cabinet was set at a temperature regime of 25/15°C (day/night) with a 12 h photoperiod. The light intensity of the germination cabinet approximated 10.5 microeinsteins m^{-2} sec^{-1}. The temperatures closely approximate average maximum and minimum temperatures for autumn (April) in the Eastern Goldfields and alternating temperatures have been shown to improve germination in the genus *Atriplex* (Young *et al.*, 1980) and other species (Thompson *et al.*, 1977). The tests were run for 28 days. Each dish was checked daily and any germinants were recorded and removed. Germination was considered to have occurred when the radicle reached a length of 2 mm. Previcur ™ (1% v/v) was used to control fungal growth.

After 28 days, ungerminated seeds in the 40 g L^{-1} NaCl treatment were removed for an assessment of their ability to recover. The seeds were rinsed thoroughly in deionised water and transferred to a new petri dish set up as above but containing deionised water only. The seeds were allowed to germinate under the same conditions for a further 14 days.

2.2.3 Data analysis

The germination rate (GR) for each treatment was calculated as follows (Osborne *et al.* 1993):

$$GR = \frac{(n_1 \times t_1) + (n_2 \times t_2) + \ldots\ldots + (n_x \times t_x)}{\Sigma_n}$$

Where:

n_1 = no. of germinants on first day of germination
t_1 = days from start to first germination
x = no. of days to final germination
Σ_n = total no. of seeds germinated.

Final germination percentages and germination rates for individual species were analysed using a one way ANOVA. The square root of each percentage value was arcsine transformed which is the preferred transformation for percentages when they are very high or very low (Zar, 1996). The germination rate data were log transformed prior to analysis to normalize the values. Where significant differences among the means were detected, Tukey's multiple range test was used to determine significant differences between pairwise comparisons among individual treatments. Treatments where zero values were recorded for germination rates were excluded. The number of germinants from the recovery experiment was adjusted to take account of any germinants occurring in the original 40 g L^{-1} NaCl treatment. The response to increasing NaCl concentration between species was determined by calculating germination for each species as a proportion of the NaCl treatment achieving the highest germination, with transformation and analysis by one way ANOVA and Tukey's test as before. All analyses were undertaken using Analyse-It v.1.5 software (Analyse-It Software Ltd, Leeds, UK) and $P < 0.05$ used to define statistical significance.

A tolerance index was devised to enable a ranking to be made of the salt tolerance of the species assessed. An index has been shown to be useful tool in comparing responses between species to salinity and other environmental stresses (van der Moezel *et al.*, 1991). The index is based on two key features attributed to the seeds of halophytes (Ungar, 1995). These attributes are, firstly, an ability to germinate under more saline conditions than other species and, secondly, an ability to exhibit dormancy under highly saline conditions while remaining viable so that germination may still occur when salinity is reduced. The tolerance index (TI) is:

$$TI = LC_{50} * RR$$

Where:

LC_{50} = NaCl level (in g L^{-1}) at which germination is reduced to 50% of that occurring in a deionised water control, and

RR = germination achieved in deionised water after exposure to 40 g L^{-1} NaCl
for 28 days relative to the deionised water control.

The LC_{50} values were determined using binomial distributions calculated by EC-TOX 1.1 (Bureau of Water Management, Connecticut Department of Environmental Protection, Hartford, Connecticut, USA) to a 95% confidence level. Values for recovery ratios ranged from 0 (no germination after exposure to 40 g L^{-1} NaCl) to in excess of 1 (where greater germination after exposure to 40 g L^{-1} NaCl was achieved compared with a control). Germination achieved in the original 40 g L^{-1} treatment was taken into account in determining the recovery ratio.

For ease of comparison, where the results obtained by other researchers are discussed, their values have been converted from the units they have used (%, mol m^{-3}, bars) to the units contained herein (g L^{-1}). Conversions from bars to g L^{-1} were made using a factor (-1.736) derived from Taylor (1991).

2.3 Results

2.3.1 Seed weights

Mean seed weights for each species are given in Table 2.2. Seed weights ranged from 0.33 ± 0.12 mg in *Puccinellia ciliata* to 6.99 mg in *Thinopyrum elongatum*. Within the chenopods, the seeds of annual species tended to be smaller than those of perennial species.

2.3.2 Germinability in NaCl solutions

The seed germination responses to different concentrations of NaCl solutions for each species are shown in Figs. 2.1 and 2.2. The controls (0 g L^{-1} NaCl) gave seed germination greater than 70% for most species, although germination of only 59.1% and 34.0% was achieved in *Atriplex vesicaria* and *Casuarina obesa* respectively. In comparison with the seed germination recorded in the controls, the overall germination

Table 2.2: Mean (± SD) seed weights for ten plant species used for germination testing. Except where otherwise shown, means are from three replicates of 50-100 seeds. Data for *Thinopyrum elongatum* is from Symonds Seeds Pty Ltd (pers. comm.). ND = no data.

Species	Mean seed weight (mg)
Atriplex codonocarpa	0.92 ± 0.15
Atriplex holocarpa	1.10 ± 0.22
Atriplex nummularia	1.38 ± 0.10
Atriplex vesicaria	1.23 ± 0.18
Casuarina obesa	ND
Maireana georgei	1.37 ± 0.01
Maireana pentatropis	0.91 ± 0.07
Puccinellia ciliata	0.33 ± 0.12
Secale cereale	ND
Thinopyrum elongatum	6.99

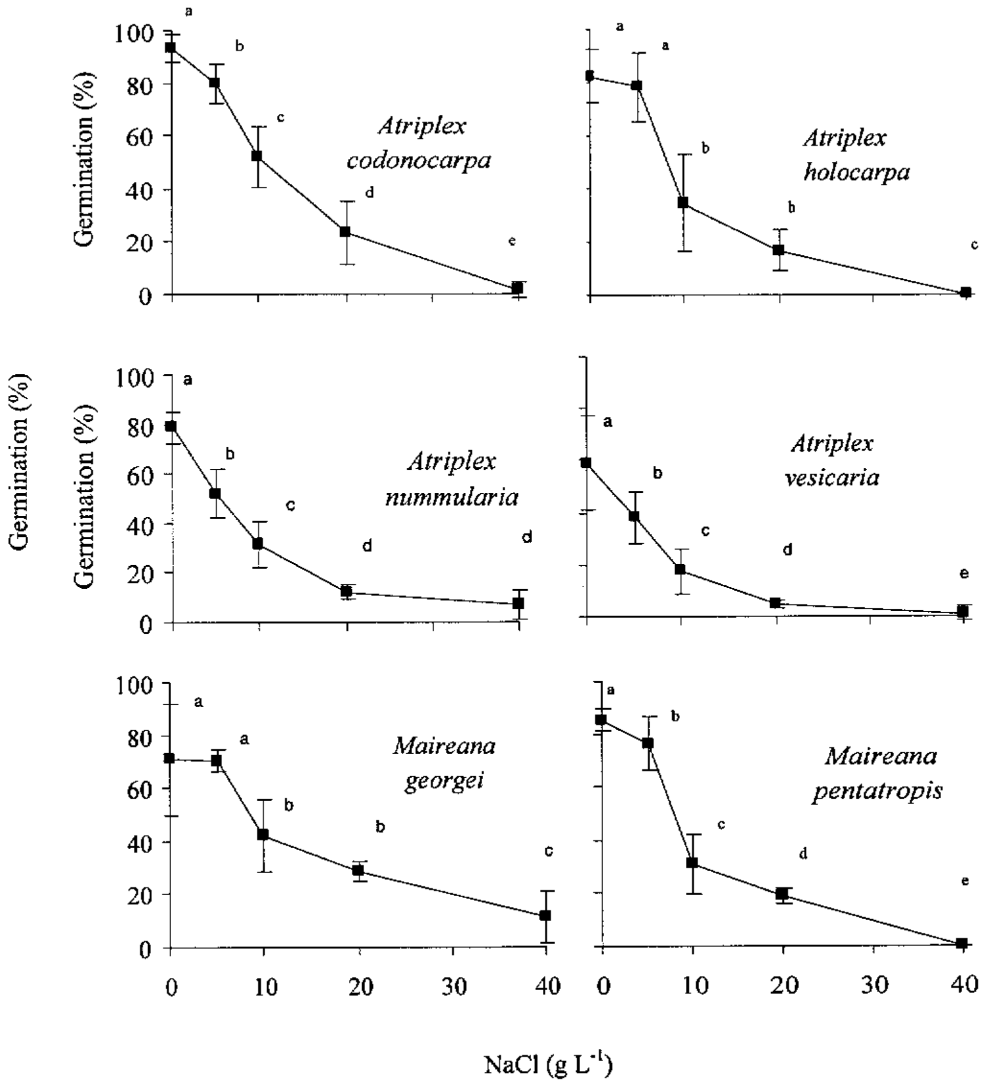

Figure 2.1: Mean seed germination (± SE) in solutions of increasing NaCl concentration for chenopodiaceous species. Different letters indicate statistically significant differences ($P < 0.05$) between treatments within each species (by Tukey's test).

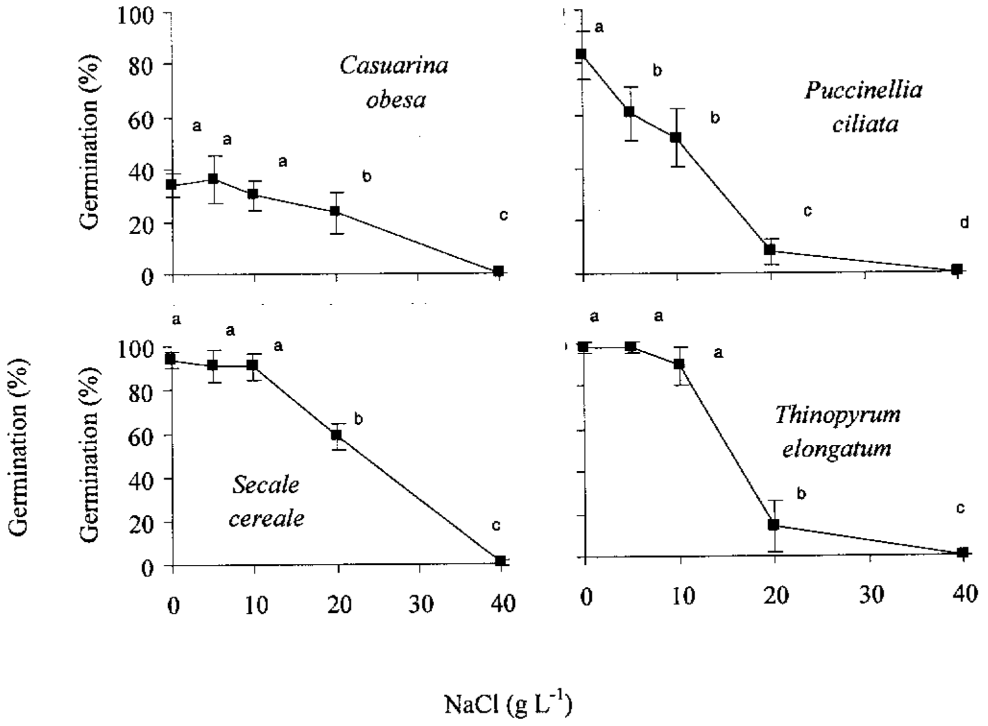

Figure 2.2: Mean seed germination (± SE) in solutions of increasing NaCl concentration for three grass species and *Casuarina obesa*. Different letters indicate statistically significant differences ($P < 0.05$) between treatments within each species (by Tukey's test).

percentage was significantly reduced by the 5 g L^{-1} NaCl solution for *Atriplex codonocarpa, A. nummularia, A. vesicaria, Maireana pentatropis* and *Puccinellia ciliata*; by the 10 g L^{-1} NaCl solution for *Atriplex holocarpa* and *Maireana georgei*; and, by the 20 g L^{-1} NaCl solution for *Thinopyrum elongatum*, *Casuarina obesa* and *Secale cereale.* In each case, increasing NaCl concentrations further reduced germination. Few seeds of any species germinated in the 40 g L^{-1} NaCl solution. Each increase in NaCl concentration up to 20 g L^{-1} NaCl resulted in a significant decrease in germination in *Atriplex nummularia* and *A. vesicaria.*

2.3.3 Germinability after exposure to 40 g L^{-1} NaCl

The results of the recovery experiments are shown in Fig. 2.3. Exposure to 40 g L^{-1} NaCl solution for 28 d did not significantly reduce the subsequent ability of seeds of *Atriplex nummularia, A. holocarpa* or *Casuarina obesa* to germinate. The treatment resulted in a significantly greater germination in the seeds of *Atriplex vesicaria* while significantly reducing the ability to germinate in all other species. The reductions ranged from the almost complete loss in germinability in *Secale cereale* to species such as *Thinopyrum elongatum* (87.3%) and *Maireana pentatropis* (75.3%) that still achieved a high germination percentage. The large majority of *S. cereale* seeds were soft and decayed after 28 d at 40 g L^{-1} NaCl.

2.3.4 Germination rate in various NaCl solutions

Changes in seed germination rate in response to increasing NaCl concentrations varied between species (Figs. 2.4 and 2.5). The germination rate of *Atriplex vesicaria, A. nummularia* and *Maireana georgei* did not significantly change with increasing NaCl concentration. In other species, the germination rate was significantly reduced at either 5 or 10 g L^{-1} NaCl and decreased further with increasing NaCl concentration. Where seeds had been exposed to 40 g L^{-1} NaCl for 28 d, germination in *Atriplex holocarpa, A. nummularia, A. vesicaria* and *Casuarina obesa* occurred more rapidly than in the control.

2.3.5 Tolerance index (TI)

The tolerance index (TI) value for each species is shown in Table 2.3. Values ranged from 0.2 (*Secale cereale*) to 23.0 (*Casuarina obesa*) with most species ranked between 5 and 10. A recovery ratio of more than 1 was achieved by *C. obesa* and *Atriplex vesicaria*. When presented as a scatterplot (Fig. 2.6), *S. cereale* and *C. obesa* showed distinct differences in their responses compared with the other species. The responses from the chenopods, with the exception of *A. vesicaria*, were similar.

Table 2.3: Tolerance index (TI) values for ten species assessed for NaCl tolerance at seed germination. TI is the product of LC_{50} value and the recovery ratio.

Species	LC_{50} for germination (g L^{-1} NaCl)	Recovery ratio (RR)	TI
Atriplex codonocarpa	8.8	0.74	6.5
A. holocarpa	9.2	0.82	7.5
A. nummularia	7.7	0.90	7.0
A. vesicaria	6.7	1.47	9.8
Casuarina obesa	23.0	1.10	25.3
Maireana georgei	14.1	0.47	6.7
M. pentatropis	8.5	0.88	7.5
Puccinellia ciliata	11.5	0.50	5.7
Secale cereale	22.2	0.01	0.2
Thinopyrum elongatum	14.6	0.89	13.0

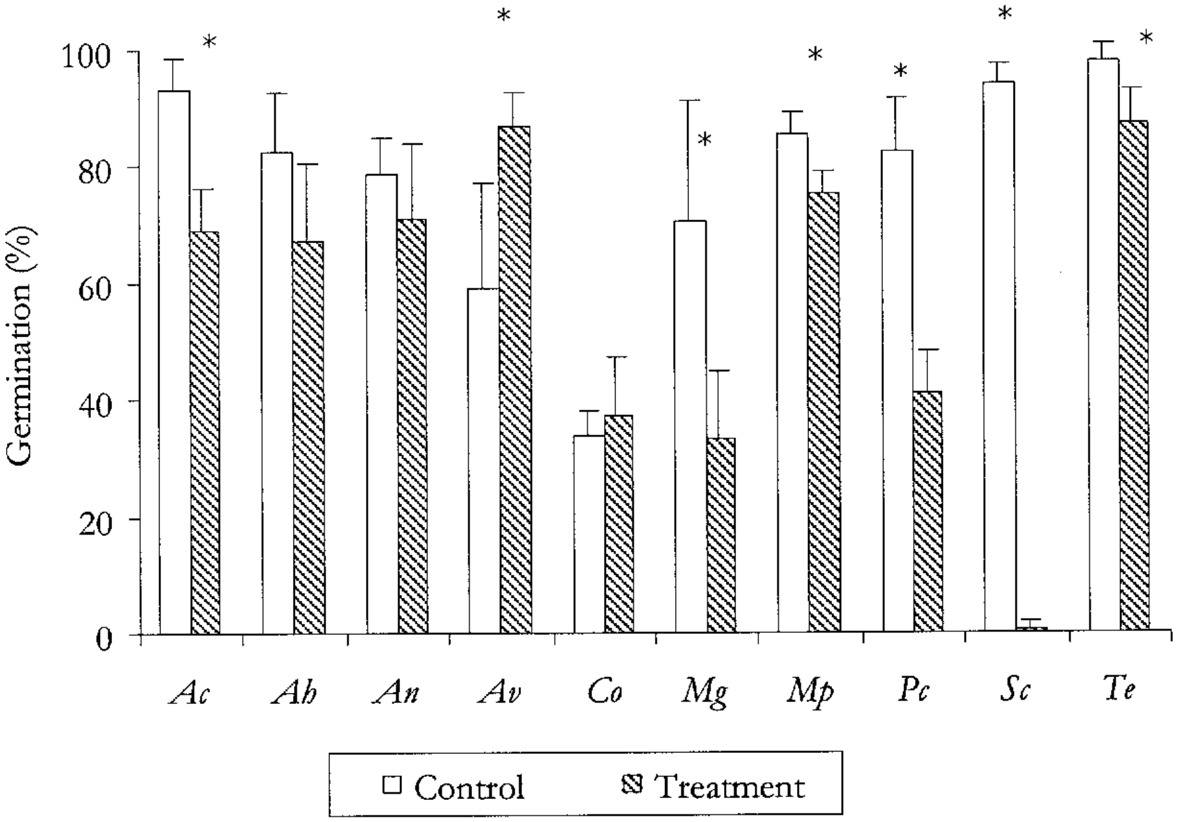

Figure 2.3: Germination of seeds in deionised water after 28 d in 40 g L^{-1} NaCl solution (treatment) compared with germination in the control. Species are *Atriplex codonocarpa* (*Ac*), *A. holocarpa* (*Ah*), *A. nummularia* (*An*), *A. vesicaria* (*Av*), *Casuarina obesa* (*Co*), *Maireana georgei* (*Mg*), *M. pentatropis* (*Mp*), *Puccinellia ciliata* (*Pc*), *Secale cereale* (*Sc*) and *Thinopyrum elongatum* (*Te*). Asterisks indicate significant differences ($P < 0.05$) determined by Tukey's test.

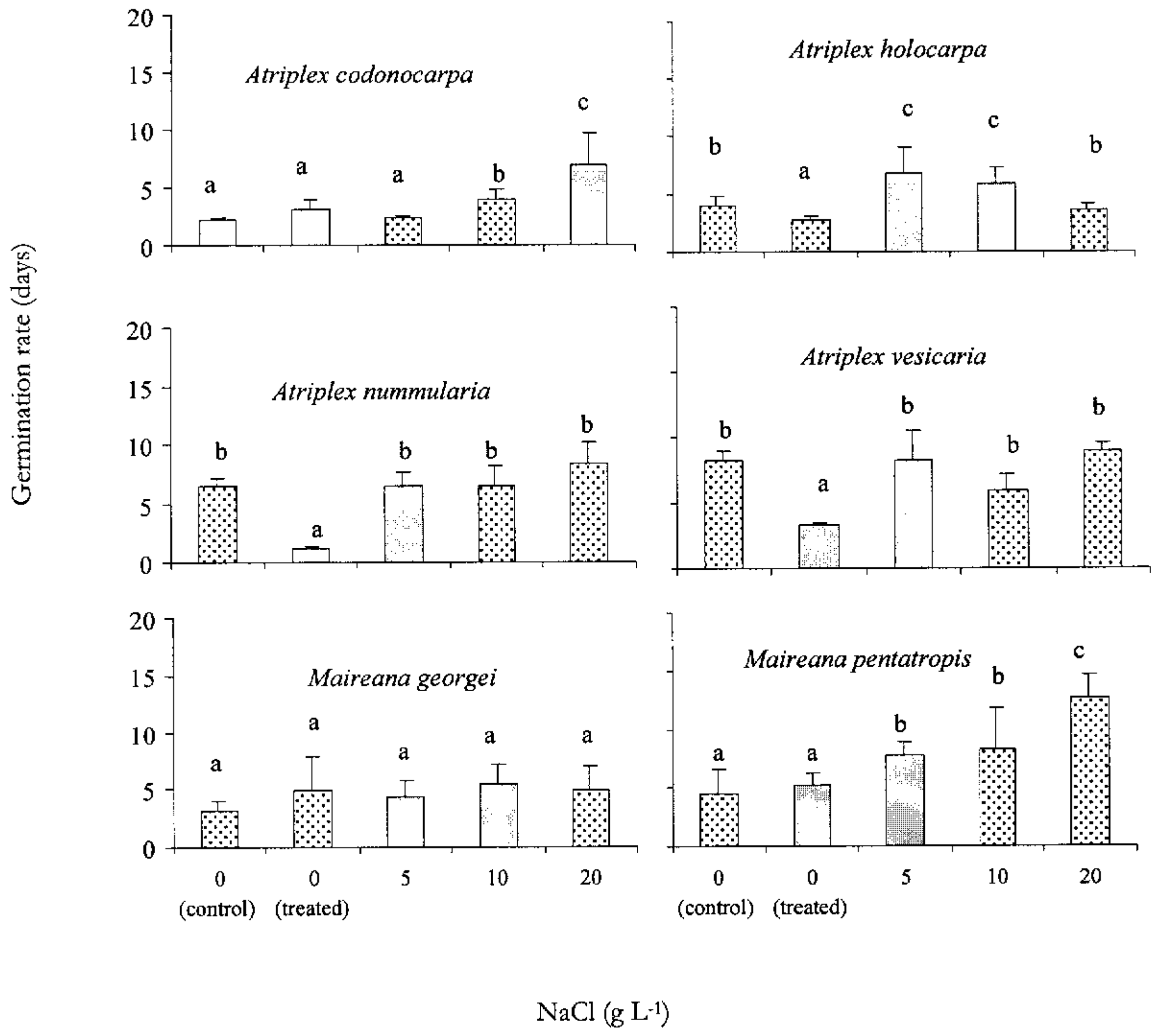

Figure 2.4: Germination rate (± SE) of seed of chenopodiaceous species exposed to different concentrations of NaCl. The 0 g L^{-1} (treated) data shows the germination rate in 0 g L^{-1} NaCl after 28 d at 40 g L^{-1} NaCl without germination. Different letters indicate significant differences (*P* < 0.05) by Tukey's test.

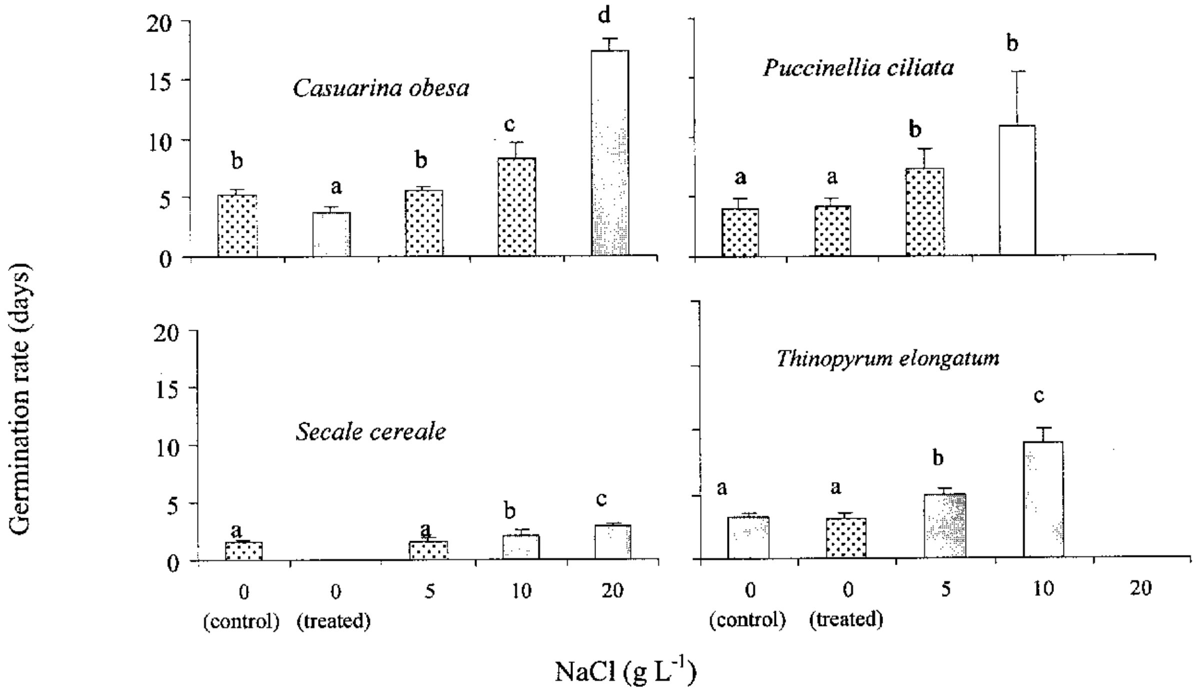

Figure 2.5: Germination rate (± SE) of seeds of grass species and *Casuarina obesa* exposed to different concentrations of NaCl. The 0 g L^{-1} (treated) data shows the germination rate in 0 g L^{-1} NaCl after 28 d at 40 g L^{-1} NaCl without germination. Different letters indicate significant differences ($P < 0.05$) by Tukey's test. No germination rate was calculated for *Thinopyrum elongatum* (20 g L^{-1} NaCl), *Puccinellia ciliata* (20 g L^{-1} NaCl) and *Secale cereale* (0 g L^{-1} NaCl treated) due to insufficient germination.

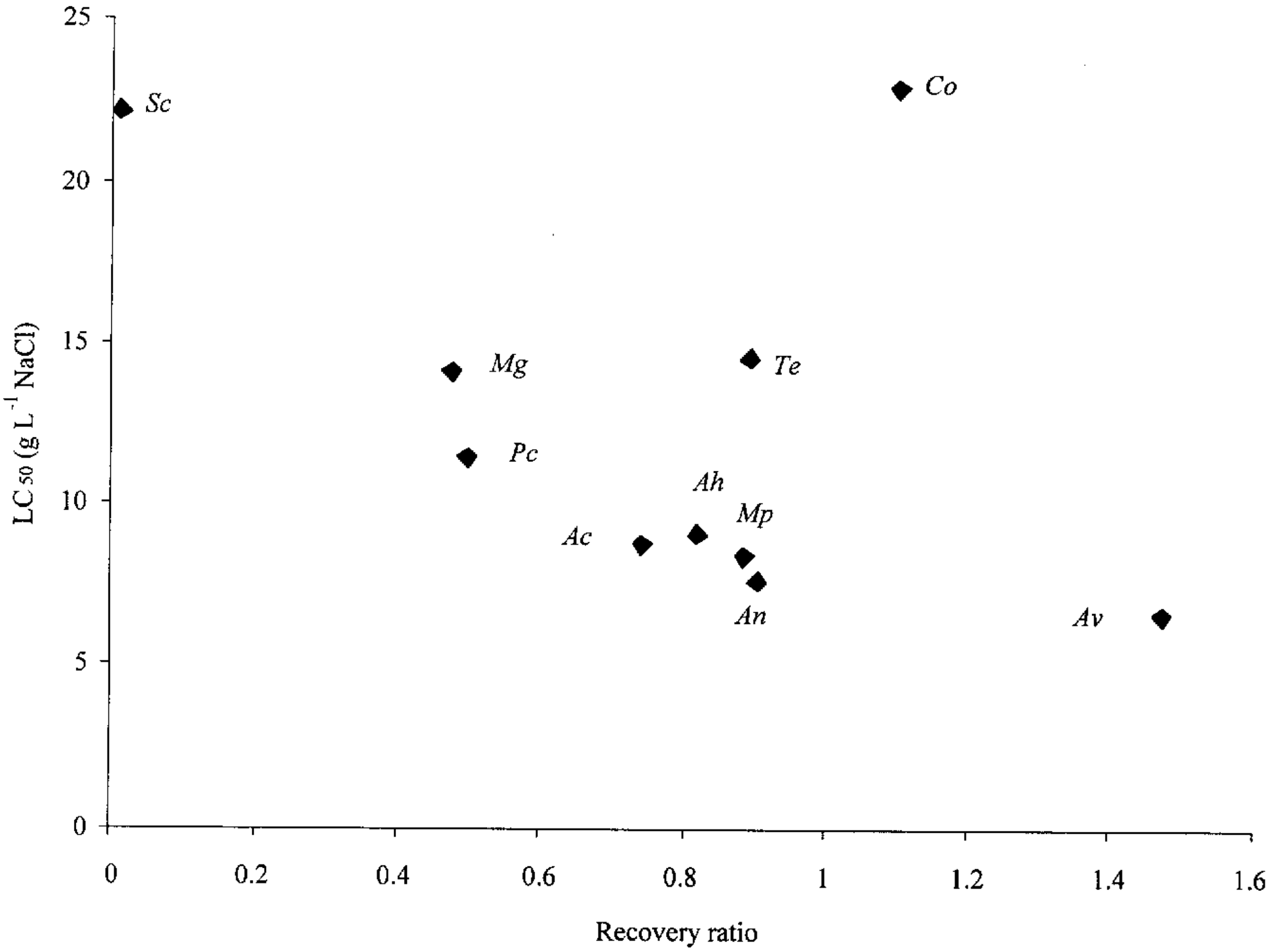

Figure 2.6: Scatterplot of species responses to NaCl at germination. LC_{50} (g L^{-1} NaCl) is the level at which germination is reduced by 50% and the recovery ratio is the germination obtained, relative to a control, after prior exposure to a concentration of 40 g L^{-1} NaCl for 28 days. Species are *Atriplex codonocarpa* (*Ac*), *A. holocarpa* (*Ah*), *A. nummularia* (*An*), *A. vesicaria* (*Av*), *Casuarina obesa* (*Co*), *Maireana georgei* (*Mg*), *M. pentatropis* (*Mp*), *Puccinellia ciliata* (*Pc*), *Secale cereale* (*Sc*) and *Thinopyrum elongatum* (*Te*).

2.4 Discussion

Ungar (1995) stated that the seeds of halophytes have evolved three strategies for survival in saline environments. These strategies are: an ability to germinate at moderate to high salinities, induction of dormancy under more highly saline conditions, and, recovery of germination when salinity levels decrease. The physiology behind these strategies is not well understood and it is not known if salt tolerance at the germination stage is under hormonal control or if compatible osmotica protect enzymes from the low water potentials that occur under saline conditions (Ungar, 1995).

The strategies described by Ungar (1995) are important characteristics of seeds of species considered for use in revegetation of salt-affected land. In the experiments described here, seeds of all species were able to germinate in NaCl solutions up to 20 g L^{-1} and all, except *Secale cereale*, exhibited dormancy under higher salinities and an ability to recover when salinity decreased. The results were in broad agreement with those of other researchers. Among the grasses, Marcar (1987) recorded a comparable result for *Elytrigia pontica*, a tall wheatgrass variant, which showed no reduction in germination up to 10.9 g L^{-1} NaCl while Myers and Couper (1989) showed *P. ciliata* to be reduced to 50% of its optimal germination at 6 g L^{-1} NaCl. A similar result was obtained for *P. nuttaliana* which germinated in a medium with a water potential equivalent to 10.6 g L^{-1} NaCl but showed a sharp decrease at 8 g L^{-1} (Macke and Ungar, 1971). Marcar (1987), however, found that reduction in germination of *P. ciliata* did not occur until 16.4 g L^{-1}, suggesting other factors, such as seed age and storage conditions, may have an effect on salt tolerance at germination. Within the chenopods, the effect of increasing NaCl in reducing germination was most marked in the perennial saltbushes, *A. nummularia* and *A. vesicaria,* with salt-induced dormancy occurring at lower salinities than the annual or short-lived chenopods. The overall germination results compare with those obtained by Fletcher *et al.* (1989) who recorded a 50% reduction in germination between 10 and 20 g L^{-1} for *A. bunburyana*, *A. vesicaria*, *A. nummularia* and *A*. sp. 'Pintharuka'. Stewart and Osborne (1993) recorded a decrease in germination of *A. nummularia* and *A. vesicaria* at 27 g L^{-1} NaCl. In *A. semibaccata*, Rogers (1997) noted germination of naked seeds was unaffected up to 15 g L^{-1} NaCl with some germination still obtained at 25 g L^{-1} NaCl. Germination was substantially inhibited in 20 g L^{-1} NaCl in *A. patula* (Ungar, 1996) and *A. griffithii* var. *stocksii* (Khan and Rizvi, 1994). In the bluebushes, similar results were obtained for five species of *Maireana* and the 50% reduction occurred at concentrations in excess of 25 g L^{-1} NaCl for another chenopod, *Eriochiton sclerolaenoides* (Osborne *et al.*, 1993).

Recovery from exposure to 40 g L^{-1} NaCl was strong in *T. elongatum* but less so in *P. ciliata.* A similar observation was made by Marcar (1987). In *S. cereale*, recovery did not occur at all. This suggests that *S. cereale* may be regarded as a salt-tolerant glycophyte rather than a halophyte, as the ability to recover after exposure to high salinity is a criterion attributed to halophytes (Ungar, 1995). This factor gave *S. cereale* the lowest tolerance index (TI) of all species tested. All of the chenopods and *Casuarina obesa* showed the ability to recover after exposure to 40 g L^{-1} NaCl and germination in *C. obesa*, *A. holocarpa*, and *A. nummularia* was not significantly affected by prior exposure to this concentration. An exception was that of the seeds of *A. vesicaria* which showed an increase in germination. This response suggests that germination was stimulated by exposure to high NaCl, a phenomenon recorded for some other halophytes (Keiffer and Ungar, 1997).

While overall germination was reduced by increasing NaCl concentration in all species, the rate at which seeds germinated was unaffected by NaCl in *A. nummularia*, *A. vesicaria* and *M. georgei*. This suggests that there may be marked variability in the point at which dormancy is induced by NaCl concentration between the seeds of each of these species. The germination rate in *A. holocarpa*, *A. nummularia*, *A vesicaria* and *C. obesa* was increased by prior exposure to 40 g L^{-1} NaCl, suggesting that at least some part of the germination process had occurred at the high NaCl concentrations. A possible explanation for this could be related to the dissolution of salts contained within the seeds. High external salt concentrations may act to increase the water content of the seed, as low salt concentrations would also do. Both high and low salt concentrations would assist with the dissolution of solid salts within the seed but high salt concentrations would prevent germination from being initiated. When seeds are transferred from high salt solutions to low salt solutions, germination can occur more rapidly because the salts contained within the seed are already in solution. This aspect of germination is worthy of further investigation and the phenomenon could be used to obtain more rapid germination in many species, both halophytic and glycophytic (Heydecker *et al.*, 1973).

The application of a TI helped to group the individual species responses to NaCl at germination. The TI highlighted the high salt tolerance of *C. obesa* and *T. elongatum* relative to the other species, and the high similarity in responses from most of the chenopods. The TI could be adopted for comparison of results obtained by other researchers. While the LC_{50} is readily calculated, irrespective of the concentrations of NaCl used, the exposure of seeds to differing concentrations and durations of high NaCl levels could affect the determination of the recovery ratio. However, the reduction in germination of *Atriplex* spp. after exposure to high salinity may not relate directly to the level of salinity, as Keiffer and Ungar (1997) found germination in *A. prostrata* to be reduced over time, regardless of the level of salinity to which the seeds were exposed. The TI alone, however, is unlikely to provide an indication of the responses likely to occur in the field. For example, *T. elongatum*, while more salt-tolerant at germination than native chenopods, is much less successful under field conditions in the Eastern Goldfields (G. Barrett, pers. obs.; Chapter 5). Clearly, other factors, such as soil moisture and nutrient status, play an important role.

There are a number of implications for the likely germination responses under field conditions of the seeds studied here. These responses are likely to favour the early establishment of the colonising annual and short-lived perennial species, especially in more saline situations, while allowing the subsequent germination of the seeds of perennial species if and when salinity is reduced. In the chenopod, *Kochia scoparia*, germination and emergence decreased by over 3% for each 1 dS m^{-1} increase over 12 dS m^{-1} in soil electrical conductivity, but relatively short term reductions in salinity stimulated germination considerably (Steppuhn and Wall, 1993). There appears, however, to be limited research of germination levels under field conditions in relation to disturbed land. Some inferences may be drawn from studies of salt marshes where recruitment of plants is limited by high substrate salinities in bare patches between plants. In these environments, plant recruitment is dependent on either clonal growth processes or unpredictable 'windows' of low salinity in the bare patches (Shumway and Bertness, 1992). Species exploiting these 'windows' are more likely to be annuals as they tend to have a more consistent seed bank than perennial species (Ungar and Woodell, 1993). In chenopod shrublands, regeneration of *Atriplex vesicaria* may only occur every 3-5 years depending on rainfall (Williams, 1979). When salinity is sufficiently low for germination of all species to occur at more or less the same time, germination and early growth of long-lived perennials may be slower. As moisture levels in surface soils decrease, annuals set seeds and die while perennial species can continue growth using deeper reserves of moisture. In highly salt-affected areas undergoing revegetation, micro-scale differences in salinity assume importance. More research is required on germination and early growth under field conditions.

In conclusion, in terms of germination, salinity should not be a limiting factor up to an equivalent of 10 g L^{-1} NaCl and, for some species, germination still occurs up to 20 g L^{-1} NaCl. Different species show different patterns of salt-induced dormancy and these are likely to be important in how the vegetation of rehabilitated areas establishes.

3.0 SALT TOLERANCE DURING GERMINATION AND EARLY GROWTH OF TWO SUCCULENT CHENOPODS (*HALOSARCIA* SPP.) FROM WESTERN AUSTRALIA

3.1 Introduction

In the Eastern Goldfields of Western Australia, revegetation is conducted following gold and nickel mining. Mining can expose saline soil and waste rock horizons and hypersaline groundwater is often used for mineral processing and other uses. As a result, land requiring revegetation can be moderately to severely saline and landforms may differ considerably to those that existed previously. Salt-tolerant plants from the Chenopodiaceae (mainly *Atriplex* and *Maireana* spp.) are frequently used for revegetating these areas through direct seeding (Fletcher *et al.,* 1989). They are also used for rehabilitation in agricultural areas of Western Australia where, in addition to their tolerance to salt-affected soils, they are useful as fodder plants. Their success in this environment has led to their use on degraded land in other arid parts of the world (Malcolm, 1989; Le Houèrou, 1992). Other genera from the Chenopodiaceae, while also salt-tolerant, are not as widely used for revegetation after mining because their seeds are not as readily collected, they are not suitable as forage plants (therefore limiting subsequent land uses) or they are perceived to have narrow environmental tolerances (Barrett, 1994).

One such genus is *Halosarcia* in the tribe Salicornieae. With one exception, the 23 *Halosarcia* spp. are endemic to Australia (Wilson, 1980). They, and other members of the Salicornieae, are perennial shrubs termed "samphires", with fleshy, articled stems and are usually associated with salt-affected areas where waterlogging can occur. While a number of taxa are widespread in Western Australia, they have been used sparingly in land rehabilitation programs, except in some areas of the Western Australian wheatbelt where they are useful for vegetating saline areas prone to waterlogging (Malcolm and Cooper, 1988). They often occur naturally around inland salt lakes with some taxa also having a coastal distribution (Wilson, 1980). No *Halosarcia* species was included in an extensive collection from Australia and overseas to assist in establishing forage in salt-affected areas of south-western Australia (Malcolm *et al.,* 1984) although Malcolm and Swaan (1989) recorded *Halosarcia* spp. successfully invading growth trials conducted on salt-affected agricultural areas. *H. pergranulata* subsp. *pergranulata* has been used with some success in revegetating salt-affected mined areas (Short and Colmer, 1999) and fly ash lagoons (Jusaitis and Pillman, 1997). Other related taxa have been used for treatment of saline effluent, e.g. *Suaeda esteroa* (Brown *et al*., 1999), or as a potential commercial oilseed crop e.g. *Salicornia bigelovii* (Glenn *et al*., 1991).

While there have been numerous studies of germination in chenopods, including *Atriplex* (Young *et al.,* 1980; Fletcher *et al.,* 1989; Malcolm *et al.,* 1982; Mikheil *et al.,* 1992) and *Maireana* (Osborne *et al*., 1993), there have been few studies of germination in *Halosarcia.* Malcolm (1964) looked at germination in two varieties of *Arthrocnemum halocnemoides* [synonymous with *H. pergranulata* and *H. pterygosperma* following the revisions of Wilson (1980)]. There are also some germination studies of closely related genera (e.g. *Salicornia*), usually species that occur in salt marshes (eg. Philipupillai and Ungar, 1984). Similarly, there have been numerous studies into the early growth of *Atriplex* spp. under saline conditions (eg. Greenway and Osmond, 1970; Galloway and Davidson, 1993; Ungar, 1996; Katembe *et al*., 1998), and others that have examined salt tolerance in other members of the Salicornieae eg. *Sarcocornia* and *Salicornia* spp. (eg. Naidoo and Rughunanan, 1990; Ayala and O'Leary, 1995; Keiffer *et al*., 1994). There has, however, been little research into salt tolerance during early growth in *Halosarcia* (Short and Colmer, 1999).

The aim of this study was to assess the salt tolerance at germination and during early growth in two species of *Halosarcia* and to relate it to the salt tolerance of other halophytes, the environments in which they occur and their potential for use in revegetation of disturbed saline land.

3.2 Materials and Methods

3.2.1 Species selection and seed collection

Two species, *Halosarcia halocnemoides* subsp. *halocnemoides* P.G. Wilson and *H. pruinosa* (Paulsen) P.G.Wilson, were selected for testing of seed germination responses. They were selected following preliminary testing (Table 3.1) I conducted of the seed germination of a number of *Halosarcia* spp. that occur naturally in the Eastern Goldfields region of Western Australia. While germination in *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa* was readily achieved, germination in the other taxa (*H. pergranulata* subsp. *pergranulata*, *H. pergranulata* subsp. *elongata*, *H. peltata*, *H. indica* subsp. *bidens* and *H. doleiformis*) was inhibited, apparently due to physical dormancy mechanisms (see Chapter 4) or some other impediment to germination.

Both taxa occur naturally across much of Western Australia, South Australia and Victoria. *H. halocnemoides* subsp. *halocnemoides* is a much branched subshrub growing to 0.2 m tall. Some variants are the only plant species present at the innermost zone of vegetation of inland salt lakes (Wilson, 1980). *H. pruinosa* is a larger shrub growing to 1 m (Wilson, 1980). Seeds were collected from plants that had colonised saline and alkaline silt loam disturbed soils over a shallow (< 1.5 m), saline water table at Lakewood, Western Australia (30°48'S, 121°32'E) in December 1997. Plants of *H. halocnemoides* subsp. *halocnemoides* were colonizing an area with a veneer of saline gold tailings eroded from nearby mine tailings dump. For each species, fruiting pseudospikes (Wilson, 1980) were collected and dried. Seeds were obtained by gently crushing the dried pseudospikes by hand, and separating the seeds from the other plant material by sieving. Mean seed weight for each taxon was obtained by weighing three replicates of 50 seeds.

Preliminary germination testing indicated that no pretreatment of the seeds of either species was necessary to obtain satisfactory germination percentages. All seeds,

Table 3.1: Results of preliminary testing of seed of *Halosarcia* spp. All seed tested was collected < 2 mo prior to testing except *H. pergranulata* subsp. *pergranulata* which was collected 1 y previously. Seeds were collected from ~10 individual plants in each case. Seed weights are mean ± SD of five batches of 50 seed each. Germination tests conducted as described in 3.2.2 but without replication. Taxa with woody (W) pericarps were tested with and without pericarp while taxa with membraneous (M) pericarps were tested only with the pericarp removed.

Taxon	Collection location	Seed weights (µg)	Pericarp type (M or W)	Germination (%)	
				Pericarp removed	Pericarp not removed
Halosarcia doleiformis P.G. Wilson	Hannans Lake, Western Australia (30°48'S, 121°30'E)	229 ± 4	M	10.3	-
H. halocnemoides subsp. *halocnemoides* P.G. Wilson	Lakewood, Western Australia (30°48'S, 121°32'E)	99 ± 13	M	73.3	-
H. indica subsp. *bidens* (Nees) P.G. Wilson	Lake Arrow, Western Australia (30°28'S, 121°25'E)	526 ± 19[1]	W	3.3[2]	46.7
H. peltata P.G. Wilson	Hannans Lake, Western Australia (30°48'S, 121°30'E)	167 ± 21	W	16.0	6.7
H. pergranulata subsp. *elongata* P.G. Wilson	Lake Arrow, Western Australia (30°28'S, 121°25'E)	146 ± 2	M	0[3]	-
H. pergranulata subsp. *pergranulata* P.G. Wilson	Lakewood, Western Australia (30°48'S, 121°32'E)	258 ± 8	M	23.3	-
H. pruinosa (Paulsen) P.G.Wilson	Lakewood, Western Australia (30°48'S, 121°32'E)	109 ± 9	M	92.9	-

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[1] Seed plus woody pericarp.
[2] Improved germination (~50%) achieved after priming seed in 40 g L^{-1} NaCl solution.
[3] Most seeds appeared 'unfilled'.

however, were routinely surface sterilized using 1% sodium hypochlorite followed by rinsing in deionised water.

3.2.2 Seed germination testing

The germination testing was conducted during early 1998. Seeds were tested for germinability in 90 mm petri dishes with two filter papers (Whatman No.1) moistened with 5 mL of a NaCl solution. The solutions used were made up using deionised water and contained 0, 5, 10, 20 and 40 g L^{-1} NaCl. The NaCl levels were selected as representative of the range of soil conditions likely to be encountered and within the range in which at least some germination was possible and are the same as those used in Chapter 2. Five replicates of 30-35 seeds each were used for each treatment. The petri dishes were placed in polyethylene bags to minimise evaporation losses and then transferred to a germination cabinet (Lindner & May Pty Ltd, Windsor, Brisbane) in a randomised block design. The germination cabinet was set at a temperature of 35/5°C (day/night) with a 12 h photoperiod. This temperature regime was selected based on the most successful of a number of regimes used by Malcolm (1964) to obtain germination in the seeds of two closely related taxa. The tests were run for 28 days. Each dish was checked daily and any germinants were recorded and removed. Germination was considered to have occurred when the radicle reached a length of 1 mm. Previcur™ (1% v/v) was used to control any fungal growth.

After 28 days, ungerminated seeds in the 20 and 40 g L^{-1} NaCl treatments were removed for an assessment of their ability to recover. The seeds were placed in a beaker of deionised water and gently stirred for 10 s to remove any residual surface salts. They were then transferred to a new petri dish set up as above but containing deionised water only. The seeds were allowed to germinate under the same conditions as previously for a further 14 days.

3.2.3 Seedling growth experimental conditions

Seedlings of *H. pruinosa* were obtained from seeds germinated in a moist sand/peat mix

(2:1). Seedlings were transferred to coarse river sand in 140 mm (0.5 L) pots when 10 mm tall. As viable seeds of *H. halocnemoides* subsp. *halocnemoides* were not available at the time of the seedling growth trial, seedlings about 50 mm tall were taken from the field location at Lakewood (see section 3.1.2) and placed in 500 mL pots as above. All plants were watered regularly with a nutrient solution suitable for Western Australian salt lake species (T.D. Colmer and J. English, pers. comm.). The constituents of the nutrient solution (values in mmol L^{-1}) were: Na^+, 10; K^+, 10; NH_4^+, 0.2; Ca^{2+}, 10; Mg^{2+}, 1.0; NO_3^-, 1.4; Cl^-, 18.6; SO_4^{2-}, 10; HPO_4^{2-}, 0.5; Fe-EDTA, 0.05; $H_2BO_3^-$, 0.00625; Mn^{2+}, 0.0005; Zn^{2+}, 0.0005; Cu^{2+}, 0.000125; and Mo^{2+}, 0.000125.

After a 30 d recovery period for the *H. halocnemoides* subsp. *halocnemoides* seedlings, the growth trial commenced in February 2000. Thirty healthy and similarly-sized plants from each taxa were selected from those available. Plants were grown in a naturally lit glasshouse. Mean maximum and minimum glasshouse temperatures during the course of the growth trial were 25.9 ± 1.8 °C and 14.5 ± 4.7 °C respectively with automatic cooling used to maintain maximum temperatures at 27°C or below. Six plants were watered with either 0, 5, 10, 20 or 40 g L^{-1} NaCl solutions with nutrients added as above. The added nutrients gave the control solution based on deionised water an effective NaCl concentration of 0.5 g L^{-1}. From the beginning of the growth trial, NaCl concentrations were gradually increased by 5 g L^{-1} NaCl at 2 d intervals to reach the maximum level of 40 g L^{-1} after 16 d. Measures of the salinity of the amended nutrient solutions (Table 3.2) showed them to range from 2.88 to 61.7 dS m^{-1} (electrical conductivity) and –0.1 to –2.22 MPa (osmotic potential).

Plants were subirrigated in trays 50 mm in height (six plants per tray) and flushed with 150 mL of nutrient solution every 2 d. Nutrient solutions were completely replaced each week. To reduce evaporation and algal growth, the soil surface in each pot was covered with 2 mm polyethylene pellets, to a depth of 5 mm, and a polyethylene panel was used to cover the exposed water surface around the pots in each tray. The position of each tray within the glasshouse was altered weekly on a grid pattern to reduce the possible effects of variable environmental conditions.

Table 3.2: Electrical conductivity (EC) and osmotic potential (OP) of nutrient solutions. EC was determined by direct measurement. OP was calculated from EC using a factor given by Taylor (1991).

NaCl (g L^{-1})	EC (dS m^{-1})	OP (MPa)
0.5	2.88	-0.10
5.5	11.1	-0.40
10.5	19.1	-0.69
20.5	34.9	-1.26
40.5	61.7	-2.22

3.2.4 Seedling harvest procedure

Plants were harvested from 0800-1000 on day 73 (*H. pruinosa*) and day 80 (*H. halocnemoides* subsp. *halocnemoides*). Plants in replicate one of each treatment were harvested first, then those of replicate two and so on, so as to minimize any effects on time of day for the treatment comparisons. Shoot tips (last three articles and internodes) were removed from each plant, weighed, sealed in vials and placed on ice prior to deep freezing at -80°C for determination of osmotic potential later. Plants were then carefully removed from each pot and the roots rinsed in deionised water and gently dried on paper towels. Shoots and roots were separated and, after fresh weights were obtained, all plant material was dried for 48 h in a forced-draft oven at 70°C. Dry weights were then obtained. Ash content of dried shoots was subsequently determined by placing the dried plant material in a furnace for 2 h at 560°C.

3.2.5 Growth measurements and succulence

Shoot length was measured on day 1 and when the plants were harvested. Relative growth rates (RGR) of shoots (ash-free dry weight basis) were determined by a comparison with an initial harvest of six plants using the following formula for RGR (Hunt, 1982):

$RGR = (1 / W) \times (dW / dT)$ where

W = weight at commencement of growth trial, and

T = time (length) of growth trial.

Shoot:root ratios were calculated on a dry weight basis. Succulence was determined by the ratio of shoot wet weight to dry weight.

3.2.6 Measurement of sap osmotic potential

The osmotic potential of the freeze/thawed tissue samples were subsequently measured using a ONE-TEN™ freezing point depression osmometer (Fiske Associates, Massachusetts, USA). Shoot tips were thawed by placing their sealed vials in a water bath at 50°C for 60 s after which the tips were crushed in a stainless steel press to extrude the sap. Ten μL of the extruded sap was diluted with deionised water at a ratio of 1:1 (0.5-10 g L^{-1} NaCl treatment) or 1:2 (20-40 g L^{-1} NaCl treatment) and immediately analysed. The osmometer was calibrated with 50 and 850 mmol kg^{-1} osmolarity standards. Osmotic potential was converted from mOsm kg^{-1} H_2O to MPa using the formula given by Money (1989).

3.2.7 Data analyses

Analysis of seed germination data and the calculation of a tolerance index (TI) were conducted as described in Chapter 2. All other analyses were by one-way analysis of variance using Analyse-It v.1.5 (Analyse-It Software Ltd, Leeds, UK). All analyses used $P < 0.05$ to define statistical significance. Where significant differences between treatments occurred, means were separated using Tukey's multiple range test. As *H. pruinosa* seedlings were grown from seeds and *H. halocnemoides* subsp. *halocnemoides* transplants were obtained from the field, interspecific comparisons of early growth were not made. For ease of comparison, where the results obtained by other researchers are discussed, they are converted to the units used herein (g L^{-1}, MPa), if required (see section 2.2.3).

3.3 Results

3.3.1 Effect of NaCl on germination

Halosarcia pruinosa seeds weighed 109 ± 9 μg (9,174 seeds g^{-1}) and *H. halocnemoides* subsp. *halocnemoides* seeds weighed 99 ± 13 μg (10,101 seeds g^{-1}). Germination responses to different concentrations of NaCl solution for each species are given in Fig. 3.1. High germination occurred for controls in both *H. halocnemoides* subsp. *halocnemoides* (68.0%) and *H. pruinosa* (93.3%) but was significantly reduced by the 20 and 5 g L^{-1} NaCl solutions respectively. No germination occurred in either taxon at 40 g L^{-1} NaCl. Increasing NaCl concentration to 20 g L^{-1} caused a greater relative decrease in germination in *H. pruinosa* than in *H. halocnemoides* subsp. *halocnemoides*. Exposure to 20 or 40 g L^{-1} NaCl solutions for 28 d did not significantly affect the germination subsequently attained in deionised water for either taxon (Fig. 3.2).

NaCl concentration did not affect the rate of germination in *H. halocnemoides* subsp. *halocnemoides* at or below 10 g L^{-1} NaCl. Seeds placed in deionised water after 28 days at 20 or 40 g L^{-1} NaCl solutions subsequently germinated at the same rate as the controls (Fig. 3.3). In contrast, the rate of germination in *H. pruinosa* decreased with increasing NaCl concentration at all concentrations above the control. Prior exposure to 20 or 40 g L^{-1} NaCl solutions significantly increased the subsequent germination rate of *H. pruinosa* compared with the control although seeds exposed to 40 g L^{-1} NaCl were significantly slower to germinate than those exposed to 20 g L^{-1} NaCl.

The tolerance index (TI) for each taxon is shown in Table 3.3. The values indicate that *H. halocnemoides* subsp. *halocnemoides* (17.4) is more salt-tolerant than *H. pruinosa* (10.7), mainly due to a greater reduction by *H. pruinosa* for germination occurring at higher NaCl concentrations and an apparent stimulation of germination in *H.*

halocnemoides subsp. *halocnemoides* by exposure to high NaCl concentrations.

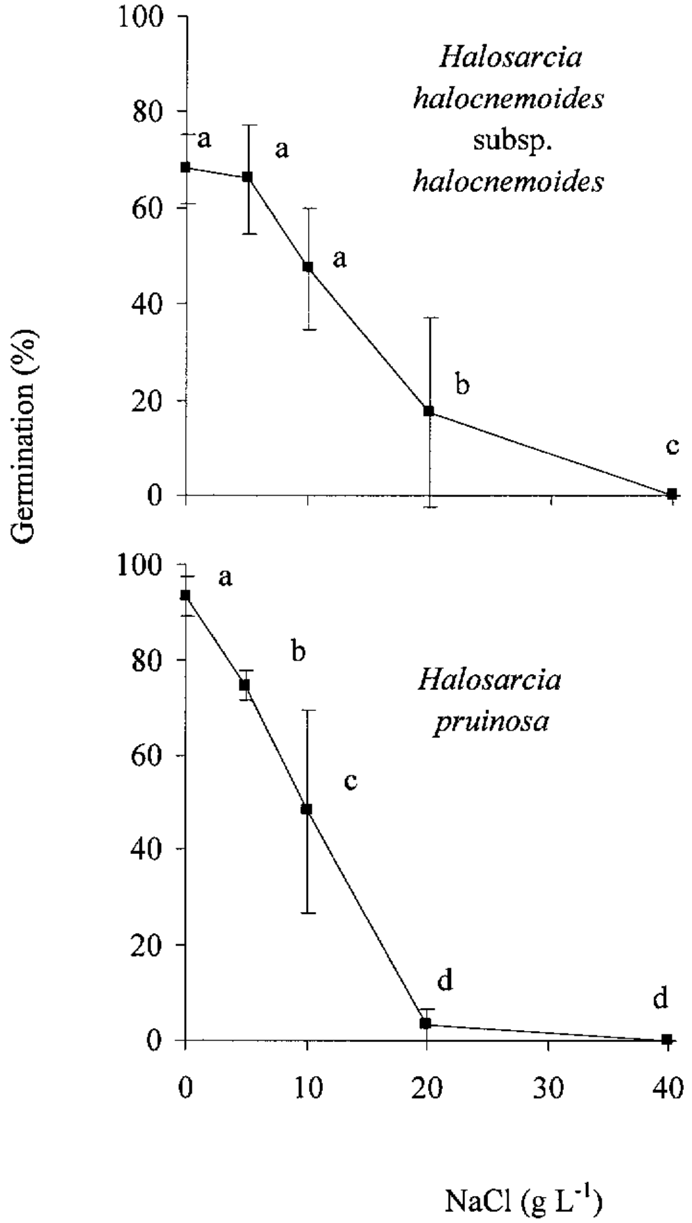


Figure 3.1: Mean seed germination (± SE) in solutions of increasing NaCl concentration for *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa*. Different letters indicate statistically significant differences ($P < 0.05$).

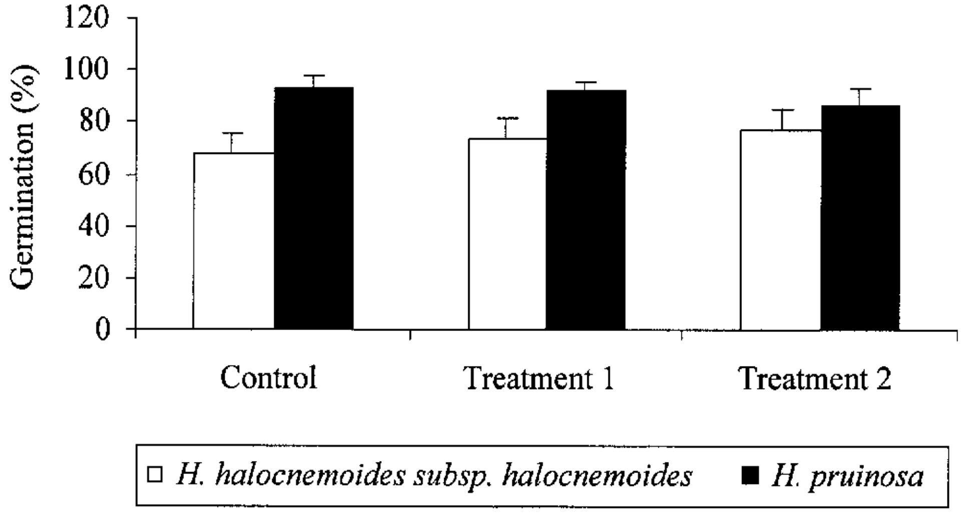


Figure 3.2: Mean seed germination (±SE) in *Halocarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa* in deionised water after 28 d at 20 g L^{-1} NaCl (treatment 1) or 40 g L^{-1} NaCl (treatment 2) compared with a control. There was no significant difference within taxa.

Table 3.3: Tolerance index (TI) of *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa* assessed for NaCl tolerance at seed germination. TI is the product of LC_{50} value and the recovery ratio.

Species	LC_{50} for germination (g L^{-1} NaCl)	Recovery ratio (RR)	TI
Halosarcia halocnemoides subsp. *halocnemoides*	15.4	1.13	17.4
H. pruinosa	11.6	0.92	10.7

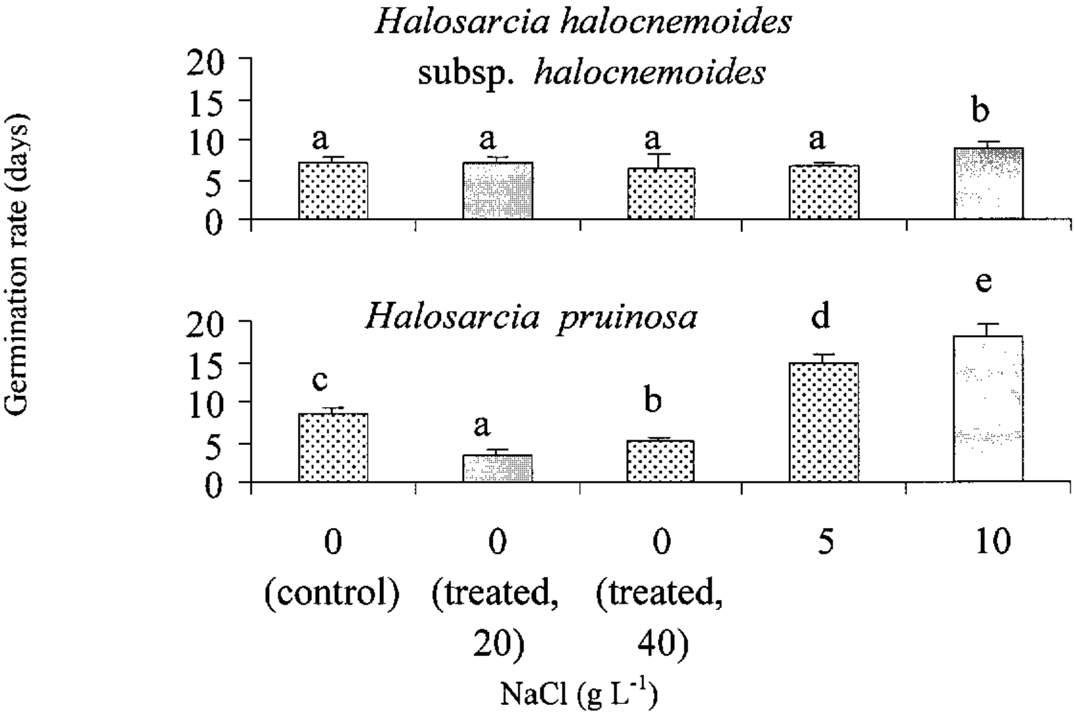


Figure 3.3: Germination rate (mean ± SE days to germination) of *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa* exposed to different concentrations of NaCl. The 0 g L^{-1} (treated) data shows the germination rate in deionised water after 28 d at 20 or 40 g L^{-1} NaCl. No germination rate was calculated for exposure to 20 or 40 g L^{-1} NaCl as there was insufficient germination. Different letters indicate significant differences ($P < 0.05$).

3.3.2 Effect of NaCl on early growth

All plants survived and grew in NaCl concentrations up to 40.5 g L^{-1} although two plants in the 20.5 g L^{-1} NaCl treatment for *H. pruinosa* suffered insect damage during the course of the experiment and were excluded from any analyses. Increasing NaCl concentration up to 40.5 g L^{-1} did not significantly affect the RGR values obtained for either taxon (Table 3.4). The RGR for *H. halocnemoides* subsp. *halocnemoides* ranged from 61.7 to 100.3 mg g^{-1} d^{-1} while that for *H. pruinosa* ranged from 162.3 to 191.8 mg g^{-1} d^{-1}. Overall shoot growth in both taxa was unaffected by NaCl although shoot elongation in *H. pruinosa* (1.05-1.55 mm d^{-1}) was much greater than in *H. halocnemoides* subsp. *halocnemoides* (0.17-0.26 mm d^{-1}). Shoot succulence in *H. halocnemoides* subsp. *halocnemoides*, as determined by shoot wet weight/dry weight ratios, was lowest at the highest concentration of NaCl (Table 3.5). There was no significant difference recorded in the succulence of *H. pruinosa* shoots. Shoot fresh weights (Fig. 3.4) were reduced by low (0.5 g L^{-1}) and high (40.5 g L^{-1}) NaCl concentrations in *H. halocnemoides* subsp. *halocnemoides* but were unaffected by NaCl concentration in *H. pruinosa*. Root fresh weights, however, were reduced by 40.5 g L^{-1} NaCl concentrations in both taxa. Shoot dry weights (Fig. 3.5) in *H. halocnemoides* subsp. *halocnemoides* were significantly greater at 20.5 g L^{-1} NaCl but were unaffected by NaCl concentration in *H. pruinosa*. As for fresh weights, however, root dry weights were lowest at the highest concentrations, and shoot/root ratios for both taxa were significantly lower at 40.5 g L^{-1} NaCl (Fig. 3.6).

Crystalline salt was observed on the articles of *H. pruinosa* plants in the two highest NaCl treatments during the last three weeks of the experiment. This salt was removed during the harvesting process and did not contribute towards fresh weight, dry weight or ash measurements. Shoot ash content in both taxa increased with increasing NaCl concentration, ranging from 31.8% of dry weights in *H. halocnemoides* subsp. *halocnemoides* and 31.7% in *H. pruinosa* to 43.1% and 47.3% respectively (Fig. 3.7), although organic matter production was not significantly different in either taxon. These data, and those for osmotic potential of sap (π_{sap}) in shoot tips (Fig. 3.8), were both indicative of higher concentrations of ions in plants exposed to higher external NaCl concentrations. In *H. halocnemoides* subsp. *halocnemoides,* π_{sap} ranged from –3.7 MPa down to –6.6 MPa with increasing NaCl concentration. In *H. pruinosa*, the comparable values were –2.2 and –4.8 MPa. These values were at least 2 MPa less than the culture solutions.

Table 3.4: Mean relative growth rates (RGR) (mg g^{-1} d^{-1}) (± SE) for shoots (ash-free dry weight basis) of *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa* grown in sand culture.

	RGR (mg g^{-1} d^{-1})	
NaCl ($g L^{-1}$)	*Halosarcia halocnemoides* subsp. *halocnemoides*	*H. pruinosa*
0.5	66.2 ± 12.7	191.8 ± 129.8
5.5	63.7 ± 18.9	174.1 ± 73.2
10.5	94.3 ± 31.3	166.8 ± 45.7
20.5	100.3 ± 36.9	165.9 ± 67.9
40.5	61.7 ± 29.4	162.3 ± 87.1

Table 3.5: Mean shoot succulence (± SE), as determined by shoot wet weight/dry weight ratios, for *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa*. Significantly different means indicated by letters; no letters means no difference.

NaCl ($g L^{-1}$)	Shoot wet weight/dry weight	
	Halosarcia halocnemoides subsp. *halocnemoides*	*H. pruinosa*
0.5	8.27 ± 1.22 ab	12.86 ± 2.10
5.5	9.79 ± 1.48 b	13.00 ± 2.25
10.5	9.36 ± 1.17 ab	12.10 ± 2.30
20.5	9.74 ± 1.11 b	11.66 ± 1.03
40.5	7.63 ± 0.52 a	10.34 ± 0.49

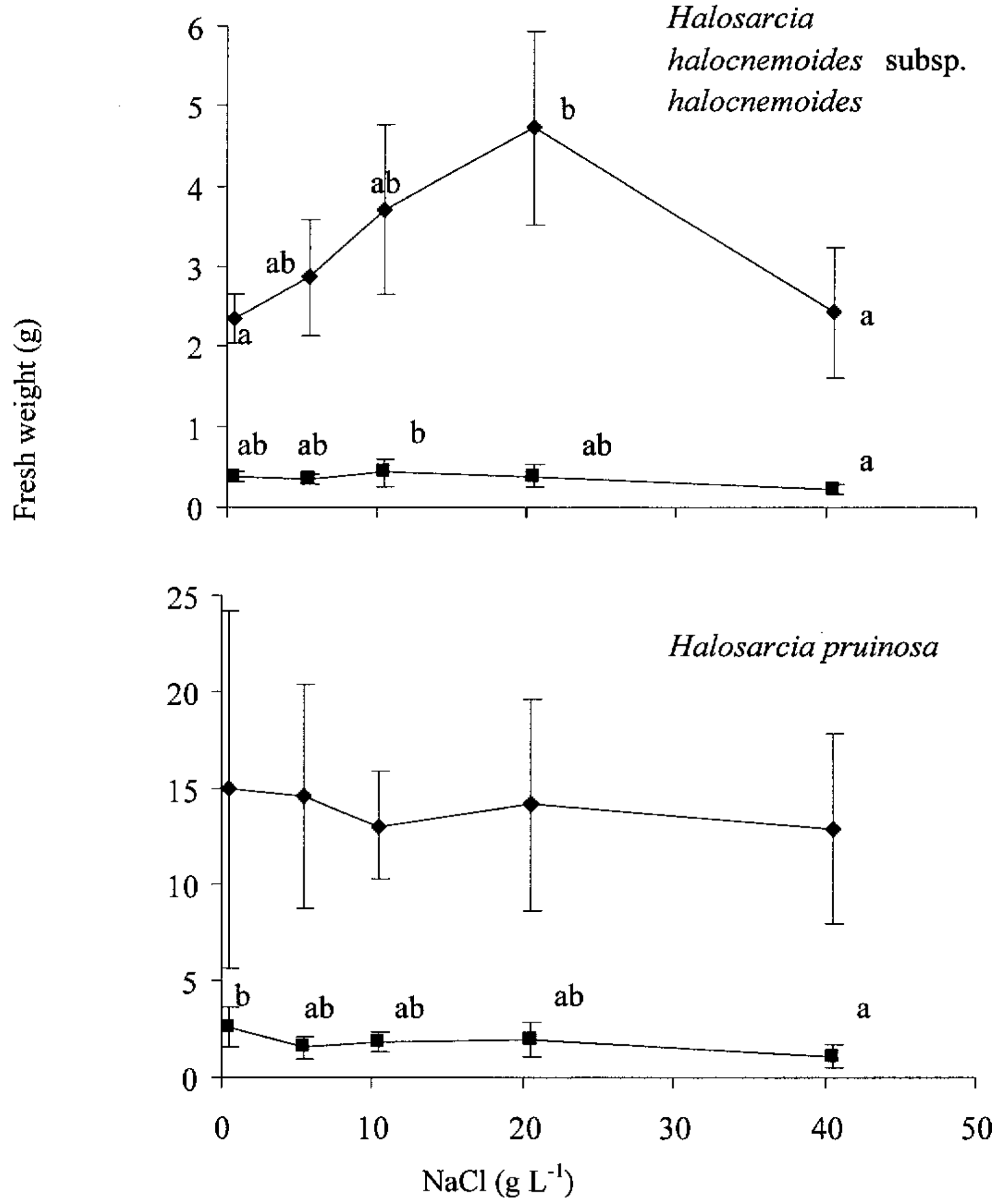


Figure 3.4: Mean fresh weight (± SE) of *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa* shoots (◆) and roots (■). Different letters indicate significant differences ($P < 0.05$). No letters means no difference.

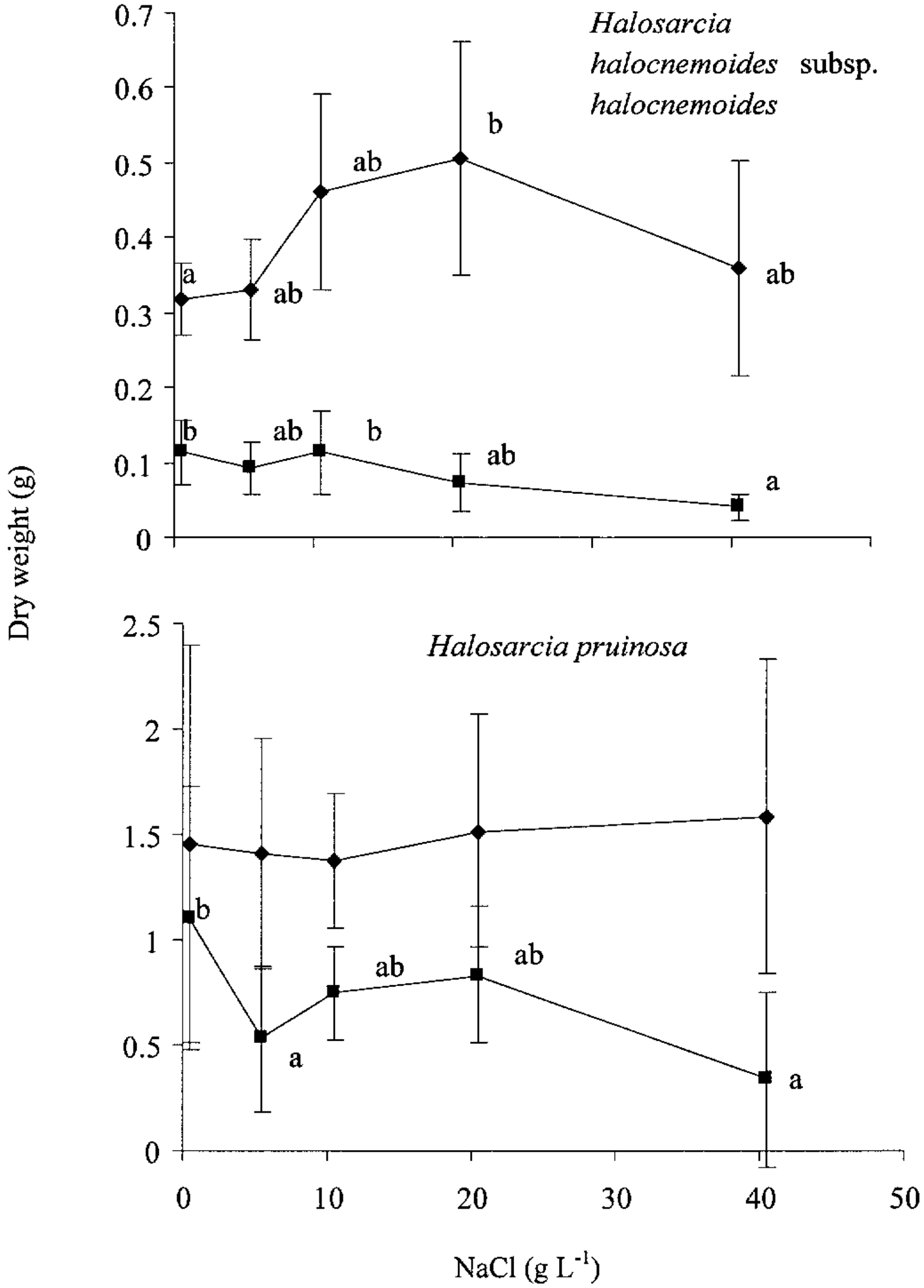


Figure 3.5: Mean (± SE) dry weight of *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa* shoots (◆) and roots (■). Different letters indicate significant differences ($P < 0.05$). No letters means no difference.

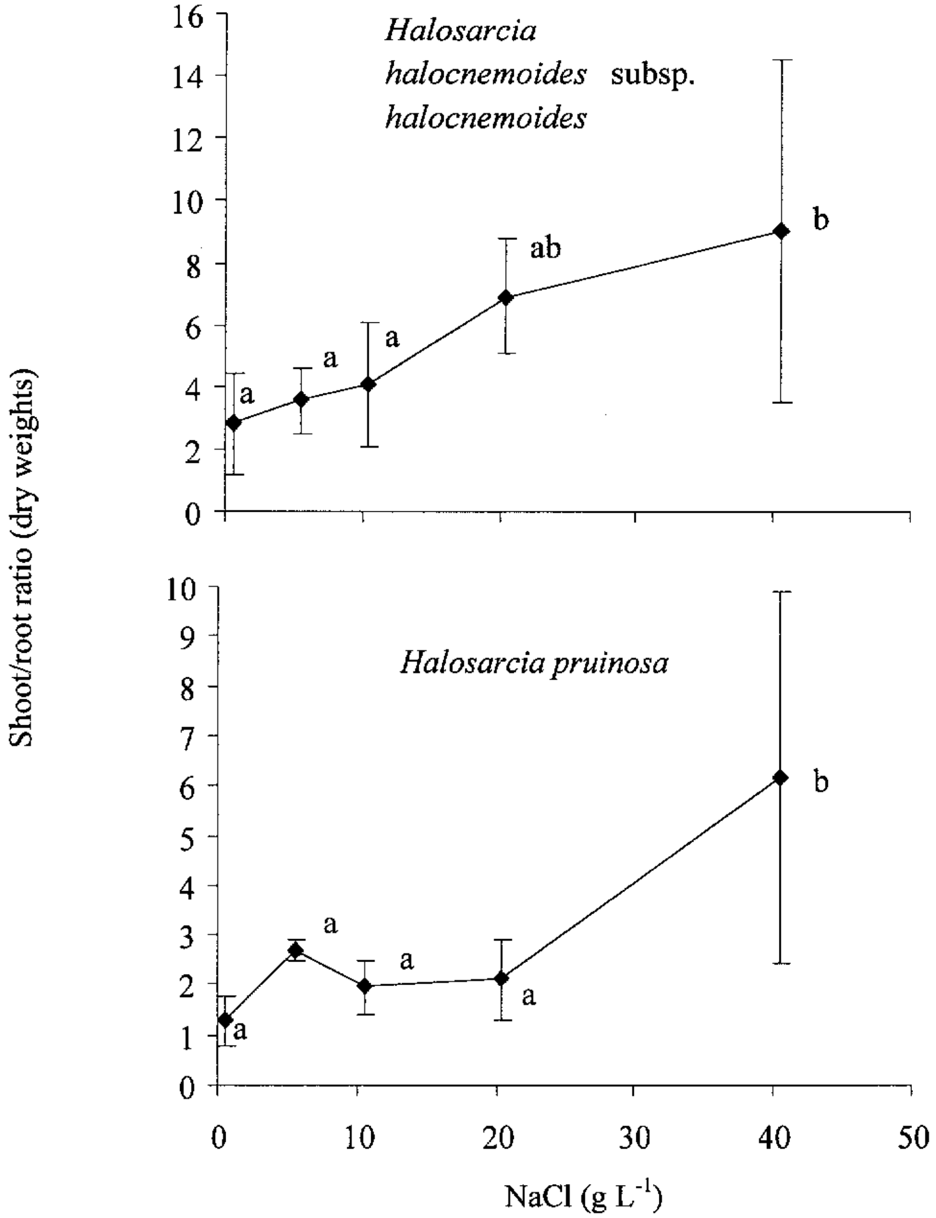


Figure 3.6: Mean (± SE) shoot:root ratios (dry weight basis) of *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa*. Different letters indicate significant differences ($P < 0.05$).

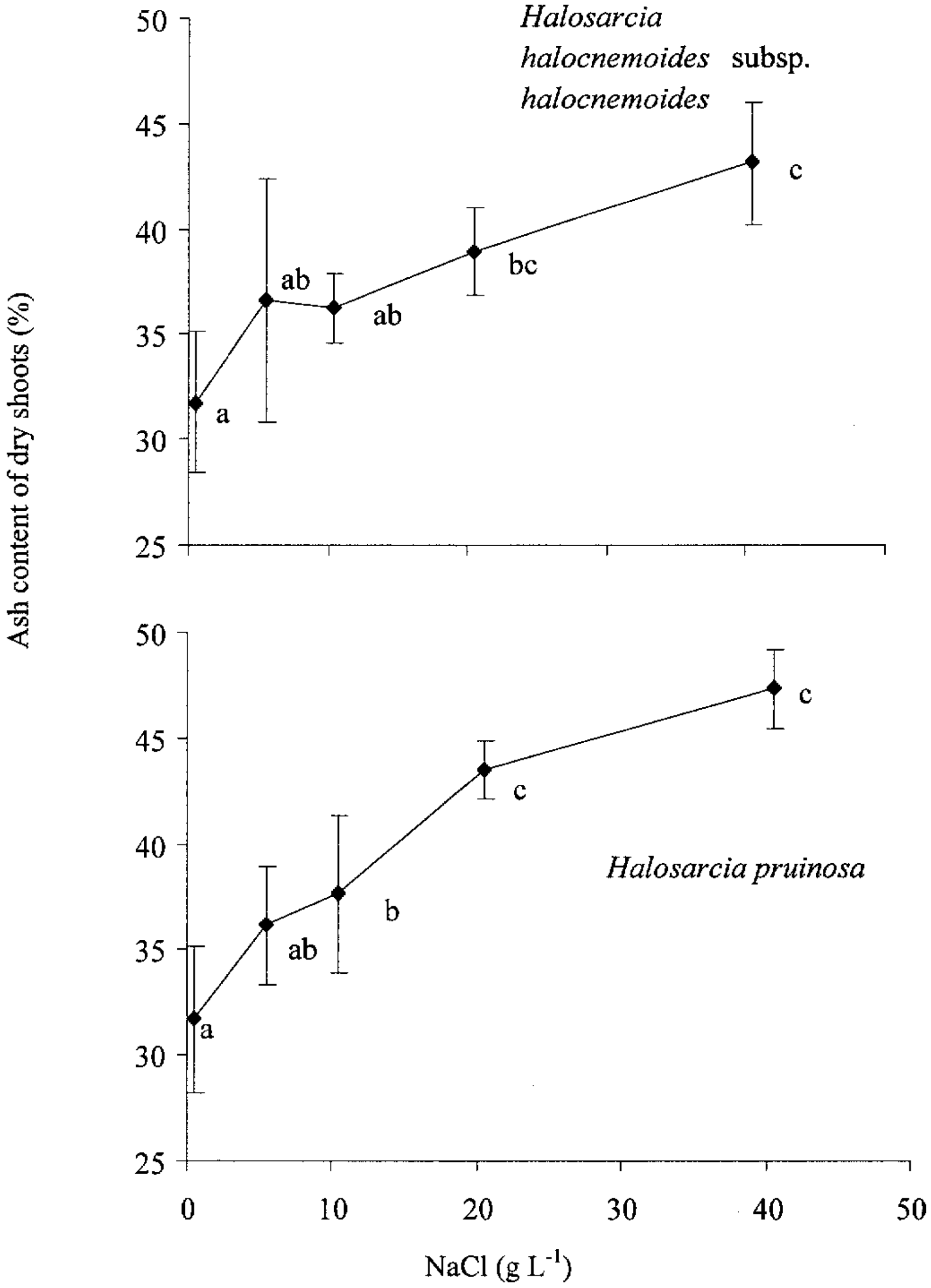


Figure 3.7: Mean percentage ash content (± SE) of dry shoots of *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa*. Different letters indicate significant differences ($P < 0.05$).

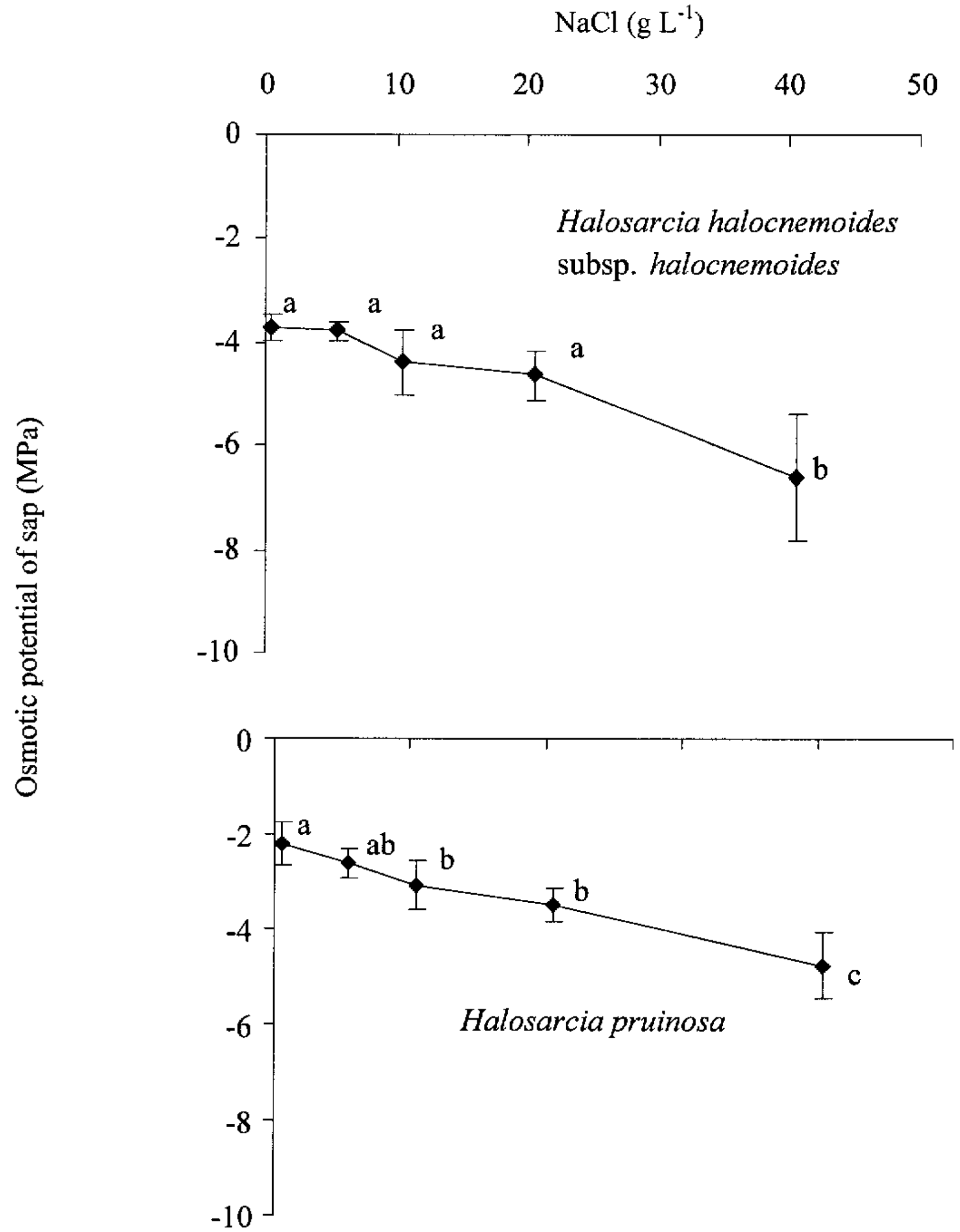


Figure 3.8: Mean (± SE) osmotic potential (MPa) of sap in shoot tips of *Halosarcia halocnemoides* subsp. *halocnemoides* and *H. pruinosa*. Different letters indicate significant differences ($P < 0.05$).

3.4 Discussion

Germination in the genus *Halosarcia* has been infrequently studied, but from the limited available information, the germination responses to salinity of the taxa studied here are comparable with those of other *Halosarcia* spp. but are less salt-tolerant than some other members of the Chenopodiaceae. Both taxa showed an ability to germinate in solutions up to 20 g L^{-1} NaCl though no seeds of either taxon germinated in the next highest treatment (40 g L^{-1} NaCl). A 50% reduction in germination occurred at 15.4 and 11.6 g L^{-1} NaCl for *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa* respectively. Evidence supporting the difference in germination response between *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa* was observed in the field during seed collection, where only seedlings of *H. halocnemoides* subsp. *halocnemoides* commonly occurred, despite comparable soil conditions and a high availability of viable seeds (G. Barrett, unpubl. data). In two other closely related taxa, Malcolm (1964) showed a 50% reduction in germination of *H. pergranulata* subsp. *pergranulata* (formerly *A. halocnemoides* var. *pergranulata*) occurred at 20 g L^{-1} NaCl but at only 8 g L^{-1} NaCl in *H. pterygosperma* subsp. *pterygosperma* (formerly *Arthrocnemum halocnemoides* var. *pterygosperma*).

While the upper limit for germination under saline conditions for the taxa studied here would appear to be not far beyond 20 g L^{-1} NaCl, it is much lower than the limits determined for *Salicornia pacifica* var. *utahensis* (50 g L^{-1} NaCl) (Khan and Weber, 1986), *Arthrocnemum indicum* (58.5 g L^{-1} NaCl) (Khan and Gul, 1998) and *Allenrolfea occidentalis* (46.8-71 g L^{-1} NaCl) (Gul and Weber, 1999; Blank *et al.*, 1994). These differences, however, could be attributable to suboptimal temperature or photoperiod conditions that can affect germination under saline conditions (Gul and Weber, 1999). In other taxa, substantial germination was achieved in *Haloxylon ammodendron* and *H. persicum* at 39 g L^{-1} NaCl (Tobe *et al.*, 2000) and germination was optimal in *Suaeda monoica* at 29.3-35.1 g L^{-1} NaCl (Chapman, 1974).

While seed dormancy was induced by high NaCl concentrations, the seeds of *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa* both germinated readily when returned to deionised water. A similar stimulation of germination upon return to low NaCl concentrations has been recorded in *Salicornea europaea* and *Suaeda calceoliformis*, even after exposure to very high salinity (100 g L^{-1} NaCl) for periods of up to two years (Keiffer and Ungar, 1997). Seeds of *H. pruinosa* germinated much more rapidly after exposure to high NaCl, suggesting some part of the germination process in that taxon takes place in highly saline solutions. This response was not observed in *H. halocnemoides* subsp. *halocnemoides*. Accelerated germination after an osmotic treatment has been observed in a number of species and the phenomenon is not restricted to halophytes (Heydecker *et al.*, 1973). The difference in response between *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa* may be attributable to differences in the morphology of the testa. The testa in *H. halocnemoides* subsp. *halocnemoides* is crustaceous while that of *H. pruinosa* is described as membraneous (Wilson, 1980). This characteristic of the seeds of *Halosarcia* is so distinctive that it was once a basis for taxonomic division, although this is no longer the case (Wilson, 1980). As the majority of the NaCl content of the seed is likely to reside in the testa, as is the case in *Salicornia pacifica* subsp. *utahensis* (Khan *et al.*, 1985), testa morphology is likely to affect germination characteristics (see Chapter 4). Seeds with membraneous testas are more likely to be 'primed' by exposure to high external NaCl concentrations, and thus germinate more rapidly when conditions are suitable, than those seeds with crustaceous testas. The thickness of the surrounding pericarp often has an inverse relationship with that of the seed (Wilson, 1980) and this too may be important in germination.

Values for a salt tolerance index at germination, based on Ungar's (1995) criteria, were greater for *H. halocnemoides* subsp. *halocnemoides* (17.4) and *H. pruinosa* (10.7) than for a number of other halophytes (*Atriplex* and *Maireana* spp.) from the Chenopodiaceae where the values ranged from 6.5 to 9.8 (Chapter 2). This confirms that germination may not be a limiting factor in considering their suitability for use in saline land rehabilitation programs in areas where field establishment of other chenopods can be achieved.

Both taxa also demonstrated substantial salt tolerance during early growth. Growth for *H. halocnemoides* subsp. *halocnemoides* was greatest at 20.5 g L^{-1} NaCl (100.3 mg g^{-1} d^{-1}) and at 0.5 g L^{-1} NaCl (191.8 mg g^{-1} d^{-1}) for *H. pruinosa*, although no significant difference was detected between treatments for either taxa. These growth rates, however, were comparable to growth recorded in another succulent halophyte, *Salicornia bigelovii* (up to 124 mg g^{-1} d^{-1} at 35.1 g L^{-1} NaCl) (Ayala and O'Leary, 1995). Plants of both taxa continued to survive and grow at 40.5 g L^{-1} NaCl and organic matter accumulation was not reduced. Some succulent halophytes demonstrate optimal growth under saline conditions (Gorham, 1996). Optimal growth, as organic matter accumulation, was recorded at 9.9 g L^{-1} NaCl in *Suaeda maritima* (Yeo and Flowers, 1980), 11.7 g L^{-1} NaCl in *Salicornia bigelovii* (Ayala and O'Leary, 1995) and 17.6 g L^{-1} NaCl in *Sarcocornia natalensis* (Naidoo and Rughunanan, 1990). In *Halosarcia pergranulata* subsp. *pergranulata*, shoot biomass was optimal in treatments between 0.6 and 11.7 g L^{-1} NaCl and declined thereafter (Short and Colmer, 1999). Shoot growth in *H. halocnemoides* subsp. *halocnemoides* was optimal at 20.5 g L^{-1} NaCl but in *H. pruinosa* it was unaffected by NaCl concentration (although there was considerable variability within treatments for the latter taxon and experiments of greater duration or replications may have given a different result). Root growth, however, was reduced by 40.5 g L^{-1} NaCl in both taxa and shoot/root ratios were sharply higher at this concentration. This response suggests growth and survival in the longer term will be reduced at this NaCl concentration. Conversely, the roots of *Salicornia bigelovii* were less affected by increasing NaCl than were the shoots (Ayala and O'Leary, 1995).

Shoots in both taxa were able to make osmotic adjustments under increasing external NaCl concentration and did not show visual evidence of ion toxicity. Halophytes can make rapid osmotic adjustments in response to changes to their external environment (Mc Nulty, 1985) and π_{sap} fell in both *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa* to a degree comparable with other halophytes, including *Sarcocornia natalensis* (Naidoo and Rughunanan, 1990) and *H. pergranulata* subsp. *pergranulata* (Short and Colmer, 1999). The reductions in π_{sap} corresponded with the increasing ash content of shoots and similar patterns have been recorded in other halophytes where they were correlated with reductions in photosynthesis and chlorophyll content (Kolchevski *et al.*, 1995). Shoot succulence was reduced by high NaCl concentrations in *H. halocnemoides* subsp. *halocnemoides*, in contrast to the responses recorded in *Arthocnemum fruticosum* (Eddin and Doddema, 1986) and *Sarcocornia natalensis* (Naidoo and Rughunanan, 1990) but similar to *H. pergranulata* subsp. *pergranulata* (Short and Colmer, 1999). Increasing succulence is a strategy adopted by many halophytes to cope with high internal salt concentrations (Gorham, 1996) and it is unclear why this should not be evident in *Halosarcia*. Clearly, however, both *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa* are able to accumulate substantial quantities of inorganic ions and make the necessary osmotic adjustments to allow growth to continue. It may be that other mechanisms, such as some manner of salt excretion, may also be utilized although the means by which this is achieved in other halophytes, such as salt glands or bladders, do not appear to be present in *Halosarcia*. At the cellular level, it is assumed an osmotic balance is made possible by the presence of unidentified organic solutes within the cytoplasm to counter NaCl concentrations in the vacuole (Short and Colmer, 1999).

In conclusion, *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa* are more salt-tolerant at germination than some other Western Australian chenopods from the genera *Atriplex* and *Maireana,* but are not among the most salt-tolerant of the entire family, Chenopodiaceae. Germination within *Halosarcia* remains poorly understood and further research is required to clarify the roles of the testa and the pericarp. The greatest shoot growth in *H. halocnemoides* subsp. *halocnemoides* occurred at 20.5 g L^{-1} NaCl, within the range reported for other succulent halophytes, but *H. pruinosa* growth was not significantly reduced by 40.5 g L^{-1} NaCl. Root growth in both taxa was reduced by 40.5 g L^{-1} NaCl. The effect of NaCl concentration on root growth and the subsequent growth and survival warrants further research.

4.0 POTENTIAL OF THE HALOPHYTE, *HALOSARCIA PERGRANULATA* SUBSP. *PERGRANULATA*, FOR USE IN SALINE LAND REHABILITATION: SEED DORMANCY AND GERMINABILITY

4.1 Introduction

In the Eastern Goldfields region of Western Australia, gold mining is an important contributor to the regional economy. Disturbance after gold mining commonly leaves saline landforms requiring rehabilitation. The salinity arises from the widespread use of hypersaline (> 50 g L^{-1} total dissolved solids) groundwater for mineral processing and the evaporative losses of this water that may occur (Chapter 1). Other sources of salinity include waste material from saline horizons and from mining activities occurring on or near salt lakes (Chapter 1).

The seeds of halophytic species are commonly used in mine revegetation programs. Research into revegetation after mining has identified species from the Chenopodiaceae, in particular *Atriplex* (saltbushes) and *Maireana* spp. (bluebushes), as suitable for use (Fletcher *et al.*, 1989). Chenopods, especially *Atriplex* spp., have been used in various parts of the world to reclaim extensive areas of salt-affected and desertified land and also produce fodder for browsing animals (Malcolm, 1989; Le Houèrou, 1992).

With 302 Australian species in the Chenopodiaceae, the large majority of which is endemic (Wilson, 1984), there has been interest in broadening the usage of chenopods to include taxa with putatively greater salt and waterlogging tolerances than taxa already in common usage (Barrett, 1994). This would have the advantage of improving plant species diversity in rehabilitated areas that, in turn, would give a more sustainable plant cover under variable environmental conditions. Taxa that could fulfil this role include those from the tribe *Salicornieae* that comprises succulent shrubs with fleshy articles in lieu of leaves (cladodes). These shrubs frequently occur on saline soils in arid Western Australia (Wilson, 1984).

Limiting factors in the use of any species in a revegetation program utilising chenopods may include inadequate access to viable seeds (Vlahos *et al.*, 1991; Strawbridge *et al.*, 1997) and poor germination in the field. In many species, seed set may be low or germination of viable seeds limited by dormancy mechanisms. At least some taxa in the *Salicornieae* appear to exhibit physical dormancy (Chapter 3) and this is likely to be related to the encapsulation of the seed within either a crustaceous testa or a persistent pericarp (Wilson, 1980). Seed dimorphism and polymorphism also occur in the Chenopodiaceae with different seed types having different germination characteristics (Khan and Ungar, 1984; Philipupillai and Ungar, 1984).

H. pergranulata subsp. *pergranulata* P.G. Wilson has already been used with some success in the revegetation of salt-affected agricultural and mined land (Malcolm and Cooper, 1988; Short and Colmer, 1999) and waste fly ash lagoons (Jusaitis and Pillman, 1997) but there is little knowledge of its reproductive and seed biology. This study followed preliminary germination testing of seeds from a range of *Halosarcia* spp. where some displayed low germinability of apparently viable seeds (Chapter 3; G. Barrett and M. Calvert, unpubl. data). I studied viability, germinability and dormancy in seeds of this taxon, which is common across much of southern Australia (Wilson, 1980), with a view to elucidating the requirements for optimal seed germination and thereby improving the utility of the taxon in mine revegetation programs. Additionally, the ion content of seeds was determined for comparison with that of seeds in other halophytic species. Germination in apparently viable seeds without any form of pre-treatment has ranged from 0 to 43%, depending on the temperature regime used (Malcolm, 1964; G. Barrett and M. Calvert, unpubl. data). Malcolm (1964) achieved improved germination using scarification and suggested that the seed coat plays a role in inhibiting germination.

4.2 Materials and Methods

4.2.1 Reproductive biology of Halosarcia pergranulata *subsp.* pergranulata

The taxonomy of *H. pergranulata* subsp. *pergranulata* has been reviewed by Wilson (1980). The flowers occur in axillary clusters of three forming a pseudospike, or thyrse (hereafter called “spike”). They are hermaphroditic, although in Western Australia the stamens are usually vestigial and apparently non-functional. Seed formation, therefore, is assumed to be parthenocarpic. Seeds occur in fruitlets along a spike that is subterminal on a branchlet. The fruitlets in *H. pergranulata* subsp. *pergranulata* and some other *Halosarcia* spp. are membranous but other taxa in the genus have fruitlets that are woody or pithy. The seed coat comprises two layers, an inner membranous layer (tegumen) and an outer testa. In contrast to the fruitlets, the testa in *H. pergranulata* subsp. *pergranulata* is hard and brittle (crustaceous) but may be membranous in other *H.* spp. The hardness of the testa in *Halosarcia* tends to be inversely proportional to the hardness of the pericarp or fruitlet. The persistence of the pericarp in some taxa may serve to protect the embryo in a similar manner to the crustaceous testa in other taxa. Both strategies are likely to serve the purpose of protecting the embryo during adverse environmental conditions, such as high temperatures or salinity.

4.2.2 Seed collection and preparation

Seeds were collected at Lakewood, Western Australia (30°48'S, 121°32'E), from plants in an area rehabilitated after disturbance from mining activity. Soils in the area are a saline and alkaline silt loam. Dry spikes containing seeds were collected and taken to the laboratory. Spikes were gently crushed using a rolling pin and sieved to separate seeds from the pericarps. Aborted seeds (seeds that were abnormally narrow or small), and seeds damaged during their removal from the spikes, were removed and discarded. Aborted seeds formed about 2% of the total seeds. Mean weight of individual plump seeds were 0.239 ± 0.009 mg ($n = 100$).

4.2.3 Ion content of seeds

Three 0.5 g batches of seeds were ground with a mortar and pestle, dried at 80°C and digested with nitric acid and analysed for Ca, Mg, Na and K content by inductively coupled plasma atomic emission spectrometry (ICPAES).

4.2.4 Electron microscopy

Microstructures of seeds that may have a role in the uptake of oxygen and water were examined using a Philips XL30 scanning electron microscope at the Electron Microscopy Laboratory, Department of Applied Physics, Curtin University of Technology. Seeds were dried through immersion in increasing concentrations of acetone solutions (20, 40, 60, 80, 90, 100%) changed every 24 h. They were mounted on SEM stubs using carbon gel and were gold-coated prior to examination.

4.2.5 Viability testing

Seed viability was assessed using a tetrazolium salt biochemical test (International Seed Testing Association, 1993). Seeds were drawn at random from the batch described in 4.2.2. Using a scalpel, a small portion of the testa adjacent to the usual location of radicle emergence was nicked and removed from each seed (Fig. 4.1a). Seeds were then allowed to imbibe by placing in a petri dish for 24 h on a filter paper moistened with deionised water. Each seed was then cut laterally to expose the proximal and distal ends of the embryo, immediately transferred to a filter paper moistened with 1% tetrazolium chloride solution (pH 7.0) in a petri dish and left for 24 h at room temperature. After 24 h, the embryo of each seed was checked for the level of pink staining under a dissecting microscope. If the embryo had not emerged through swelling, it was removed by gently squeezing the seed.

To validate the staining response, it was compared with that obtained for seeds from the same batch that had been heated at 105°C for 24 h.

4.2.6 Germination response to seed nicking

The testa of each seed was nicked as described above to expose the embryo and allow diffusion of oxygen and uptake of water. Additionally, a portion of the testa of other seeds were cut and removed, either near the distal end of the embryo (Fig. 4.1b) or adjacent to the perisperm (Fig. 4.1c). Care was taken not to damage the embryo or remove any perisperm. Seeds with intact testas were used as a control.

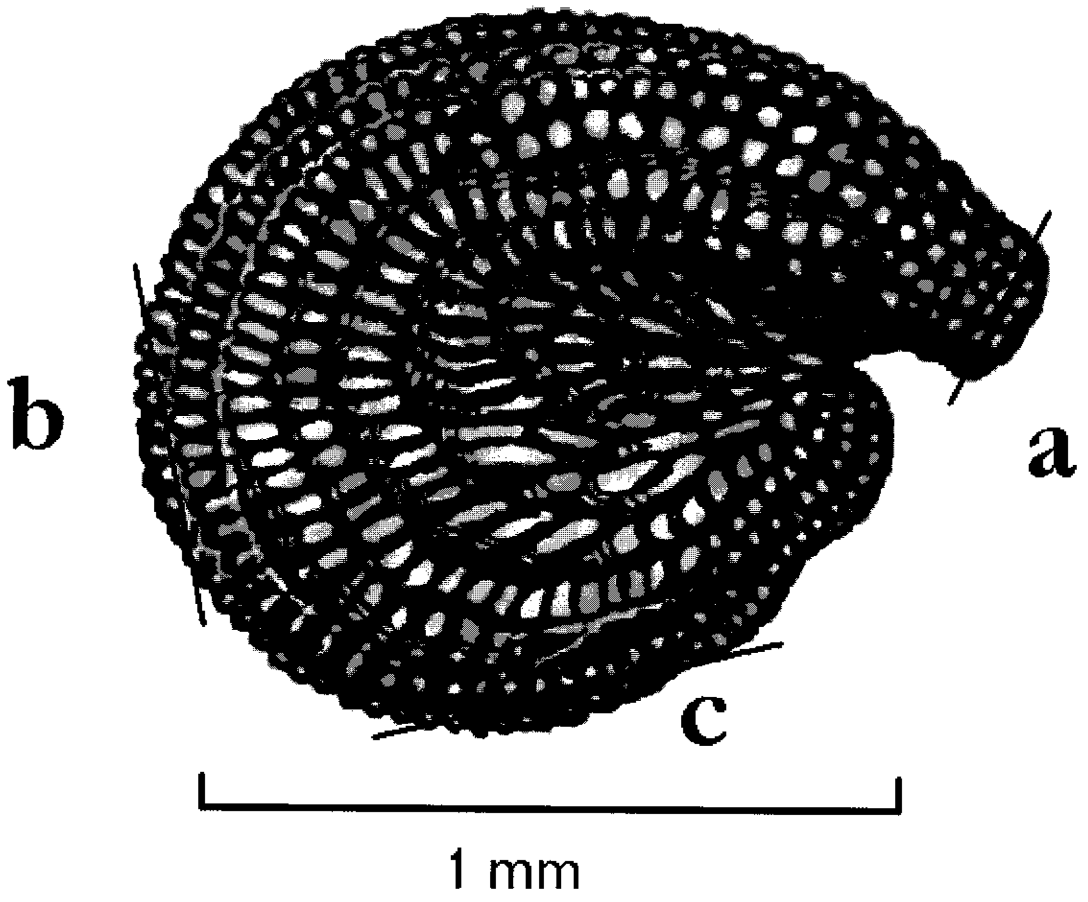


Figure 4.1: Lateral view of seed of *Halosarcia pergranulata* subsp. *pergranulata* (Lakewood). Germinability was tested after removal of portions of the testa from adjacent to the radicle (micropylar) end (a), the perisperm (b) and the plumule end (c). Drawing adapted from Wilson (1984).

Seeds from each treatment were tested for germinability in 90 mm petri dishes with two filter papers (Whatman No. 1) moistened with 5 mL of deionised water. Five replicates of 30 seeds each were used for each treatment. The petri dishes were wrapped in a clingfilm (Mono-Rap™) to minimise evaporation losses and then transferred to a germination cabinet (Lindner & May Pty Ltd, Windsor, Brisbane). The germination cabinet was set at a temperature of 35/5°C (day/night) with a 12 h photoperiod. This temperature regime was selected as it was the most successful of a number of regimes tested by Malcolm (1964) in obtaining germination in the seeds *Halosarcia* (formerly *Arthrocnemum*) spp.

The tests were run for 28 days. Each dish was checked daily and any germinants were recorded and removed. Germination was considered to have occurred when the radicle extended a distance of 1 mm from the testa. Where seed treatments resulted in emergence of the plumule rather than the radicle, germination was recorded if all essential structures were well developed, complete and healthy (International Seed Testing Association, 1993). The presence of ungerminated fresh seeds (firm with an embryo of healthy appearance) and dead seeds (soft with no embryo, or an abnormal embryo) were also recorded. Previcur™ (1% v/v) was used to control any fungal growth.

Statistical analysis of germination data was conducted as described in section 2.2.3.

4.2.7 Germination response to position of funicle

Examination by SEM suggested that the position of the funicle (seed stalk) in relation to the micropyle (ovular pore) could be significant in controlling ingress of water and oxygen, thereby delaying or preventing germination. Germination testing was conducted as described in 4.2.6. Germination of seeds with micropyles covered by the funicle and germination of seeds without the micropyle covered was tested.

4.3 Results

4.3.1 Electron microscopy

Scanning electron microscopy showed the presence of a structure at the radicle end of the seed believed to be a micropyle through which water and oxygen may enter (Fig. 4.2a). A hilum (point of attachment) was located in an adjoining recessed area and the funicle, where still attached to the hilum, was observed to lay across the micropyle in some seeds (Fig. 4.2b) and not in others (Fig. 4.2c).

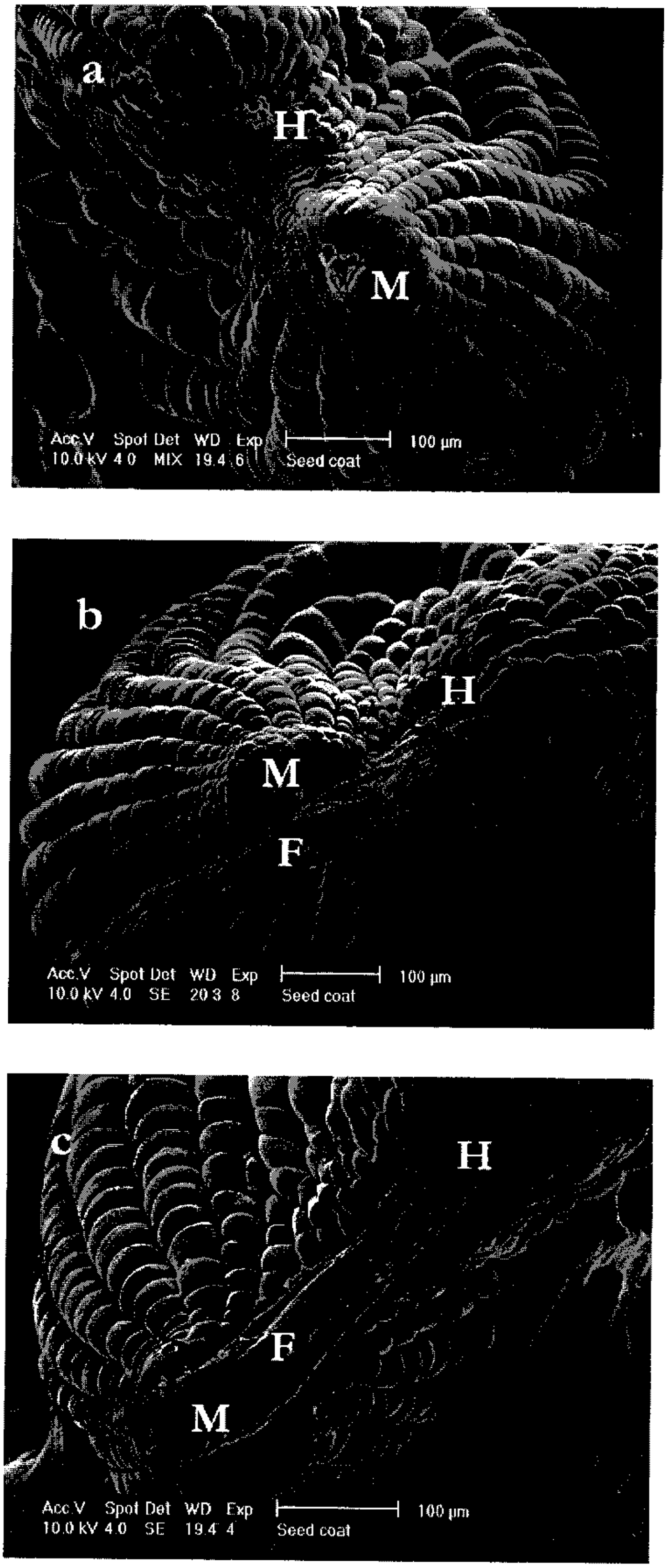


Figure 4.2: SEM images of seeds of *Halosarcia pergranulata* subsp. *pergranulata*. Images show seed without funicle (a) or with funicle lying partially (b) or wholly (c) across the micropyle (micropyle obscured in c). Key: micropyle (M), funicle (F), hilum (H).

4.3.2 Ion content of seeds

The cation concentration of seeds is shown in Table 4.1. The cations were dominated by Na, with Mg, Ca and K in similar amounts.

Table 4.1: Mean (± SE) ion concentration of seeds of *Halosarcia pergranulata* subsp. *pergranulata* from Lakewood, Western Australia. Values are mean of three replicates.

Cation	Ion concentration ($mmol\ g^{-1}$)
Ca	0.135 ± 0.004
Mg	0.205 ± 0.004
Na	1.072 ± 0.025
K	0.182 ± 0.004

4.3.3 Viability testing

A mean of 85.9% of the embryos of *H. pergranulata* subsp. *pergranulata* seeds were assessed as viable using the tetrazolium test (Table 4.2, Fig. 4.3). Of the remaining seeds, tetrazolium did not stain the embryos of 5.1% and a further 9% of seeds did not contain embryos. No staining of embryos occurred in control seeds.

Table 4.2: Effect of tetrazolium salt biochemical testing on apparently viable seeds of *Halosarcia pergranulata* subsp. *pergranulata*. Control (non-viable) seeds were exposed to 105°C for 24 h prior to the tetrazolium test. No data available on embryo presence or absence in control seeds. Values are mean ± SE of 30 seeds with 5 replicates.

Effect on embryo	Test seeds (%)	Control seeds (%)
Stained	85.9 ± 6.7	0 ± 0
Unstained	5.1 ± 2.8	100 ± 0
No embryo	9.0 ± 6.3	-

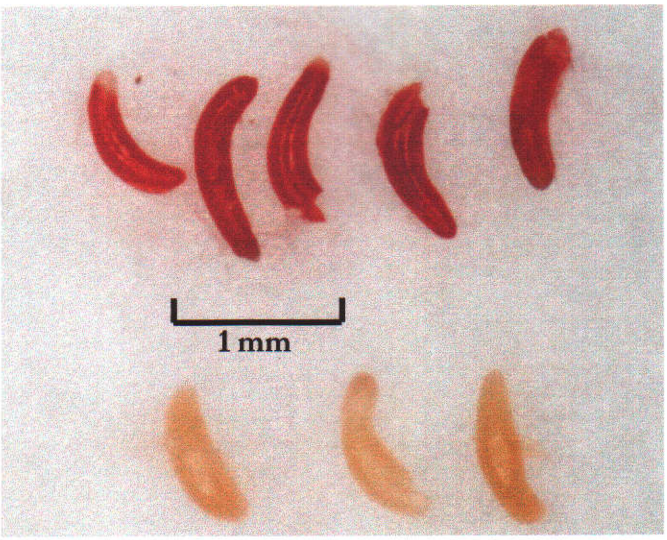


Figure 4.3: Embryos of *Halosarcia pergranulata* subsp. *pergranulata* after tetrazolium treatment. Embryos were scored as viable (top) or non-viable (bottom).

4.3.4 Germination response to seed nicking

Germinability was greatest in seeds nicked near the radicle or the perisperm (Table 4.2, Fig. 4.4). Germination was significantly lower ($P < 0.05$) in seeds nicked near the plumule and lower again in the control seeds that had not been nicked. Germination occurred most rapidly when seeds were nicked near the radicle.

Table 4.3: Effect of testa removal on germination percentage of seeds of *Halosarcia pergranulata* subsp. *pergranulata*. Control seeds had intact testa. Ungerminated fresh seeds were those remaining firm and full. Significant differences ($P < 0.05$) in the germination achieved were determined by ANOVA and Tukey's multiple comparison test. Values are mean ± SE of 30 seeds with five replicates.

Seed	Control (%)	Location of testa removal (%)		
		radicle	plumule	perisperm
Germinated seeds	38.0 ± 10.7 c	79.4 ± 4.3 a	56.0 ± 10.4 b	80.0 ± 5.8 a
Ungerminated fresh seeds	45.3 ± 11.5	1.3 ± 1.8	1.3 ± 1.5	1.3 ± 1.8
Ungerminated dead seeds	16.7 ± 5.3	19.3 ± 4.9	42.7 ± 13.6	18.7 ± 4.5

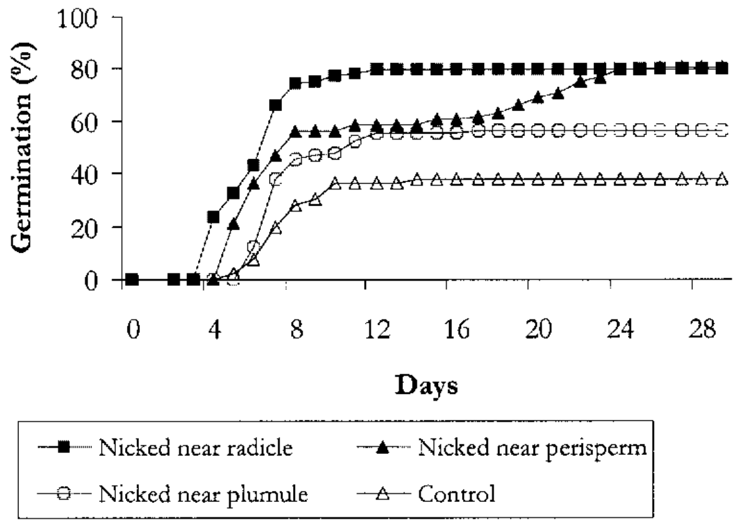


Figure 4.4: Germination of *Halosarcia pergranulata* subsp. *pergranulata* (Lakewood, Western Australia) seeds with testa nicked at different locations on the seed compared with controls (intact testa).

In control seeds, and seeds nicked near the radicle or perisperm, radicle emergence was usually preceded by a splitting of the testa from the micropylar end along an axis over the embryo towards the distal end of the seed. Seedling emergence from seeds nicked near the plumule usually occurred without this splitting of the testa. In these cases, the cotyledons often emerged completely from the testa soon after germination, while those germinants with the radicle emerging from the area near the micropyle retained their cotyledons within the testa until root development was further advanced. Germinants not emerging at the radicle end often had little or no root elongation and development, and once emerged completely from the testa, no further development occurred. These seeds were scored as non-viable as germination did not result in a healthy seedling.

4.3.5 Germination response to position of funicle

Germination of seeds where the funicle covered the micropyle was not significantly different from that in seeds where the micropyle was uncovered (Table 4.4). The germination obtained was not significantly different from that of the control shown in Table 4.3.

Table 4.4: Mean germinated and ungerminated seeds (% ± sd) of *Halosarcia pergranulata* subsp. *pergranulata* seed where the micropyle was either covered or not covered by the funicle. Ungerminated fresh seeds were those remaining firm and full. There was no significant difference (using one-way ANOVA) between treatments.

Seed	Micropyle covered by funicle	Micropyle not covered by funicle
Germinated seeds	32.0 ± 11.3	33.7 ± 6.2
Ungerminated fresh seeds	45.1 ± 6.2	45.7 ± 4.5
Ungerminated dead seeds	22.9 ± 6.4	20.6 ± 5.1

4.4 Discussion

Viability of seeds of *Halosarcia pergranulata* subsp. *pergranulata* was in excess of 85%, but germination levels were much lower (38%). Removal of a portion of the testa by nicking it with a scalpel significantly improved germination such that all viable seeds were able to germinate. Malcolm (1964) also showed scarification, (lightly rubbing with fine emery paper), improved germination in *H. pergranulata* subsp. *pergranulata* and greater germination in the seeds of other chenopods has been achieved after physical treatment of the bracts or seed capsules (Burbidge, 1945; Beadle, 1952; Ansley and Abernethy, 1985; Chapter 2).

The location of the nick on the testa was important. Complete germination was recorded when the micropyle and immediate surrounds was cut and removed. Other unrelated species have shown sensitivity to the location of scarification or wounding (Sung *et al.*, 1987). While removal of a portion of the testa at any location may allow uptake of water and oxygen, other processes may be inhibited. Where emergence of the germinant occurred other than at the radicle end, due to removal of portions of the testa at other locations, development and survival of the germinant was reduced. Lamont and Milberg (1997) found removal of part or all of the testa in a number of species from the Proteaceae reduced germination or survival of the germinants. This was attributed to desiccation or decay during germination. In *H. pergranulata* subsp. *pergranulata*, where seeds were nicked other than near the micropyle, the extending radicle may force the premature emergence of the cotyledons, where they would otherwise have remained within the testa for some time after germination commenced. As in the species studied by Lamont and Milberg (1997), this may have led to desiccation and, ultimately, lower germinant survival. The micropyle appears to be the key structure in controlling ingress of water and oxygen, similar to the strophiole in *Acacia* (Tran, 1981). In control seeds, germination occurred only at the radicle end.

Dormancy in seeds of halophytic species is usually physiological but physical dormancy, as appears to occur in *H. pergranulata* subsp. *pergranulata*, is rare. Within the Chenopodiaceae, physiological dormancy resulting from the high salt content of the bracteoles surrounding seed of *Atriplex* spp. has been well documented (Beadle, 1952; Fletcher *et al.*, 1989; Rogers, 1997). Similarly, dormancy induced by saline conditions has also been widely reported for the seeds of many species capable of suspending germination under saline conditions but retaining the ability to germinate when the saline conditions are alleviated (Ungar, 1995). While physical dormancy has been demonstrated for the seeds of *Kosteletzkya virginica* (Malvaceae) (Poljakoff-Mayber *et al.*, 1994), it does not, however, appear to have been recorded previously in the Chenopodiaceae.

Why some seeds should germinate while others of the same age do not remains unclear. There was no evidence of polymorphism, such as large numbers of seeds within a seed batch having notably different seed sizes or colours, among the seeds in my study. Polymorphism can result in different germination characteristics and has been widely recorded within the Chenopodiaceae (Beadle, 1952; Philipupillai and Ungar, 1984; Khan and Gul, 1998; Mandák and Pyšek, 1999). The possible inhibition of oxygen and water uptake through the micropyle due to coverage by the funicle, as a source of variation among seeds, was discounted here. Nevertheless, as germination of all viable seeds can be induced by its removal, it appears that the micropylar end of the seed is differentially permeable to water between seeds of the same age.

The ion concentration of seeds in *H. pergranulata* subsp. *pergranulata* is within the general range for that of other halophytes. Na concentrations of 1.072 mmol g^{-1} in seeds of this taxon is well below that recorded for *Arthrocnemum indicum* (6.57 mmol

g^{-1}) but above that recorded for four other halophytic shrub species (Khan and Ungar, 1996). In some species, the ion concentration could lead to osmotically-induced dormancy but this was not observed in *H. pergranulata* subsp. *pergranulata*, as seeds with a portion of testa removed germinated readily without any requirement for washing or soaking in water of a low salinity. The location of ions within the seeds was not assessed, but Khan *et al.* (1985) showed that the majority of Na and Cl ions in the seeds of the halophyte *Salicornia pacifica* var. *utahensis* occurred in the seed coat.

In conclusion, the testa limits germination in *H. pergranulata* subsp. *pergranulata*. Removal of a portion of the testa at the micropylar end resulted in the germination of all viable seeds. Given that dormancy in *H. pergranulata* subsp. *pergranulata* can be induced by high salinity (G. Barrett, unpubl. data), this species appears to exhibit both physiological and physical dormancy, a feature unusual in halophytes (Baskin and Baskin, 1998). Further study of the permeability of the micropyle is required to understand the factors controlling germination and to permit the reliable use of this species in land rehabilitation. Finally, the findings of this study have implications for the germination requirements of other *Halosarcia* spp. with a crustaceous testa.

5.0 EFFECTS OF SURFACE MANAGEMENT TECHNIQUES ON SEVERELY SALT-AFFECTED LAND AFTER REMOVAL OF GOLD TAILINGS IN THE EASTERN GOLDFIELDS OF WESTERN AUSTRALIA

5.1 Introduction

Methods of rehabilitating salt-affected land vary in accordance with the outcome required and the resources available. Where secondary salinisation has occurred in agricultural systems, it has been combated by sowing of salt-tolerant crops and planting of salt-tolerant shrubs and trees for fodder and fuel, with the latter often under irrigation (Abdul-Halim, 1986; Forti, 1986; Le Houèrou, 1992; Malcolm, 1989, Glenn *et al.*, 1998). In semiarid rangelands, where grazing is the predominant land use, saline scalded sites may occur where topsoil has been eroded. Ponding of water behind small embankments has been used extensively to reclaim affected areas (Jones, 1967; Cunningham, 1987). The construction of water ponding banks and other modifications to the local topography can alter soil conditions sufficiently to allow recolonisation of these areas by native shrubs and pasture grasses. Different approaches may be adopted for land rehabilitation where salinisation has occurred as a result of mining or industrial activity, including the use of sea water in mineral sands mining (de Villiers *et al.*, 1995a), brine spills from oil pipelines (Foderaro and Ungar, 1997) and open pit mining and mineral processing that expose saline materials (Chapter 1).

Retreatment of old gold mine tailings has been undertaken near Kalgoorlie-Boulder, Western Australia. The tailings are removed by hydraulic mining using hypersaline groundwater under high pressure. This water is used extensively for mineral processing and associated activities due to the absence of sufficient fresh surface or underground water (Turner *et al.*, 1993). After removal of the tailings, the final surface is highly saline and inhibitory to even the halophytic species typically used for revegetation in the region (Fletcher *et al.*, 1989). This presents difficulties in bringing the affected areas to a condition where the retirement of legal obligations under the relevant legislation governing mining activities is possible (Department of Minerals and Energy, 1996a).

In this study, some initial work on surface treatments to optimize water retention and infiltration was extended by researching the effects of temporarily ponding saline areas using waste water. These treatments were expected to reduce surface soil salinity through leaching of salts, thus facilitating the overall aim of establishing a substantial and sustainable vegetation cover.

5.2 Materials and Methods

5.2.1 General site description

The study site was immediately south-east of Kalgoorlie-Boulder, Western Australia (30°45'S, 121°28'E) (Fig. 5.1 and 5.2). Kalgoorlie-Boulder receives an average annual rainfall of 256 mm which is spread over the year. Evaporation averages 3000 mm annually. Temperatures can range from a summer maximum of 46°C to a winter minimum of -3°C. Temperature and rainfall data for the period of the trials were obtained from Climate and Consultative Services, Bureau of Meteorology, Perth, Western Australia (Fig. 5.3). Plant establishment occurs predominantly during the winter months. An agroclimatic index, such as a precipitation/potential evapotranspiration ratio (P/E_p) (Fig. 5.4), gives a more direct indication of the time of year when germination and growth are most likely (Hatfield, 1990). For crops, growth periods are regarded as periods where P/E_p exceeds 0.5 (Hatfield, 1990) and this period occurs between May and June (Fig. 5.4). Native vegetation, adapted to arid conditions, could be expected to establish and grow at lower P/E_p ratios.

The study site covered an area of about 300 ha. It had been used for over 50 years for storage of gold mine tailings up to 18 m in height. The gold tailings originated from extensive underground workings. Between 1989 and 1999 the tailings were removed for retreatment by remining them hydraulically using high pressure hypersaline groundwater (approximately 100 g L^{-1} total dissolved solids, predominantly NaCl). Surface drainage of the area was encouraged by a series of trenches designed to carry the slurry (water and tailings) away for reprocessing but infiltration and localized ponding of hypersaline water occurred widely across the area. Remnant tailings remain in some small areas.

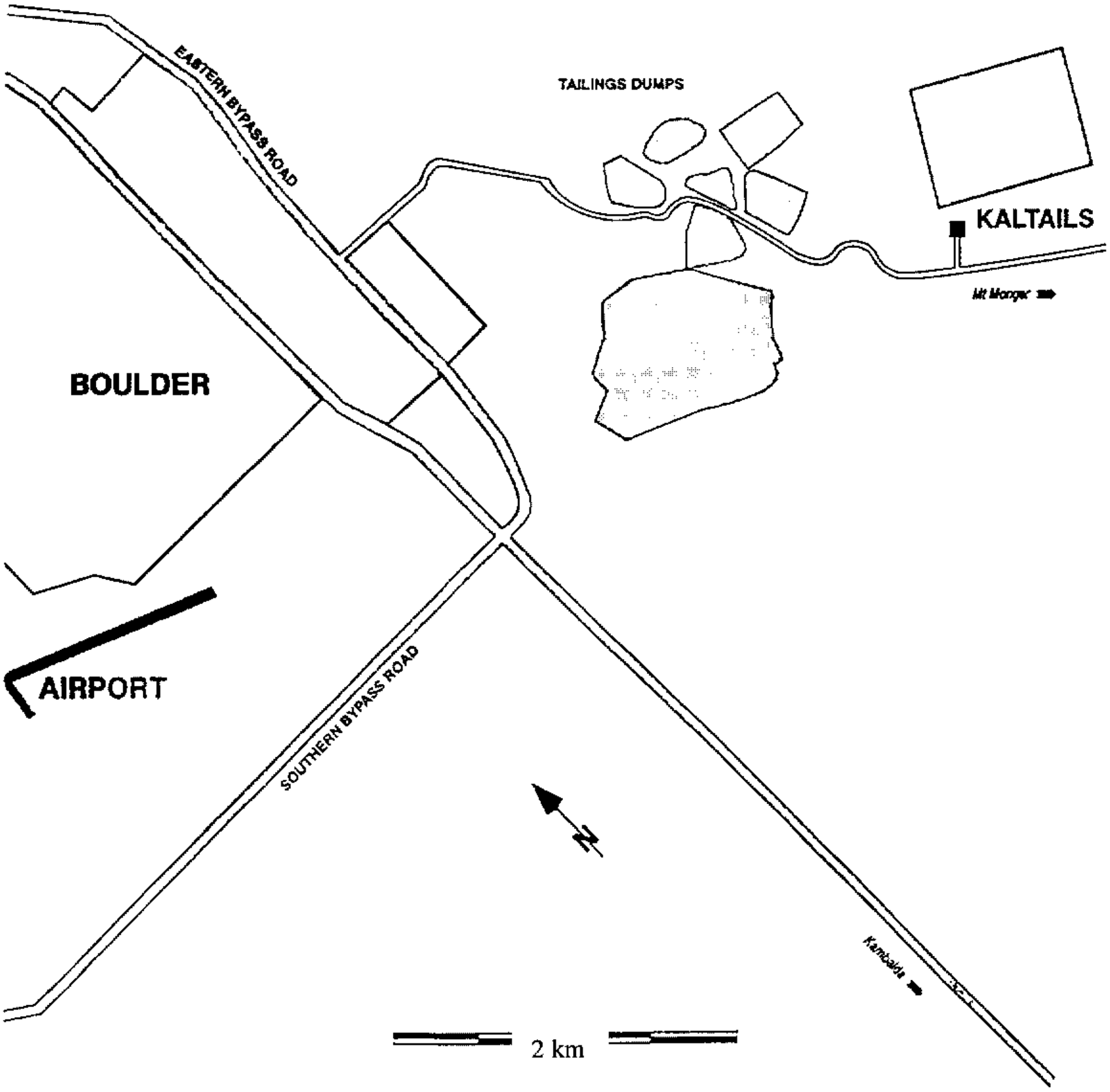


Figure 5.1: Location of old gold tailings dumps (shaded outlines) near Kalgoorlie-Boulder. The tailings dumps were removed for retreatment at the Kaltails process plant during the period 1989-1999 and stored in an adjacent new tailings storage facility.

Figure 5.2: View of old gold tailings dumps prior to their removal for reprocessing by high pressure hypersaline water. The dumps stand between 20 and 30 m high.

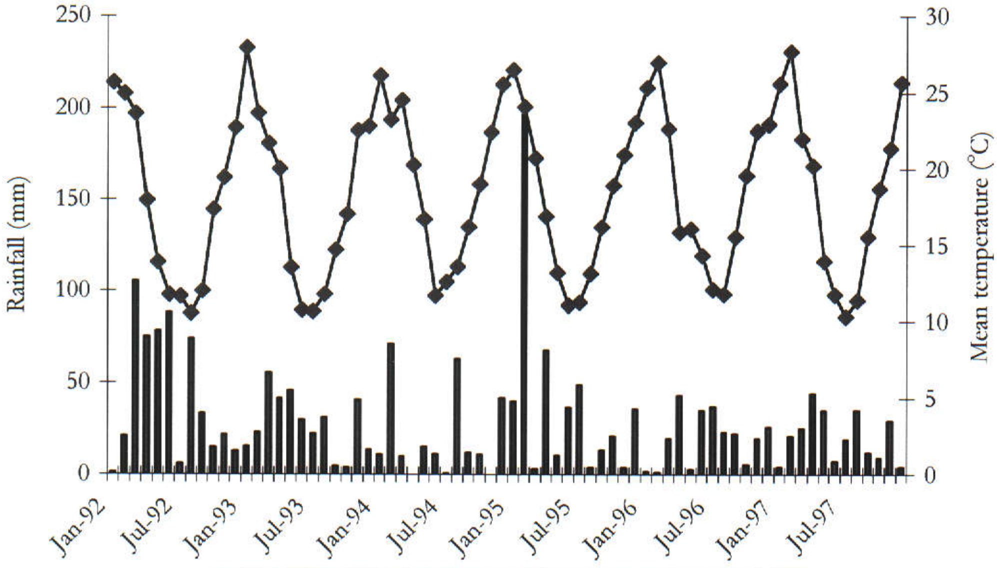


Figure 5.3: Mean monthly temperatures (°C) and rainfall (mm) for Kalgoorlie-Boulder for the period 1992-1997 (unpubl. data, Climate and Consultative Services, Bureau of Meteorology, Perth).

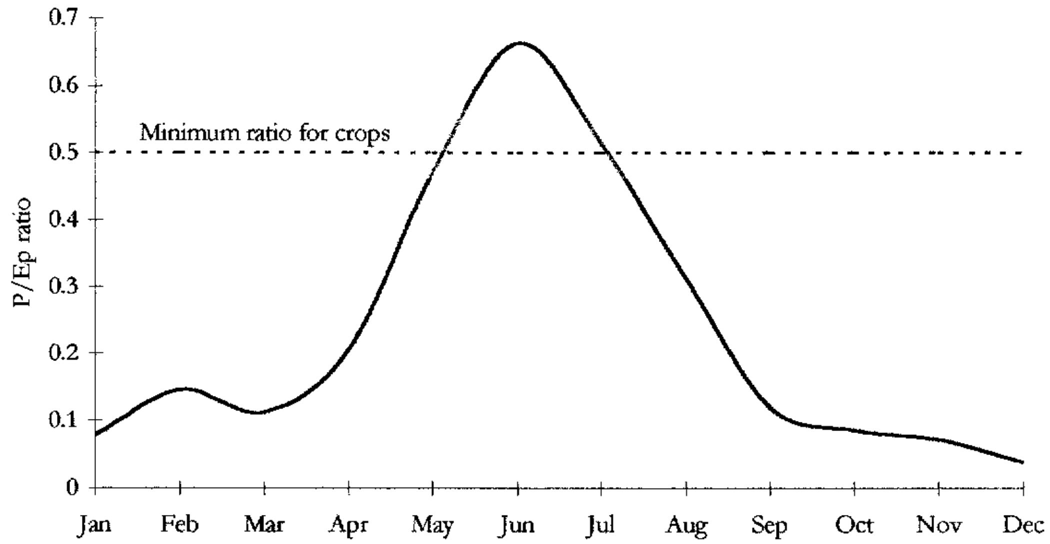


Figure 5.4: Monthly ratio of precipitation to potential evapotranspiration (P/E_p) for Kalgoorlie-Boulder based on long term mean data. Crops require a ratio of 0.5 or greater for establishment and growth (Hatfield, 1990). E_p calculated from Penman model (Hess and Stephens, 1993). Meteorological data from Climate and Consultative Services, Bureau of Meteorology, Perth.

Table 5.1: Mean, standard deviation (SD) and ranges (n = 4) for chemical characteristics of saline surface soils (0-100 mm) prior to initial surface treatment trial. EC_e values are for a saturated paste extract equivalent. Soil samples collected spring 1991.

Characteristic	Mean	SD	Range
EC_e (dS m^{-1})	50.7	14.9	32.5-65.6
pH	8.2	0.1	8.1-8.3
NO_3 (mg kg^{-1})	15.8	11.1	7-30
NH_4 (mg kg^{-1})	10.3	4.6	5-16
P (mg kg^{-1})	3	0	0-3
K (mg kg^{-1})	392	103	287-516
Organic C (%)	0.32	0.06	0.26-0.37

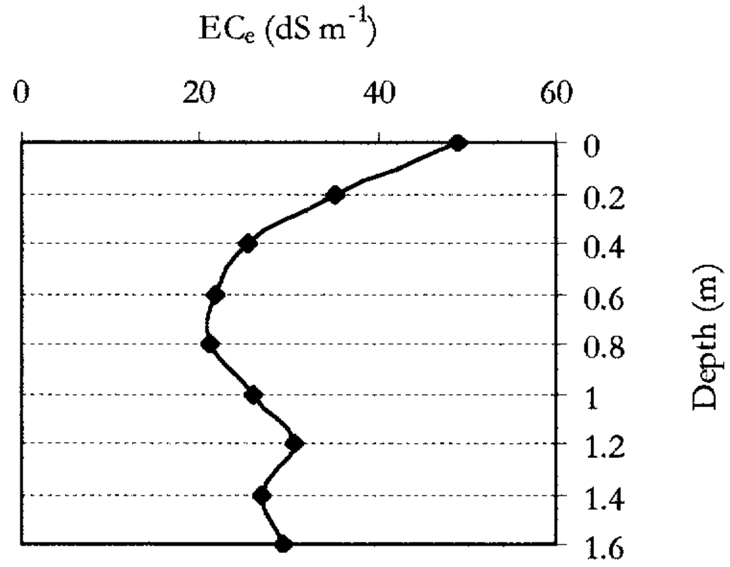


Figure 5.5: Variation in soil EC_e (saturated paste extract equivalent) with depth to 1.6 m in preliminary surface treatment trial area. Soil samples collected spring 1991 with three subsamples collected at 200 mm intervals and aggregated.

Local soil characteristics are shown in Table 5.1 and Figure 5.5. The soil is an alkaline and highly saline silt loam. The high salinity (electrical conductivity) occurs both at the surface and at depth (> 1 m). A survey of heavy metal levels within the soils (Normandy Kaltails Ltd, unpubl. data) indicated that, other than high salinity, there were no other known chemical impediments to plant growth.

5.2.2 Initial surface treatment trial

An initial trial was established in January 1992 to test methods by which salt-affected areas could be rehabilitated. An area of 0.5 ha was divided into twenty 25 m by 10 m plots (Fig. 5.6). Four treatments and a control were utilised with three plots for each. The remaining five plots were not allocated a treatment or control and served as spaces to separate active plots and for movement of earthmoving equipment. The treatments were:

- Contour ripping to a depth of 300 mm (single bulldozer tyne at 2 m intervals)

- Gravel mulching (50 mm of gravel [> 3 mm] screened from tailings processed with hypersaline water)
- Contour ripping and gravel mulching in combination
- Construction of embankments to harvest water (contour embankments to 1 m at 5 m intervals).

For monitoring purposes, soil samples were collected at six monthly intervals for the first two years. They were collected from depths of 0-200 mm and 200-500 mm from the walls of a sample hole dug by a mini-excavator. Where the treatment included contour ripping, samples were collected from the inside edge of the resulting furrow. One subsample was taken from each of three plots from the same treatments and aggregated. In the embankment treatment, sampling was conducted from the embankment itself initially and, in the fourth round of sampling, from the intervals between the embankments. Sampling of the embankment itself was discontinued thereafter. After seven years, the soils were again sampled as above but with six replicates of each treatment. Soils were typically analysed for $EC_{1:5}$ only throughout, with the exception that SAR (see section 5.2.4) was also determined for the final samples. One-way ANOVAs and Tukey's multiple range tests were used, where applicable, to detect any significant differences between treatments.

Observations on the unassisted revegetation of the treatments were made. Colonisation of some plots occurred arising from wind-blown seeds from low saltbush scrub vegetation north-east of the trial area.

5.2.3 Water ponding trial

A second trial was established in June 1995 to ascertain the value of ponding with suitable waste water. The trial utilised treated sewage water in overflow from the Boulder Sewage Works, operated by the City of Kalgoorlie-Boulder. Approval for the use of the water was given by the Western Australian Department of Health. A typical analysis of the water is shown in Table 5.2. The water used was slightly saline due to the effects of evaporation in the sewage ponds and some mixing with saline groundwater. Gravel utilised in the first trial was not available in sufficient quantities to extend its usage to this trial.

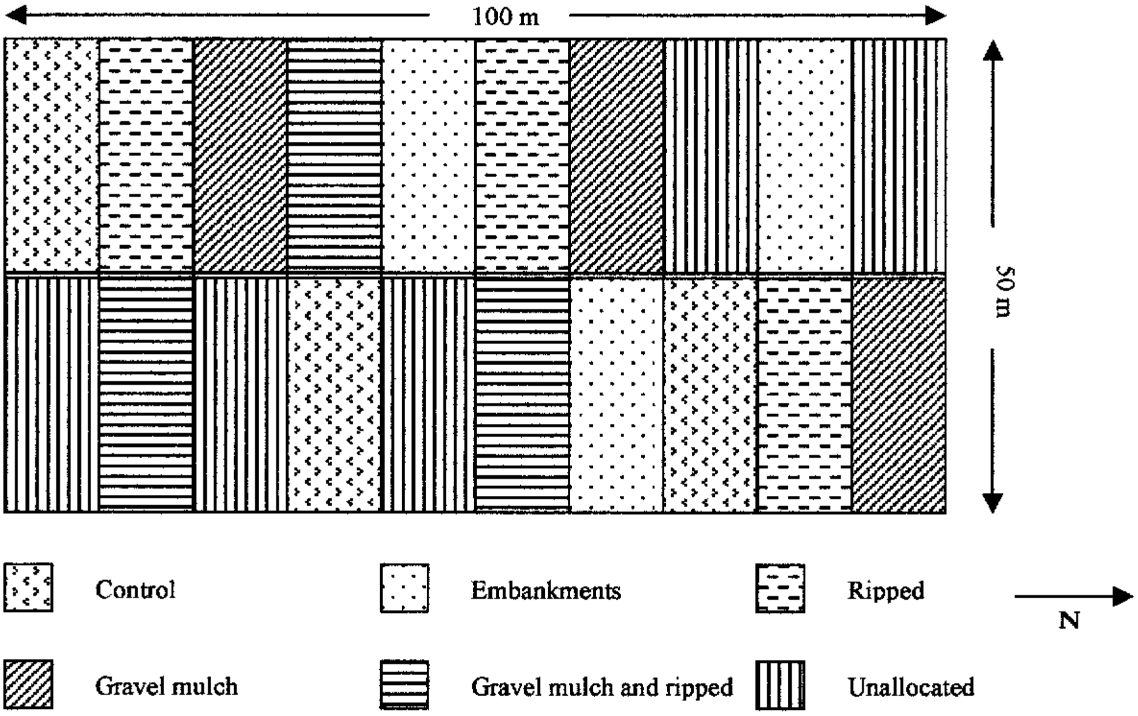


Figure 5.6: Layout of preliminary surface treatment trial commenced in January 1992. The area slopes gently to the south.

An area of 4.5 ha was selected. The natural slope of the area was surveyed and a series of embankments to 0.3 m high was constructed using a grader. The embankments were placed along the natural contours. They ranged from 20 to 120 m in length and were about 30 m apart. They were shaped with the grader cut on the downstream side of the embankment to ensure the area to be ponded maintained the original gradient up to the embankment. The embankments were compacted with the grader tyres using two passes. The intervals between embankments were tyned to a depth of 0.2 m.

A pumphouse and network of pipes were established to draw water from an overflow sump at the sewage works. The water was used to irrigate some of the southern half of the trial. Irrigation was carried out on a semi-continuous basis and was linked to rainfall and to the variable availability of overflow water. Continuous ponding of any area was avoided. Irrigation was conducted by allowing water to flow by gravity from an outlet point at a high elevation and pond against the embankments to depths up to 100 mm. Twenty eight 5 m^2 sample plots were established across the trial with half the plots receiving irrigation water and rainfall (ponded) and half rainfall only (control). The layout of the embankments and the positioning of plots are shown in Fig. 5.7. A large embankment (2 m in height) was constructed at the lowest point of the trial to prevent any offsite discharge of irrigation water. Usage of the water was conditional on the results of a microbial monitoring program that involved regular reporting to the Western Australian Department of Health. Irrigation ceased in September 1996, 15 mo after commencement of the trial.

Table 5.2: Chemical characteristics of treated sewage water used for ponding on areas undergoing rehabilitation (*n* = 3). All units in mg L^{-1} except electrical conductivity (dS m^{-1}), pH and cation/anion ratio. Data from Normandy Kaltails Pty Ltd.

Criteria	Value
Total dissolved solids	1420-2070
pH	7.1-7.6
Electrical conductivity	2.7-3.5
HCO_3	270-450
CO_3	<1
Cl	675-975
SO_4	50-95
NO_3	4.3-40
NH_3	0.6
P	4.6
Na	450-675
K	29-31
Ca	34-45
Mg	49-61
Fe	0.1-0.3
Si	6.5-39
Cation/anion ratio	0.95-1.05

In March 1996 the area was again tyned using a grader and each plot was sown with the seed mix described in Table 5.3. The seed mix comprised halophytic species of *Atriplex* and *Maireana,* commonly used in land rehabilitation in the Eastern Goldfields area (Rusbridge *et al.*, 1996), a local native samphire species, and two exotic species of salt-tolerant grass. Three of the taxa, *A. amnicola*, *M. brevifolia* and *Halosarcia pergranulata* subsp. *pergranulata,* all ranked highly in a study of plants suitable for saltland reclamation (Malcolm and Swaan, 1989) with each showing a high tolerance of saline conditions and moderate to high tolerance of waterlogging. Fertiliser was not used.

Table 5.3: Seed mix applied to plots within the water ponding trial area in March 1996. *Halosarcia pergranulata* subsp. *pergranulata* was applied as a mulched material containing seed. All other application rates are for propagules only.

Species	Common name	Application rate (kg ha^{-1})
Atriplex codonocarpa P.G. Wilson	Bell saltbush	1.0
A. holocarpa F.Muell.	Pop saltbush	1.0
A. amnicola P.G. Wilson	River saltbush	1.0
Halosarcia pergranulata subsp. *pergranulata* (J.Black) P.G. Wilson	Black-seeded samphire	1.0
Maireana brevifolia (R.Br.) P.G. Wilson	Small-leaf bluebush	0.5
Puccinellia ciliata Bor cv. Menemen	Saltmarsh grass	0.5
Thinopyrum elongatum [Host] Beauv.	Tall wheatgrass	0.5
	Total	5.5

Soil sampling was conducted in June 1995 at the commencement of the trial and after 1 and 2.5 y, with additional samples for electrical conductivity only collected after 0.5 y. Samples were obtained by trowel as a uniform column of soil to a depth of 100 mm. Three subsamples were collected from each plot on a regular grid pattern and aggregated. In November 1996, four widely-spaced plots from across the trial area were selected for examination of intra-plot variability in soil electrical conductivity. Sixteen points were sampled as above at a regular grid spacing of 1 m within each of the four 5 m^2 plots. Where applicable, one way ANOVAs and Tukey's multiple comparison tests were used to detect differences between treatments and over time. Differences regarded as significant are at the $p > 0.05$ level. All analyses were undertaken using Analyse-It v.1.5 software (Analyse-It Software Ltd, Leeds, UK).

Vegetation cover was assessed in each plot in spring 1996 (at the end of the irrigation period) and spring 1997 (one year after irrigation ceased). Within each plot, the cover for each plant species and the total cover were classified according to the following Braun-Blanquet scale, as given in Kershaw (1974):

1 = sparsely or very sparsely present; cover very small
2 = plentiful but of small cover value
3 = very numerous, or covering at least 1/20 of the area
4 = any number of individuals covering ¼ to ½ of the area
5 = any number of individuals covering ½ to ¾ of the area
6 = covering more than ¾ of the area

Species richness for each plot was also recorded. Differences in vegetation cover and species richness between treatments and over time were assessed using Mann-Whitney tests. Spearman Rank correlations were used to assess the relationships between EC_e, and vegetation cover and species richness.

5.2.4 Soil analyses

Wesfarmers CSBP Ltd performed all soil analyses. Soils were dried for 24 h at 105°C. For full analyses, soils were analysed for extractable/available P (Bray no. 2, molybdenum blue colorimetry), NO_3 (ion electrode), NH_4 (extracted with 1 mol L^{-1} KCl; indophenol blue colorimetry); Na, Ca and Mg (extracted with 1 mol L^{-1} NH_4Cl; atomic absorption spectrophotometry), pH (1:5 dilution in deionised water) and organic carbon (chromic acid digestion, colorimetry against glucose).

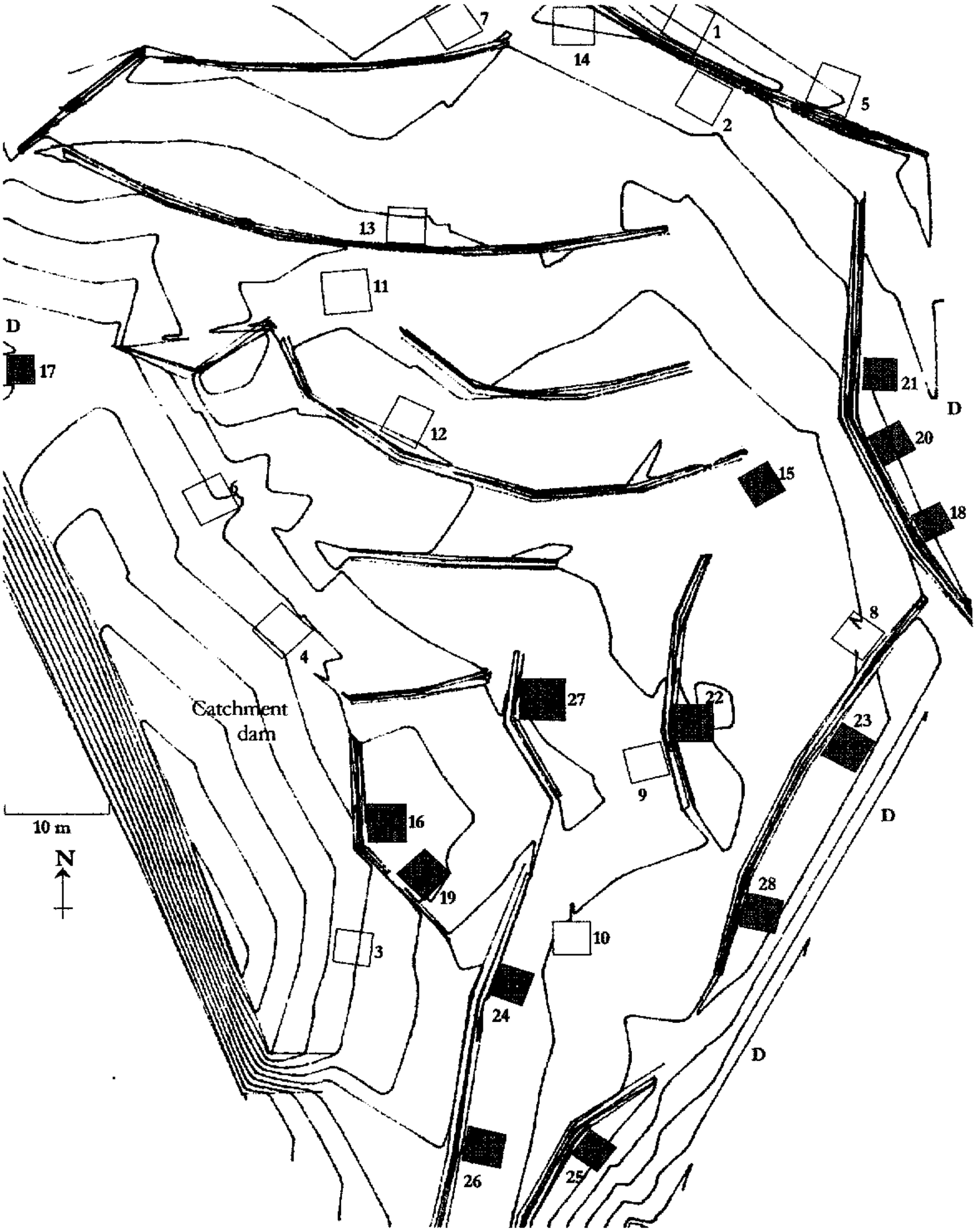


Figure 5.7: Layout of embankments and plots for water ponding trials. Contours shown are 0.5 m with area sloping from east to west. Water flowed from discharge points (D) to pond against embankments with excess water held in the catchment dam. Ponded plots are shaded, control plots unshaded.

Although extracts of the soil solution provide a better estimate of salinity, there are practical difficulties associated with its determination that make it prohibitive for routine use (Richards, 1954). Alternatively, electrical conductivity (EC) for each sample was determined as a 1:5 dilution in deionised water. All $EC_{1:5}$ values were converted to EC_e (saturated extract equivalents) using the conversion factor (9.5) calculated by Slavich and Petterson (1993) on the basis of the soils being of a silt loam texture with a saturation percentage (θ) estimated to be in the range 0.41-0.46 kg kg^{-1}. Sodium adsorption ratios (SAR) were calculated using the formula:

$$SAR = Na/[(Ca+Mg)/2]^{0.5}$$

All Na, Ca and Mg values are expressed in meq 100 g^{-1}.

Soil moisture was not recorded as sampling took place during intervals between periods of ponding, or after ponding was complete, and would not reflect values that may have occurred during or soon after ponding.

5.3 Results

5.3.1 Initial surface treatment trial

Monitoring over the first 2.5 y showed strongly seasonal trends in soil electrical conductivity in the ripped, ripped and mulched, and embankment treatments with surface soil values rising in summer and falling in winter (Fig. 5.8). The control and the mulch treatment showed little response to seasonal changes. Seasonal trends were less obvious in the subsoils (Fig. 5.9). Excluding seasonal effects, neither the treatments nor controls initially showed any trend towards change over time. After seven years, however, all treatments showed lower mean surface soil and subsoil EC_e values than the control although only the intervals between embankments were significantly lower ($p <$

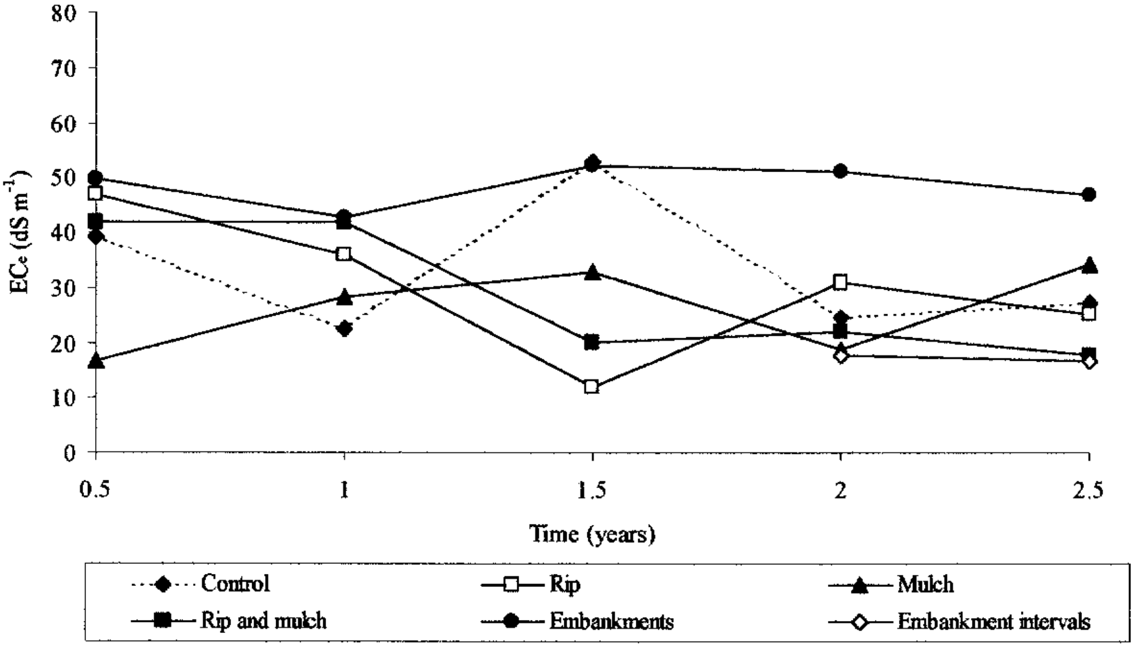


Figure 5.8: Electrical conductivity (EC_e) values in various treatments in surface soils (0-200 mm) for 2.5 y after commencement of the preliminary surface treatment trial in January 1992.

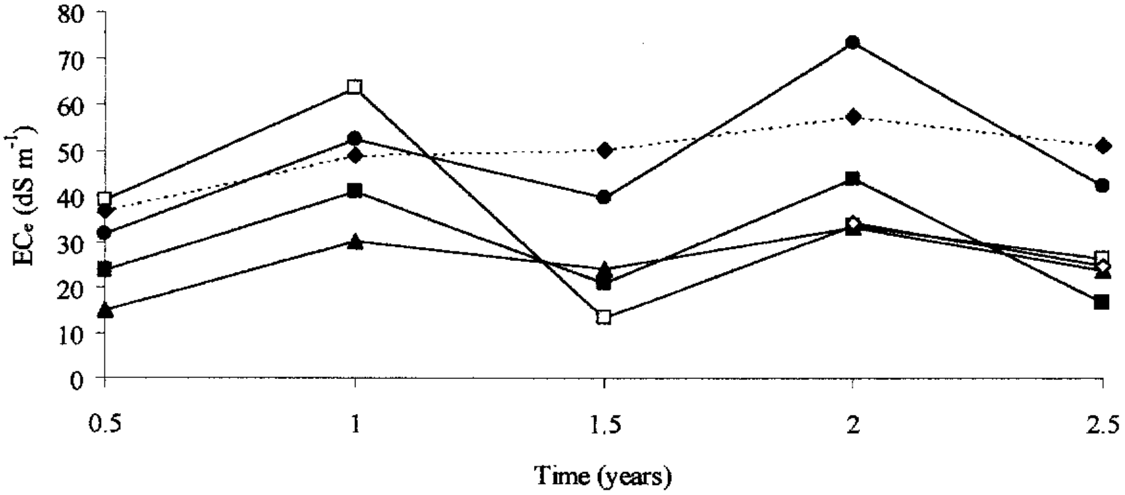


Figure 5.9: Electrical conductivity (EC_e) values in various treatments in subsoils (200-500 mm) for 2.5 y after commencement of the preliminary surface treatment trial in January 1992. Legend as for Fig. 5.8.

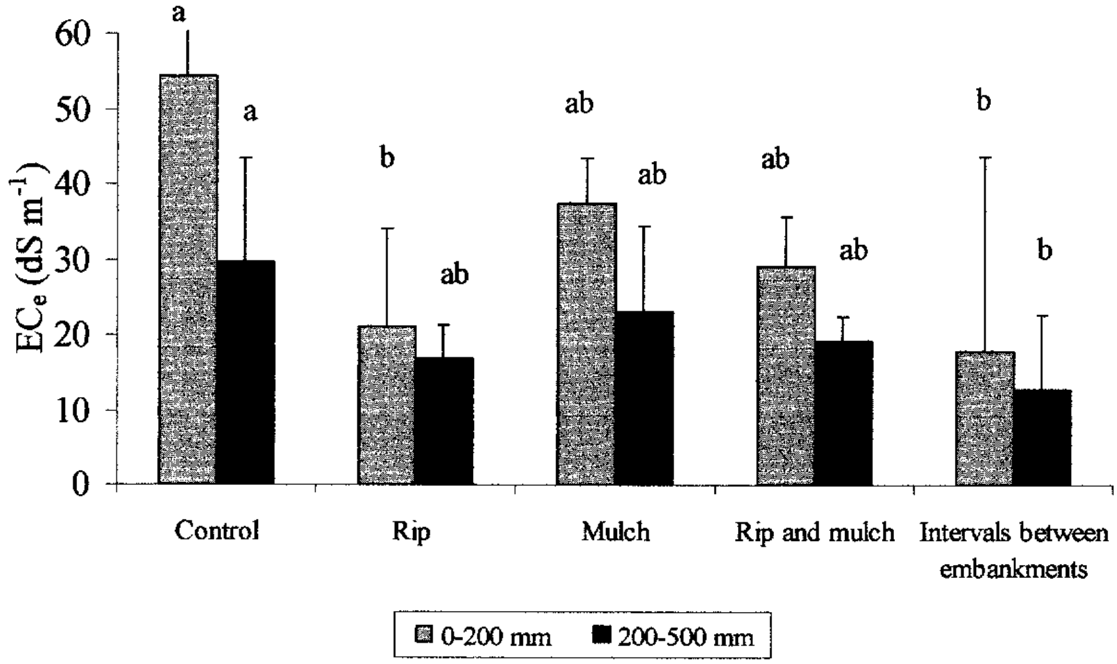


Figure 5.10: Mean (± SE) soil electrical conductivity (EC_e) in preliminary surface treatment trial after 7 y. Letters indicate significant differences ($p < 0.05$) between treatments ($n = 6$) as determined by one-way ANOVA and Tukey's multiple comparison tests.

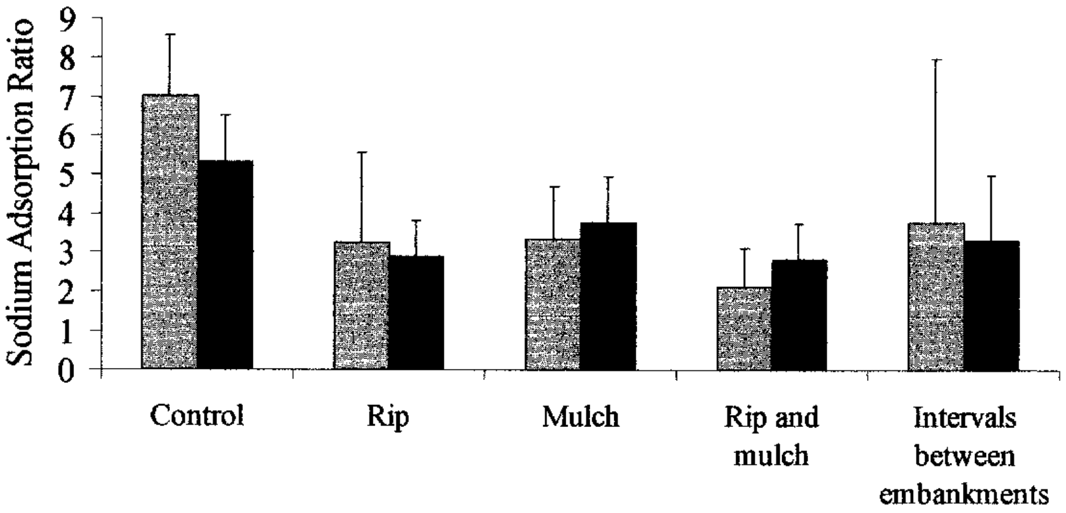


Figure 5.11: Mean (± SE) sodium adsorption ratio (SAR) values in soil profile of preliminary surface treatment trial after 7 y. There was no significant difference between values (one-way ANOVA). Legend as for Fig. 5.10.

0.05) for both surface and subsoils (Fig. 5.10). Sodium adsorption ratio (SAR) values were also lower than the control (Fig. 5.11) although these differences were not significant.

During the 7 y period of the trial, colonisation of the areas by native vegetation occurred through wind-blown seeds. Several halophytic species formed substantial cover over portions of plots on the north-eastern corner of the trial. These species included the chenopods *Atriplex stipitata*, *A. nummularia*, *A. vesicaria*, *Maireana pentatropis* and *Sclerostegia disarticulata*. Other colonizing species included *Lawrencia glomerata* and *Zygophyllum auranticum*.

5.3.2 Water ponding trial

A total of 310.8 mm of rainfall was recorded during the 15 mo period over which ponding was conducted. All ponded areas each received an estimated average of 1050 mm of waste water during the same period with ponding occurring for 20-60% of the time depending on water availability and plot location. In addition to waste water and direct rainfall, plots 16, 19, 23 and 28 received rainfall runoff from the immediate catchment area. Very little water ponded on control plots due to the limited rainfall during the trial period and small individual catchment sizes.

Most soil chemical characteristics did not change significantly with the ponding treatment or with time. Trends in pH, EC_e and SAR are shown in Fig. 5.12. Small decreases in soil pH occurred over the course of the experiment in the control plots but not in the ponded plots. Soil pH in all plots, however, remained between 7.9 and 8.9 throughout the trial. For soil EC_e, significant seasonal effects were recorded where EC_e was higher in summer and lower in winter. There was, however, no significant overall trend detected over time in either the control or ponded plots. Detailed sampling in some plots (Fig. 5.13) suggested that intraplot variability was high with values commonly ranging 60 dS m^{-1} within plots. SAR showed an overall rising trend in both the control and treated plots.

Among the soil nutrients (Fig. 5.14), only P showed a significant rising trend in response to the ponding treatment. Levels of soil P suggest the large majority of P in waste water (Table 5.2) was captured within the top 100 mm of ponded soils. Nitrogen (as NH_4) showed an increase after the first year in both the control and ponded plots but had declined again after 2.5 years. Nitrogen (as NO_3) showed an increase in the control plots after 2.5 years but otherwise there were no significant differences. A minor increase in the organic C content occurred in the ponded plots but after 2.5 years these plots were still not significantly different from the control plots.

In contrast to the relatively few differences in soil chemical characteristics, the mean vegetation cover value and species richness in the ponded plots was significantly greater than the control plots in both 1996 and 1997 (Fig. 5.15). Sixteen mo after seeding, the mean vegetation cover value for ponded plots was 2.57 compared with 0.46 for the control plots. Similarly, mean species richness was 4.29 for the ponded plots and only 0.62 for the control plots. *Halosarcia pergranulata* subsp. *pergranulata* and *Atriplex lindleyi* commonly occurred in ponded plots with some large individual *A. amnicola* shrubs giving substantial cover. All *Atriplex* spp. flowered and fruited heavily during the course of the trials and most of the other species recorded also flowered and set seeds. It was evident during the collection of soil and vegetation samples that deeper (50-100 mm), more frequent (continuous standing water for periods of 3-5 days) ponding favoured establishment of *H. pergranulata* subsp. *pergranulata* while shallow, less frequent ponding favoured establishment of *Atriplex* spp. and others (G. Barrett, pers. observ.).

Details of species occurrence by plot are given in Table 5.4. Sixteen mo after seeding, over half of the control plots still had no vegetation cover compared with only one of the 14 ponded plots. Over all plots, both vegetation cover ($r_s = -0.52, p < 0.01$) and species richness ($r_s = -0.52, p < 0.005$) were negatively correlated with EC_e (Fig. 5.16). The cessation of ponding did not appear to lead to any decline in the vegetation established,

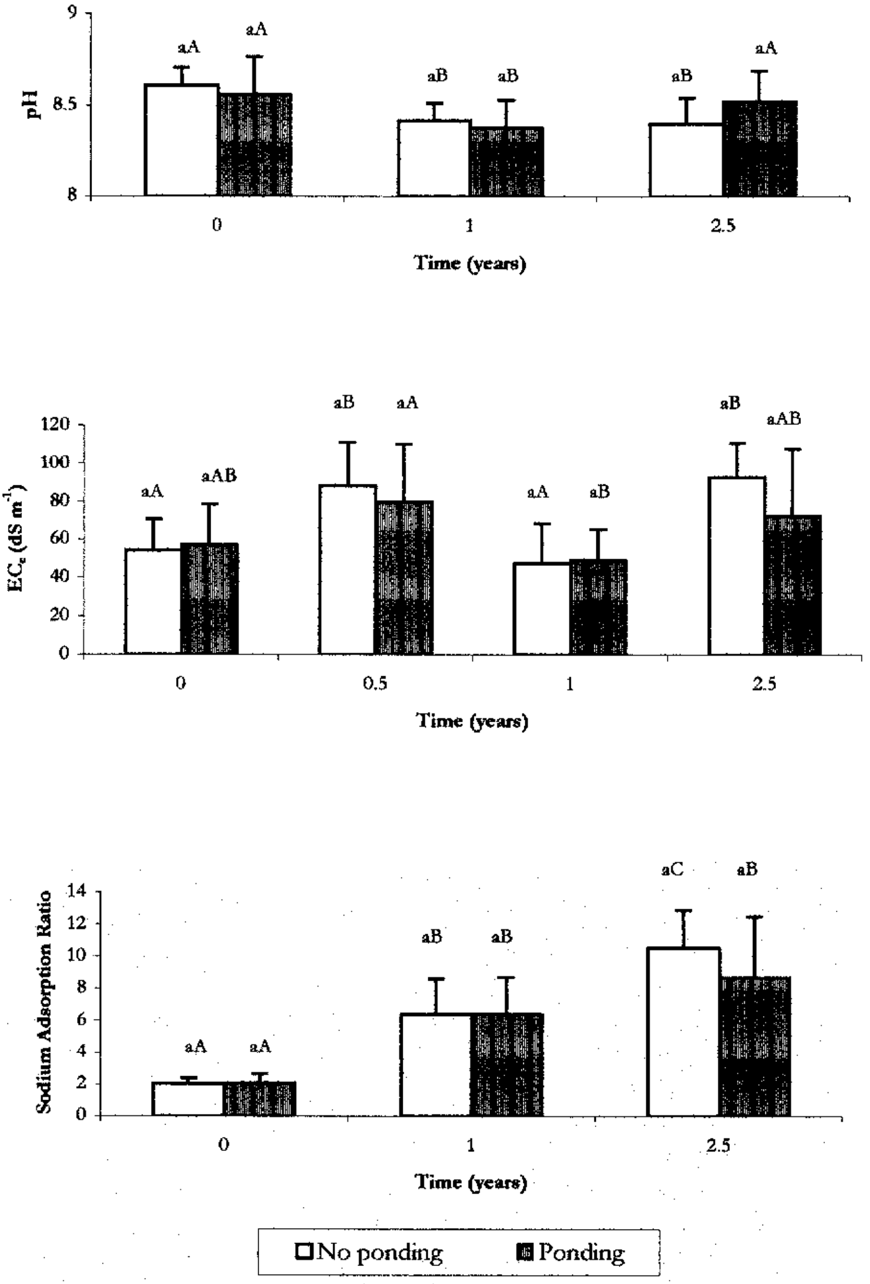


Figure 5.12: Variations in mean (± SE) values for pH, EC$_e$ (saturated soil extract equivalents) and sodium adsorption ratio (SAR) in the water ponding trial. Significant ($p < 0.05$) differences between treatments (lower case) and between samples over time (upper case) are as determined by one-way ANOVA and Tukey's multiple comparison tests.

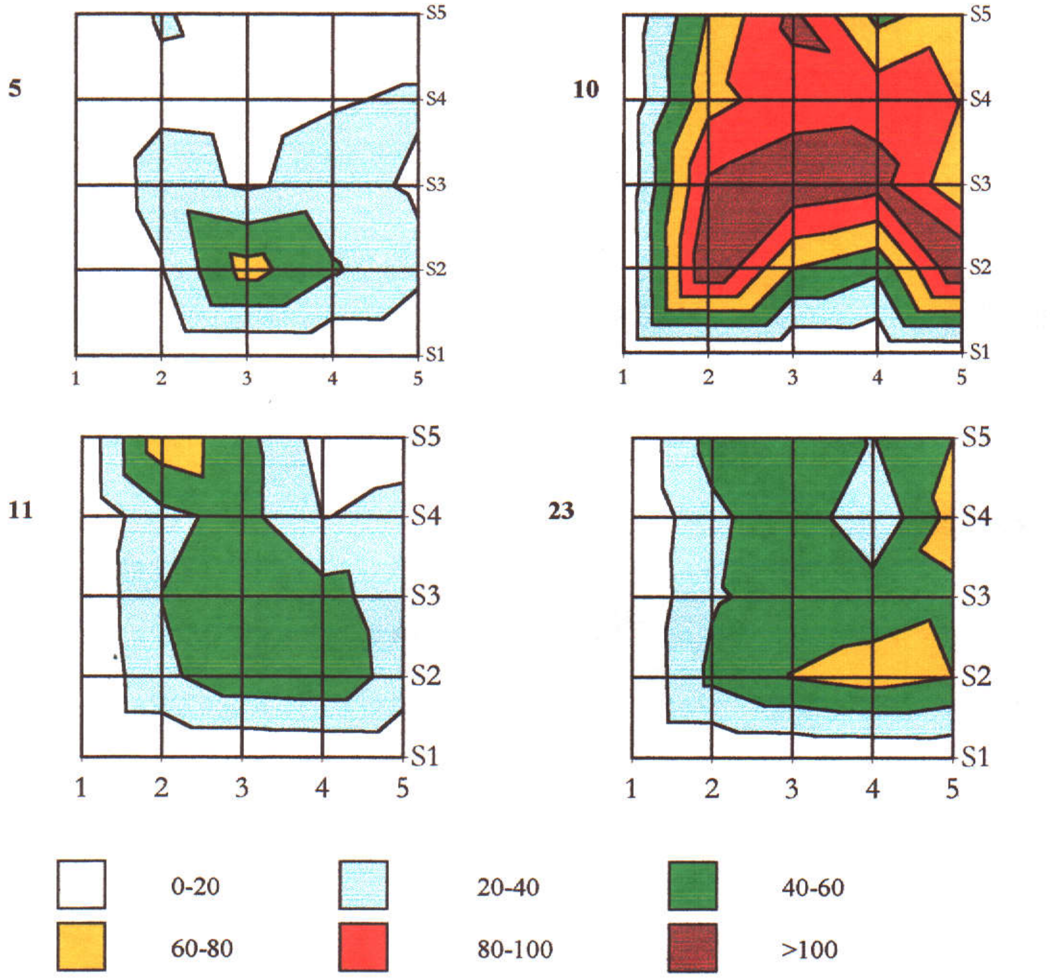


Figure 5.13: Contour maps showing patterns of soil EC_e ($dS\ m^{-1}$) in plots 5, 10, 11 and 23. Smallest grid units are 1 m^2. Soil samples were collected in November 1996. Of the plots selected, only plot 23 had received supplementary water.

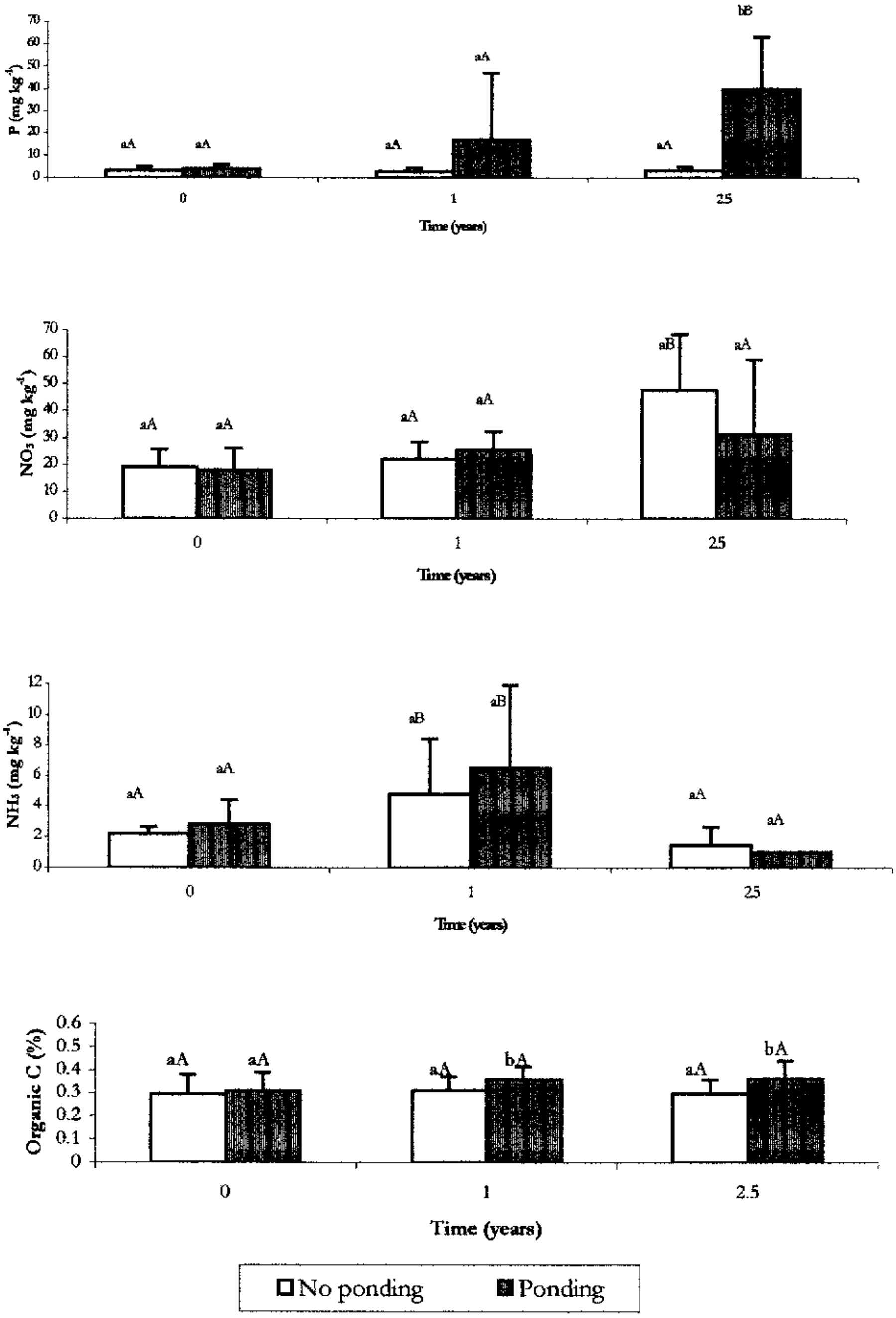
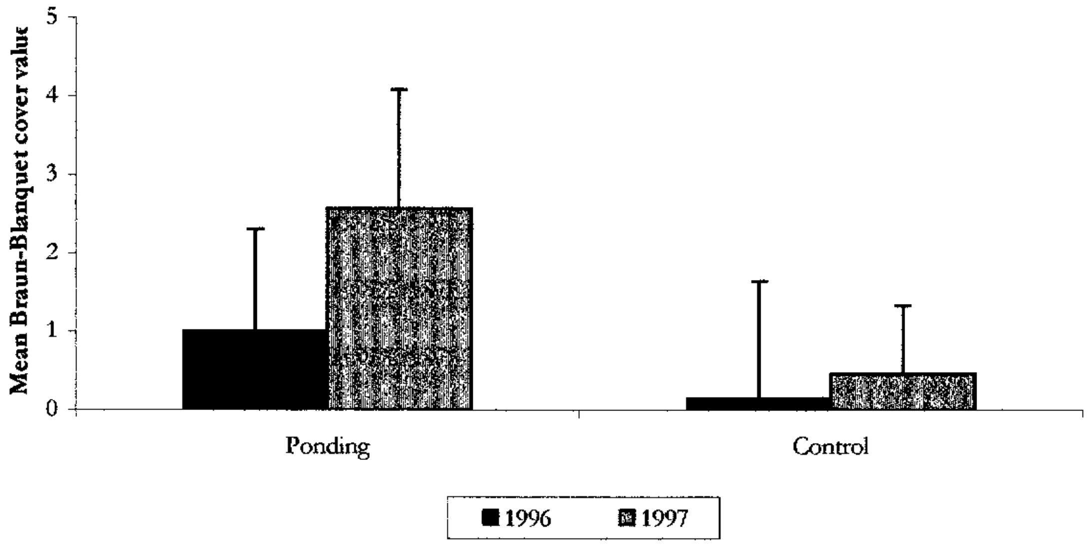


Figure 5.14: Mean (± SE) variations in P, NO_3, NH_4 and organic C content in soils from water ponding trial. Significant ($p < 0.05$) differences between treatments (lower case) and between samples over time (upper case) are as determined by one-way ANOVA and Tukey's multiple comparison tests.

Table 5.4: Braun-Blanquet vegetation cover values (1-6) for plots in water ponding trial for 1996 and 1997. Plots 1-14 are controls (no ponding) and plots 15-28 were treatments (ponding). No data for plot 2 in 1997. Asterisks indicate exotic taxa.

		1996																												
Taxa	Plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Atriplex amnicola						1																		3	4		3		1
A. codonocarpa						1								1															
A. holocarpa																												
A. lindleyi																								1			1		1
A. nummularia																												
A. stipitata																												
A. suberecta																												
A. vesicaria																												
*Conyza albida**																												
Frankenia sessilis																					1									
Halosarcia pergranulata subsp. *pergranulata*																	1			2	1		1				1		
Maireana brevifolia						1																							1
M. pentatropis																												
M. tomentosa																												
*Mesembryanthemum nodiflorum**																												
*Puccinellia ciliata**																	1			2								1	
*Spergularia rubra**																												
*Thinopyrum elongatum**																									1		1		
Zygophyllum auranticum						1																							
	Total					1								1			1			2	1		1	3	4		3	1	1

		1997																												
Taxa	Plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Atriplex amnicola						3											2			1				3	6		4		3
A. codonocarpa						1																		1		1		1	
A. holocarpa																				1									
A. lindleyi																	3	2	3	3	3	1	1	2	1	1	1		2
A. nummularia						1								1															
A. stipitata																								1					
A. suberecta																									1		1		
A. vesicaria												1																		
*Conyza albida**																					1									
Frankenia sessilis																					1									
Halosarcia pergranulata subsp. *pergranulata*					1												1	1	1	3	1		3	1	1	1	1	1	2
Maireana brevifolia																							1	1	1	1	1		2
M. pentatropis						1																						
M. tomentosa																		1										
*Mesembryanthemum nodiflorum**																	1			1				1			1		1
*Puccinellia ciliata**																				1						1		1	
*Spergularia rubra**																				1			1			1			1
*Thinopyrum elongatum**																									1				1
Zygophyllum auranticum						1																						
	Total				1	3						1		1			3	2	3	3	3	1	3	3	6	1	4	1	3



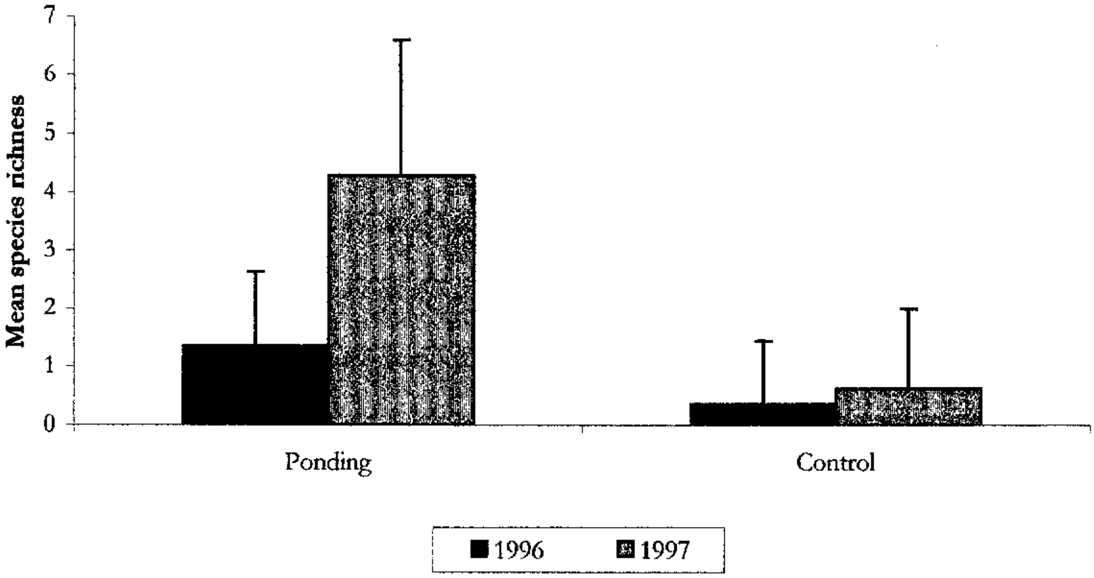


Figure 5.15: Mean Braun-Blanquet vegetation cover values and species richness for plots in the water ponding trial in spring 1996 and 1997.

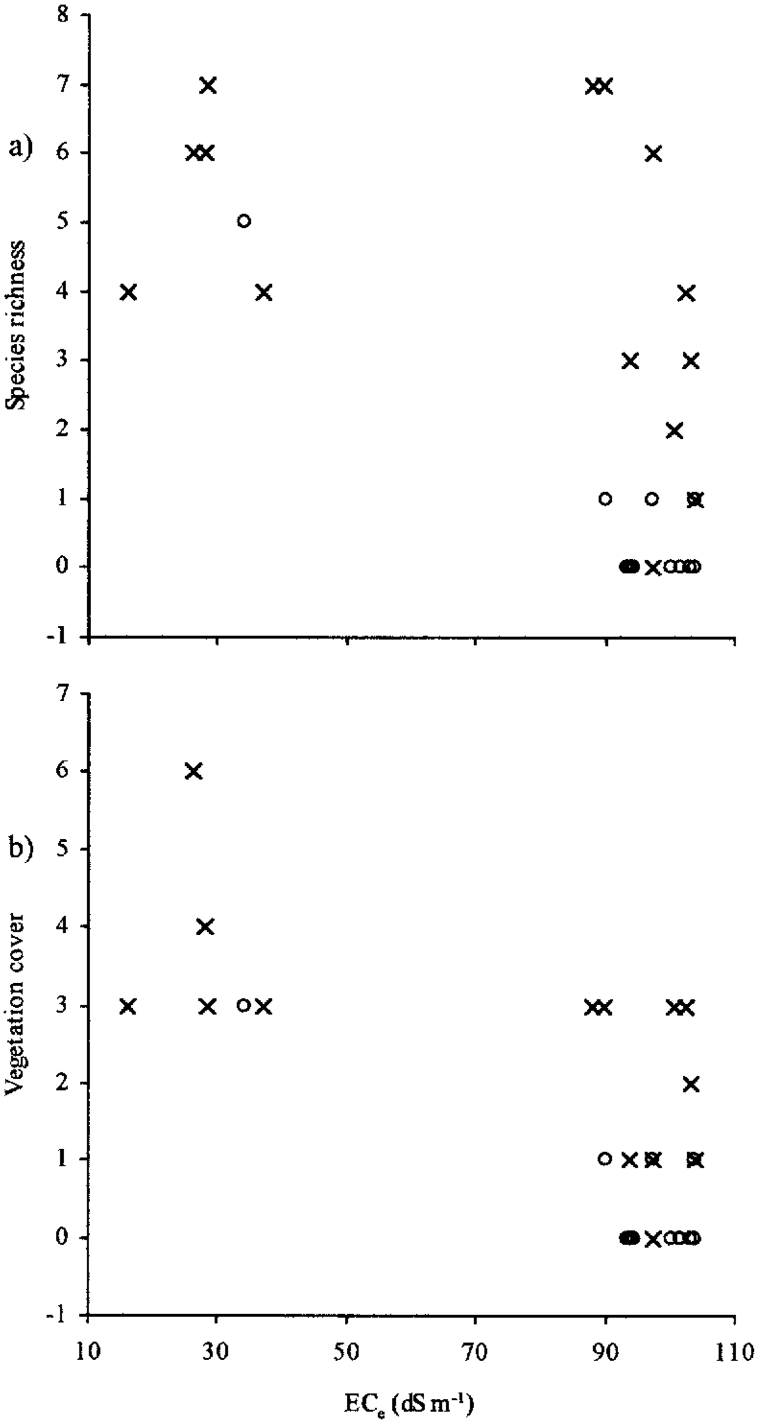


Figure 5.16: Relationship between soil EC_e and a) species richness ($r = -0.52$, $p < 0.005$, $n = 27$) and b) vegetation cover ($r = -0.52$, $p < 0.01$, $n = 27$). Vegetation cover values follow Braun-Blanquet (see 5.2.3). Data points indicate ponded plots (×) and plots without ponding (o).

as evidenced by the results from the 1997 field work and in subsequent brief inspections up to 1999 (G. Barrett, pers. observ.).

5.4 Discussion

Old gold mine tailings near Kalgoorlie-Boulder, Western Australia, have been removed for retreatment using high-pressure hypersaline water. This has exposed the underlying alkaline silt loam soil after up to 60 years of coverage by the tailings. The removal process, however, has left them highly saline ($EC_e > 50$ dS m^{-1}) and resistant to revegetation. In this research, surface treatments were examined that would potentially ameliorate soil conditions and promote a sustainable vegetation cover.

A major focus of the studies conducted here was the response of soil salinity, as determined by electrical conductivity (saturated extract equivalent) (EC_e), to various treatments. Some preliminary remarks on the use of EC_e as a key indicator of soil salinity, however, are appropriate. While EC_e provides a ready and convenient means by which to assess the salinity of soils (Richards, 1954), some authors have urged caution in relating EC_e values to the soil environment in which plants must establish and grow. Álvarez-Rogel *et al.* (1997) showed that the relationship between EC and TDS (total dissolved solids) declined at high (> 60 dS m^{-1}) EC due to the variable effects of different ions. Nadler (1997) concluded that EC_a (bulk soil EC) did not provide a good estimation of EC_w (EC of soil water) above 5 dS m^{-1} and his findings are supported by those of Kohut and Dudas (1994) who noted that saturated paste extracts have lower conductivities than immiscibly displaced soil solutions. Many of these differences relate directly to the reduced solubility of some salts in relation to others. In this respect, the soils from this study are dominated by the highly soluble NaCl and therefore the relationship between EC_e and related parameters is likely to be stronger than in soils dominated by Ca or SO_4 ions. In any event, this study examined differences in EC_e arising from the treatments and it is the differences that are more important than the absolute values, with which some caution must be exercised.

In addition to the above qualifications, data collected within this study showed evidence of significant variation in soil EC over small distances. Soil chemical heterogeneity can be statistically as large within the span of a single plant as in an entire vegetation stand (Caldwell, 1999) and spatial variability in saline soils can mask treatment effects (Semple and Koen, 1998). This was, to some degree, overcome by the collection and aggregation of subsamples, but high intraplot variability was a consideration in the interpretation of the data. A further factor affecting the analysis of the data was the strong seasonal effects in surface soils. All trials showed strong seasonal effects with EC_e rising in summer, when high temperatures and evaporation occur, and declining in winter when conditions are much more favourable for moisture retention (see Fig. 5.4). This is a common phenomenon occurring in saline soils (Smith and Stoneman, 1970) and is likely to be more pronounced in zones of lower salinity (Álvarez-Rogel *et al.*, 1997).

In the preliminary trials, a range of soil treatments, including ripping and gravel mulching, all reduced EC_e over seven years while the bare soil control remained in excess of 50 dS m^{-1}. The fall in EC_e in the treatments is likely to be due to the improved capture and subsequent infiltration of rainwater compared with bare soil. Little water infiltration appeared to occur in bare soils, despite above average rainfall during the trial period (including two large rainfall events in early 1992 and 1995). In a similar observation, Tromble (1983) showed barren soils in New Mexico, USA, remained dry even after heavy rain. Elsewhere, where rainfall can be at least partially retained on areas to be rehabilitated, falls in soil salinity have occurred. Reclaimed scalds in central western New South Wales, for example, have shown an eight-fold decrease in soil salinity where ponding banks have been used to prevent runoff (Jones, 1969). In some instances, however, earthworks may be required to not only capture all rainfall but to concentrate it onto only a portion of the affected area. The embankments utilized in the preliminary trial concentrated water between the each windrow and it was in the intervals between windrows that the lowest EC_e (< 18 dS m^{-1}) values were recorded at the conclusion of the trial. A similar approach has been used in arid areas of Pakistan where small bare soil aprons were used to promote soil moisture and forage establishment in an equivalently sized area, resulting in a greater overall forage establishment (Suleman *et al.*, 1995a, 1995b).

In some instances, earthworks and rainfall alone may still be insufficient to achieve particular vegetation objectives. Lyles and Allen (1966), for example, conducted trials on 'islands' of saline soils that were higher in elevation and clay content that the surrounding soils. The 'islands' were levelled and some water harvesting, or 'dyking', employed to reduce salt levels in the upper 900 mm of soil. Natural rainfall (around 500 mm annually) over several years, however, was not sufficient to remove and maintain soluble salts at a low level. Also in the USA, saline and alkaline spent oil-shale could only be rehabilitated and revegetated after leaching with low salt water (Scheml and McCaslin, 1973). In the water ponding trial conducted as part of this study, supplementary water from a waste water scheme significantly enhanced the establishment and growth of vegetation compared with areas which received rainfall only. In plots ponded with sewage water, however, EC_e had not significantly declined after 2.5 years and, of other soil parameters measured, only P was significantly increased by the treatment. The failure of EC_e to decline in surface soils of the water ponding experiment, while a decrease occurred in the preliminary surface treatment trial, may be attributable to the shorter duration and the use of slightly saline water in the water ponding trial. Leaching of salts, however, can be very slow as the bulk of them may be contained within soil aggregates (Armstrong *et al.*, 1998) and ponded water infiltrating the soil along preferred pathways may not sufficiently permeate the aggregates to dissolve and convey salts downwards.

Soil N did not accumulate in soil as a result of the effluent ponding. Plants may have taken up some N and ammoniacal-N can be lost rapidly from ponded effluent through volatilization (Smith *et al.*, 1996). The concentration of soil P, however, did rise in ponded soils. Yet soil P alone is unlikely to result in such a difference in vegetation establishment. It can only be attributable to the increased soil moisture resulting from the ponding treatment. Even though no measurable decrease in EC occurred in dried soil samples, the additional water would have temporarily reduced the EC of soil water, effectively elevating and prolonging the P/E_p ratio during the critical period, such that germination and establishment could occur widely. Substantial germination, even of halophytic species, would not normally occur above soil EC_e values of 16 (Chapter 2). Soil moisture requirements could be expected to be at least that of the calcareous silty clay rangelands in Jordan, where germination does not occur below 25% soil moisture (Abu-Irmaileh, 1994), and would probably need to be higher to compensate for the reduced soil water potential arising from the high soil salinity. Once established, some plants colonizing highly saline soils are able to preferentially exploit intermittent sources of low salinity water, even when the bulk of soil water is hypersaline (Yakir and Yechlell, 1995). Soil moisture can be a critical determinant of plant establishment and survival, and topographical differences within an area can have a substantial impact on the availability of soil water to plants (Coronato and Bertiller, 1996).

Soil sodicity, as determined by SAR, rose during the course of the water ponding trial, irrespective of whether the plots were treated. While the values remained below the generally accepted critical limit of 13 (Sumner, 1995), the rising trend and the presence of illite in local soils (Chemistry Centre of Western Australia, 1991) suggests that there is some potential for sodicity to occur in the future if soil EC is substantially reduced over time. In laboratory leaching trials using deionised water and soils from the preliminary trial area, hydraulic conductivity in a soil of moderate EC_e (11.4 dS m^{-1}) was less than 1% of that in a soil of high EC (35.2 dS m^{-1}) (Kibblewhite, 1995). The prospect, however, of significant future leaching of NaCl from soils appears unlikely given the results to date, although the level of soil sodicity recorded could be understated as any sodic crusts that had formed would be diluted by other soil across the range of 0-100 mm sampled. Should soil sodicity result, however, it could be alleviated by the application of gypsum (Gupta and Abrol, 1990; Qadir *et al.*, 1996).

The successful establishment of halophytic vegetation may in itself reduce surface soil EC_e levels, at least initially, through reduction of evaporation by shading of the soil surface and through active uptake of salts into plant tissues. Breshears *et al.* (1998) showed the vegetation canopy of woodland soils in a semi-arid climate to have a marked impact on microclimate and a positive effect on plant-available water and other factors important for plant establishment and survival. With regard to the uptake of salts by plants, de Villiers *et al.* (1995b) showed *Mesembryanthemum barklyi* can accumulate almost 200 kg ha^{-1} of NaCl and Zhao (1991) recorded a soil salinity reduction of up to 6.7% using *Suaeda salsa*. Unless the plants are removed, however, NaCl and other salts are returned to the soil as plant tissues break down. At the study site described herein, vegetative removal of NaCl from the soils at a rate similar to that determined by de Villiers *et al.* (1995b) would amount to only about 1% of the NaCl load in the top 0.5 m of soil. Vegetative removal, therefore, does not represent a practical option for significantly reducing the soil NaCl content. A likely impact of halophytic vegetation, however, is a redistribution of NaCl in the soil such as that described by Sharma and Tongway (1973) in relation to *Atriplex* spp. whereby salts are drawn from areas around plants ("compensation zones") to be eventually deposited beneath the canopy as dehiscent plant material breaks down ("accumulation zones"). This process may promote colonization of compensation zones by other species. Mahmood *et al.* (1994) showed that kallar grass (*Leptochloa fusca*) on saline wastelands in Pakistan reduced soil pH, salinity and sodicity and increased soil N, allowing other species to colonise kallar grass areas.

In my study, the better performed species included two, *Atriplex amnicola* and *Halosarcia pergranulata* subsp. *pergranulata*, listed by Malcolm and Swaan (1989) as the most suitable for the revegetation of salt-affected agricultural land in Western Australia. *A. lindleyi*, probably introduced to the trial erroneously as *A. codonocarpa*, was also very common where supplementary water was applied. The vegetation patterns within individual ponded plots appeared to be significantly affected by differences in ponding depth and duration. The preference of *H. pergranulata* subsp. *pergranulata* for greater depths and longer periods of ponding was expected given the natural distribution of the species along saline drainage lines (Short and Colmer, 1999) and its ability to form aerenchyma during periods of inundation (T.D. Colmer and J. English, pers. comm.). *A. amnicola* can also tolerate a degree of waterlogging under saline conditions (Galloway and Davidson, 1993). Other species occurring in the ponded areas but not included in the seed mix were likely to have been introduced either by wind dispersal or in the ponding water.

In conclusion, any severely saline and disturbed fine textured soils in semiarid or arid areas will not be easily revegetated. Any earthworks that encourage the retention and infiltration of water, however, are likely to improve the prospect of establishing halophytic vegetation. Indeed, soil moisture appears to be a key factor in determining the success or otherwise of revegetation efforts, and its maximization should be a major consideration in the design of earthworks for rehabilitation of highly saline soils. This may need to extend beyond the use of contour ripping and furrowing commonly utilized in mine rehabilitation (Fletcher *et al.* 1989; Department of Minerals and Energy, 1996a) because it may spread water too widely to be effective in highly saline soils and can lead to soil erosion if not properly designed (Macdonald and Melville, 1999). Finally, a range of native halophytic plant species is suitable for use under highly saline conditions.

6.0 USE OF CAPILLARY BREAKS TO INHIBIT RISE OF SALTS INTO A SOIL COVER OVER HYPERSALINE GOLD MINE TAILINGS

6.1 Introduction

In Western Australia, it is a legislative requirement that mine tailing surfaces be stabilized and erosion-resistant when a tailings storage facility is closed (Department of Minerals and Energy, 1996b). Due to the widespread usage of hypersaline ground water in mineral processing in the Eastern Goldfields region (Turner *et al.*, 1993), final tailing surfaces are often highly saline, such that direct revegetation is extremely difficult, if not impossible, especially as semiarid to arid conditions prevail. There is a need to develop cost-effective soil or rock covers for tailing storages that, for surface stability and aesthetic reasons, should be able to support a sustainable vegetation cover (Barrett *et al.*, 1992). A cover, therefore, should be resistant to the capillary rise of salts that could potentially occur from the underlying tailings and adversely impact on the establishment and survival of vegetation.

Few data exist on the design requirements for covers over highly saline materials such as hypersaline tailings. There is, however, a considerable body of research on covers for other toxic materials such as acid-producing mine waste and waste stored in landfills (eg. Colorado State University, 1996; Dunn and Singh, 1995; Caldwell, 1992). Covers of up to 190 cm may be required to prevent the rise of salts (White and de Jong, 1975), or an intermediate layer which forms either a physical or capillary barrier can be used (Ritcey, 1989; Dean *et al.*, 1973). The intermediate layer can be compacted clay, sand or a synthetic material (Tordoff *et al.*, 2000) or, alternatively, quantities of mine waste with suitable physical properties may be available (eg. Podhajsky, 1990). The availability of such materials is a major consideration for cost-effective rehabilitation. Over a hypersaline surface, salt weathering of rocks (Goudie, 1989) that are incorporated in a cover should be considered, as should natural weathering of unoxidised rock material.

This study examined the effect of capillary breaks on the rise of salts from a hypersaline tailing surface into a topsoil cover that was capable of supporting a sustainable vegetation cover.

6.2 Materials and Methods

6.2.1 Study site

The study site was at a gold tailings retreatment facility at Lakewood, immediately south-east of Kalgoorlie-Boulder, Western Australia (30°45'S, 121°28'E) (Fig. 1.1). Kalgoorlie-Boulder receives an average annual rainfall of 256 mm that is spread over the year. Evaporation averages 3000 mm annually. Temperatures can range from a summer maximum of 46°C to a winter minimum of -3°C (unpubl. data, Climate and Consultative Services, Bureau of Meteorology).

Once reprocessed, gold tailings are stored in a 250 ha tailings storage facility. A small trial storage facility with a surface area of 0.24 ha and a depth of 3 m was constructed adjacent to the main facility and filled with hypersaline gold tailings. All supernatant water was removed and the surface of the tailings was allowed to dry out. After drying, a visible salt crust (~1 mm thick) formed over the surface.

6.2.2 Surface capping trial

Trial plots utilizing topsoil as a cover material and two types of capillary break (nickel slag and synthetic membrane) were established in April 1996 as described in Table 6.1. Each plot was 4 m by 3 m with three replicates of each treatment. Topsoil and nickel slag were placed across the tailings surface using a bobcat. The synthetic membrane was laid across the surface and anchored with steel pegs prior to coverage with topsoil. Physical and chemical characteristics of the topsoil and tailings are given in Table 6.2.

Each plot, including the bare tailings, was planted with three seedlings of *Atriplex amnicola* P.G. Wilson (River saltbush). The seedlings were raised in river sand in 0.25 L pots and were 6 mo old when planted. Each seedling, with the soil from the pot, was planted about 1 m apart within each plot and watered weekly with 2 L of tap water for 6 months. A shallow 'dish' of an approximate diameter of 0.3 m was created around each seedling at planting to ensure the water was retained. Survival of the seedlings was recorded and, after 6 months, the surface condition of the topsoil in each plot was scored between 0 (no evidence of salt at surface) and 3 (salt staining across > 90% of the surface). At that time, two excavations were made in each plot on a regular grid pattern (the mid point between each seedling) and soil samples collected from the 300 mm soil profile for subsequent chemical analysis.

Table 6.1: Details of trial plots used in surface capping trial.

Treatment	Depth of topsoil cover (mm)	Capillary break	Comments
A	-	None	Bare tailings surface.
B	300	None	
C	300	50 mm nickel slag (iron fayalite) granules	Granules are an inert by-product of a nearby nickel smelter. Granules are typically 5-7 mm in diameter.
D	300	Rheem Polytrac 155™ synthetic membrane	Tear-resistant woven geotextile used in civil engineering applications.

The level of the perched water table within the tailings was monitored by hand augering three bore holes in the tailing surface to a depth of 3 m and fitting them with 50 mm PVC piezometers scored with a hacksaw to allow entry of water. Surface (0-100 mm) samples of the tailings were taken at the conclusion of the trial to determine the moisture content gravimetrically. The trial plots were fenced to exclude traffic and grazing. Meteorological data for the study period were obtained from the Kalgoorlie-Boulder government meteorological station.

6.2.3 Soil analyses

Wesfarmers CSBP Ltd, Bayswater, Western Australia, performed all soil analyses. Soils were dried for 24 h at 105°C. Electrical conductivity ($EC_{1:5}$) for each sample was determined as a 1:5 dilution in deionised water. All $EC_{1:5}$ values were converted to EC_e (saturated extract equivalents) using the conversion factor (9.5) calculated by Slavich and Petterson (1993) on the basis that the soil had a silt loam texture with a saturation percentage estimated to be in the range 0.41-0.46 kg kg^{-1}. Values for Na, Ca and Mg concentrations were determined by extraction with 1 mol L^{-1} NH_4Cl and atomic absorption spectrophotometry with values expressed in meq 100 g^{-1}. From these data, sodium adsorption ratios (SAR) were calculated using the formula:

$$SAR = Na/[(Ca+Mg)/2]^{0.5}.$$

Table 6.2: Physical and chemical characteristics of tailings and topsoil in surface capping trial. Where required, TDS and EC_e data were converted using the factors given by Taylor (1991).

Characteristic	Tailings	Topsoil
Particle size/ soil type	75% < 0.075 mm	Silt loam
pH	8.7	7.7
Total dissolved solids (mg kg^{-1})	92,000	320
EC_e (dS m^{-1})	143.75	0.50
Sodium adsorption ratio (SAR)	-	0.6
NO_3 (mg kg^{-1})	-	1
NH_3 (mg kg^{-1})	-	11
P (mg kg^{-1})	-	38
K (mg kg^{-1})	-	529

6.2.4 Data analyses

Soil EC_e and SAR values for each treatment were compared using Kruskal-Wallis non-parametric tests. Where significant differences were obtained, Tukey's multiple comparison test using group rank sums was used to identify which groups were different (Zar, 1996). All analyses used $P < 0.05$ to define statistical significance. Analyses were carried out using Analyse-It v1.5 software (Analyse-It Software Ltd, Leeds UK).

6.3 Results

Hypersaline process water in the piezometers remained about 170 mm below the surface of the tailings throughout the trial. Salt crusts on the surface of the tailings appeared to inhibit evaporation and the tailings remained moist immediately below the surface. Samples taken from the top 100 mm of the tailings at the conclusion of the trial contained a mean moisture content of 19.3% ($n = 3$). Rainfall during the course of the trial was 167.8 mm adjustable to an equivalent of 180.3 mm when supplementary watering is considered. The mean maximum and minimum daily temperatures during the trial were 22.4°C and 7.7°C respectively.

Soil EC_e and SAR were both significantly higher in topsoil that did not possess a capillary break (Fig. 6.1 and 6.2) and crystalline salt was evident on the soil surface when sampling these two treatments. Soil EC_e showed in excess of a ten-fold increase with a mean value of 144.0 dS m^{-1} in topsoil without a capillary break compared with 10.55 dS m^{-1} (geotextile) and 8.45 dS m^{-1} (nickel slag). Similarly, SAR showed a five-fold increase with the same values ranging from 11.2 in topsoil only to 2.1 for both of the capillary break treatments. Soil EC_e in each plot could have been affected by wind-blown salts from the tailing surface, where crusts sometimes broke free and were deposited on the topsoil. This, however, would not account for the substantial differences between treatments, and capillary rise from the tailings surface clearly was the main factor.

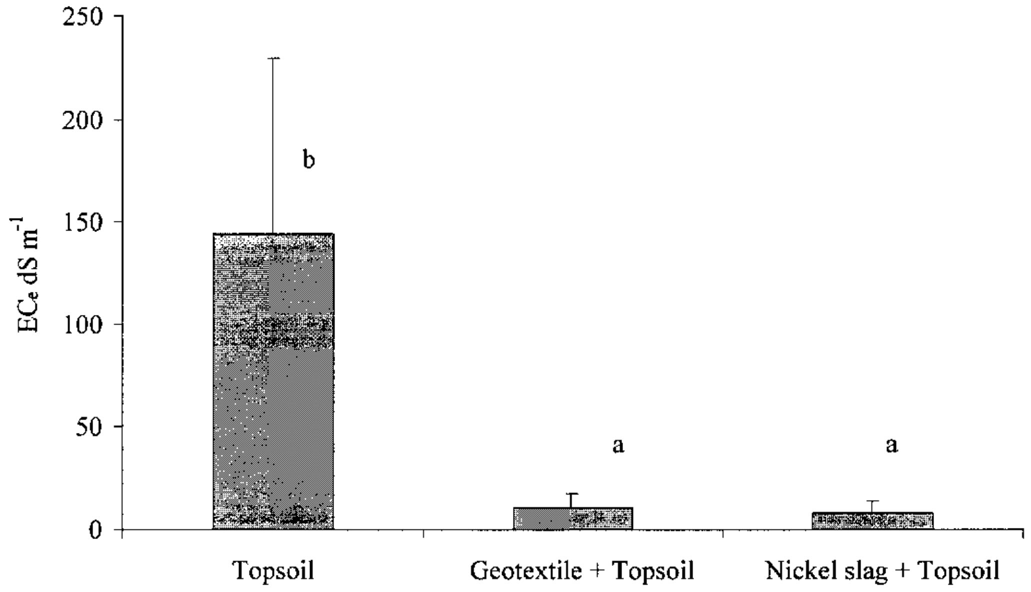


Figure 6.1: Soil EC_e values in topsoil after six months over hypersaline tailings with no capillary break compared with topsoil underlain by either geotextile or nickel slag. Letters indicate significant ($P < 0.05$) differences.

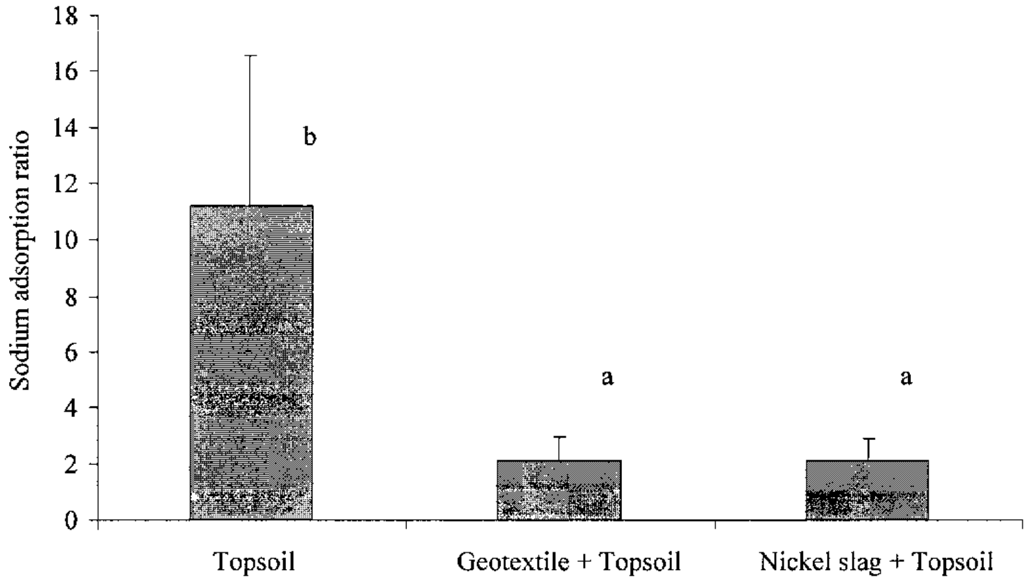


Figure 6.2: Soil SAR values in topsoil after six months over hypersaline tailings with no capillary break compared with topsoil underlain by either geotextile or nickel slag. Letters indicate significant ($P < 0.05$) differences.

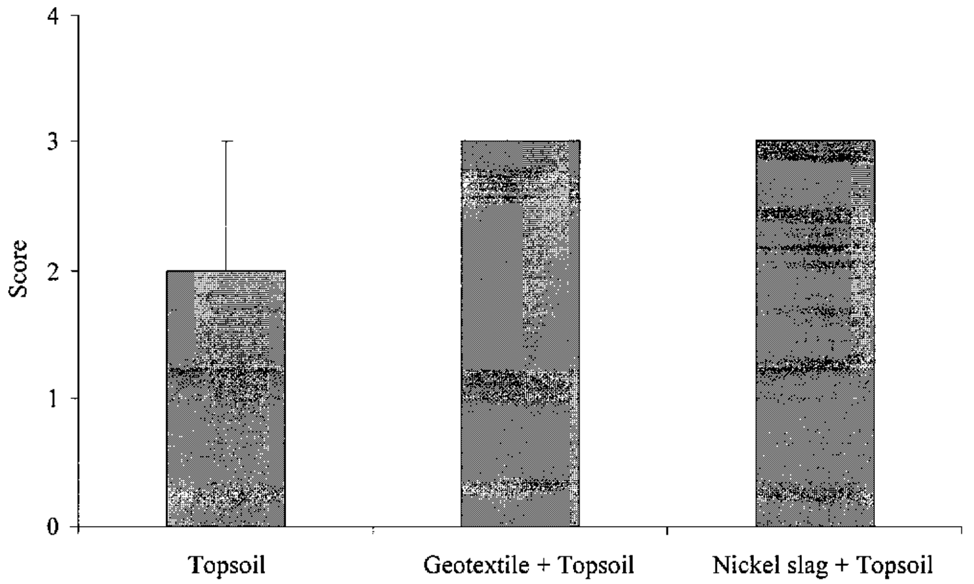


Figure 6.3: Mean surface soil condition scores ($n = 3$) of topsoil after six months over hypersaline tailings with no capillary break compared with topsoil underlain by either geotextile or nickel slag. Scores range between 0 (no evidence of salt at surface) and 3 (salt staining across > 90% of the surface).

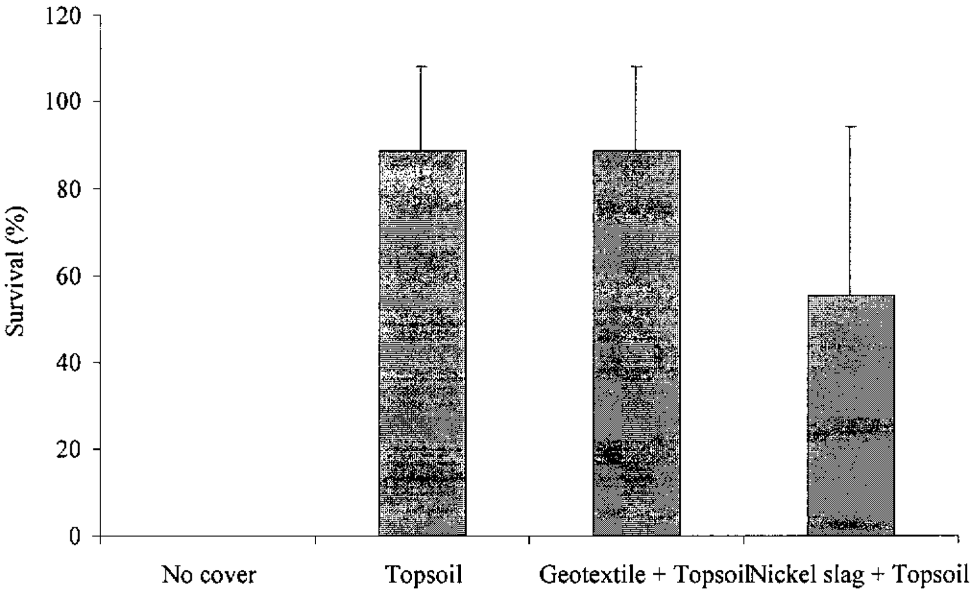


Figure 6.4: Survival (%) of *Atriplex amnicola* seedlings ($n = 9$) after six months in hypersaline tailings or in soil covers ± capillary breaks.

The actual changes in soil EC_e and SAR were not necessarily reflected by changes in visual salt at the soil surface (Fig. 6.3). While the topsoil without capillary breaks scored lowest, the differences between plots were not highlighted to the same degree as by the soil chemical data.

There was no survival of *Atriplex amnicola* seedlings when planted directly into the tailings (Fig. 6.4). All plants died within three weeks. After 6 mo, at least 50% of seedlings survived in each of the other treatments with survival best (88.9%) in the topsoil only and topsoil + geotextile treatments.

6.4 Discussion

The capillary breaks tested here were very effective in preventing the rise of salts into an overlying topsoil layer, reducing salinity and sodicity significantly. The salinity levels in the soil cover without a capillary break were likely to severely limit the establishment and survival of even highly salt-tolerant vegetation.

Bussell (2000) showed as little as 200 mm of topsoil was sufficient to establish vegetation over a hypersaline tailings surface, although the EC_e (52 dS m^{-1}) was much greater than in other treatments (11.4-20.8 dS m^{-1}) where the topsoil was underlain by a substantial (1-2 m) thickness of mine waste rock. The EC_e recorded in a topsoil only cover in Bussell's study was much lower than that of the studies described here. This may be attributable to differences in substrate salinity but it is likely a higher moisture level within the tailings studied here was the major influence in mobilizing salts into the topsoil layer. Rooney *et al.* (1998) found a capillary break layer of pea gravel (particle size of 79.9% 2-6.3 mm) with a thickness as little as 8 cm was effective in controlling upward migration of salts into a sandy clay topsoil, even under a high moisture regime (equivalent to a 991 mm rainfall). Where the moisture content of tailings is low, it may not be necessary to use capillary breaks but their use should be considered in any areas likely to accumulate water. In this study, the source of water linked with capillary rise was interstitial moisture within the tailings due to a perched water table within the tailings. Equally, water that infiltrates a permeable cover could also result in significant capillary rise but this was not believed to contribute significantly due to the low rainfall and fine soil texture.

Soil covers over toxic materials need not be deep even if revegetation is to be attempted. The large majority of tree roots occurs within the surface metre of the soil. Tree root growth is opportunistic and occurs where the environment is favourable (Perry, 1982). If the growth medium over a toxic substrate or physical barrier is shallow in depth, trees can form flattened root systems with virtually all root development at or near the surface. At an American landfill site, excavations of tree roots in shallow (100-300 mm) soils over a 450 mm layer of compacted clay showed very little root growth into the clay layer (Robinson and Handel, 1995). Functioning of the root system under such conditions, however, can be severely restricted (Harabin and Greszta, 1973) and such trees may be more susceptible to other adverse environmental factors, such as drought. For example, Enright and Lamont (1992) found shrubs establishing on a rehabilitated sand mine site were more susceptible to drought conditions where a low permeability subsoil layer was present, and the small tree *Eucalyptus sargentii* are prone to blowing over in windy conditions due to their restricted root development when planted in saline environments (E. Barrett-Lennard, pers. comm.). Furthermore, if there is upward movement of toxic material by capillary action through a sealing layer designed to have low permeability, any vegetation established over the sealing layer can be severely affected (Menzies and Mulligan, 2000).

Although plant survival in the soil covers tested here was favourable, long term survival without supplementary water was not tested. Any cover in a semi-arid area must be able to maintain a reasonable level of soil moisture to ensure plant survival through hot, dry periods. While many plant species occurring in semiarid areas are adapted to and can complete their life cycles in extended periods without rain (Esler and Phillips, 1994), soil moisture has been shown to be of major importance in the phenology of some Australian plants (eg. *Acacia* spp. - Freidel *et al.*, 1994) and methods of improving the infiltration of rainfall have been considered elsewhere in the design of new post-mining landforms (Lefebvre *et al.*, 1992). The study of moisture distribution in natural environments may also help in this regard. Runoff from stony areas assists in the longevity of grasses in eastern Australia (Hunter and Melville, 1994) and this concept could be used to improve the moisture content of selected areas in rehabilitated sites. Bussell (2000) showed *Atriplex* spp. responded differently to cover type with *A. vesicaria* favouring the topsoil only cover and *A. nummularia* preferring topsoil underlain by a rock layer. This difference is likely to be related to rooting patterns where *A. vesicaria* has a shallow, flat, fibrous root system mostly contained in the top 0.2 m while that of *A. nummularia* is deep-rooted with a strong lateral root system at depths of between 0.6 and 1.2 m (Jones and Hodgkinson, 1970). This suggests *A. nummularia* has a requirement for moisture at depth so a greater thickness of capping is likely to be required to sustain this species. The typical rooting patterns for different species, where known, should be considered when selecting species for use on covers and, indeed, root competition may be a limiting factor for above ground biomass (Belcher *et al.*, 1995). An effective vegetated soil cover, in addition to maintaining sufficient soil moisture to ensure survival and sustain growth, must also be resistant to erosion that could result from storms, and some species may perform better than others in this regard (Bent *et al.*, 1999).

The need for a full cover treatment for hypersaline tailings surfaces may be arguable. There is evidence that the surface is strongly resistant to wind erosion, at least in the short term, as potential saltation particles are bound to the surface through cement-like bonds (Nickling and Ecclestone, 1981; Zegelin *et al.*, 1997). Longer term changes, however, may reduce erosion resistance. An important factor is the rate at which tailings consolidate and dry which is greatly reduced in saline tailings due to the formation of surface crusts (Newson and Fahey, 1998). More research is needed into behaviour of these surfaces and how their properties may be altered to promote long term stability. Where a surface cover is required, more research is necessary into the depth of covers and thickness and effectiveness of capillary break layers on final surfaces that need to meet long term objectives in erosion control, stability and visual amenity.

7.0 RELATIONSHIPS BETWEEN ENVIRONMENTAL FACTORS AND VEGETATION DISTRIBUTION ON THE SHORES OF A LARGE SALT LAKE IN SEMIARID WESTERN AUSTRALIA

7.1 Introduction

The relationship between environmental gradients and the distribution of vegetation has been the subject of numerous studies in a wide range of environments. These environments include coastal and inland salt marshes (Allen *et al.*, 1997; Cantero *et al.*, 1998; Sánchez *et al.*, 1998; Zedler *et al.*, 1999), alpine and mountain environments (John and Dale, 1990; Hill, 1996; Kirkpatrick *et al.*, 1996), forests (Turton and Sexton, 1996), coastlines (Oliveira-Filho, 1993) and areas of succession following major disturbance (Tsuyuzaki and del Moral, 1994). The elucidation of these relationships can assist with the management of those areas where hypotheses can be developed about the likely impacts of environmental change. A further potential application is the use of the data to assist in the design of mined land rehabilitation programs. Rehabilitation of severely disturbed land after mining can, in theory, be based on a natural system, if there are sufficient common elements between the natural and the artificial landform. Even if substantial differences occur, a better understanding of natural systems can still aid the design, construction and sustainability of strongly modified landforms and ecosystems (Pate and Bell, 1999). There are recent examples (McKenna, 1996; Sawatsky and Beckstead, 1996) where mined landscapes have been configured based on natural systems with a view to improved erosion control and long term stability. Similar research into landforms and vegetation in the Eastern Goldfields of Western Australia, where gold and nickel mining occur, has also been conducted (Chalwell, 1996). This work was carried out with the ultimate aim of providing a reference point for the potential modification of existing land rehabilitation practices to more closely reflect natural landforms and vegetation communities.

In the Eastern Goldfields region, salinity is an important environmental factor when considering land rehabilitation options and final landforms. Mining generates saline materials that must be rehabilitated, encapsulated or stabilised in some way (Department of Minerals and Energy, 1996a). The principal source of salinity is through the widespread use of hypersaline groundwater for mineral processing (Turner *et al.*, 1993) and through other uses, such as dust suppression (Kyle 1989). As many parts of the Eastern Goldfields are underlain by shallow hypersaline groundwater (Turner *et al.*, 1993), other sources of salts include saline overburden materials, saline soils and subsoils, and salt lake sediments. Saline soils and subsoils are widespread throughout the Eastern Goldfields (Keighery *et al.*, 1992). While not limited to salt lake systems, these soils are best developed in and around those areas. Salt lake systems themselves are common in the region, as they are in much of arid and semiarid Australia (De Deckker, 1983).

The purpose of my study, therefore, was to examine local examples of naturally saline ecosystems to help develop strategies for the rehabilitation of saline mined landforms. The shores of salt lakes can support a diverse range of flowering plants, some of which can withstand high salt concentrations and inundation to various degrees. Vegetation often occurs in distinct zones related to edaphic and other environmental factors (Tiku, 1975; Krüger and Peinemann, 1996) and the biological characteristics of individual species (Joshi and Iyengar, 1982). An understanding of the variables controlling this zonation should assist with the development of mined land rehabilitation options.

7.2 Materials and Methods

7.2.1 Study area

Salt lakes in the Eastern Goldfields have features matching the general characteristics of playas and pans recognised by Shaw and Thomas (1989). They are low-lying and lack surface outflows; they are flat and vegetation-free, except at the shores, and they are occupied by ephemeral bodies of water with a hydrological budget where evaporation greatly exceeds inputs. In the Kalgoorlie region, catchment size and infiltration restrict the duration of flood events on salt lakes with few retaining water for extended periods (Johnson, 1993). Evaporation from salt lakes is the primary mechanism of groundwater discharge (Turner *et al.*, 1993). Groundwater and surface inflow together constitute the sources of salt (De Deckker, 1983; Bettenay, 1962). Most lakes were formed about 5 million years ago (J. Clarke, pers. comm.) as a series of arid climatic cycles were experienced and the hydrological systems changed from a groundwater recharge to a discharge relationship. They are believed to have been vast river systems in Tertiary times (Bettenay, 1962) with significant flows ceasing before the mid-Miocene (van de Graaff *et al.*, 1977).

The shores of Lake Lefroy, a large salt lake near Kambalda (31°13'S, 121°40'E), Western Australia, were selected for study (Fig. 7.1). The lake has a surface area of 554 km^2, is 286 m above sea level and is shaped like an inverted 'L' orientated NNE-SSW with a length of 59 km and maximum width of 16 km (Clarke, 1994a). The western and northern shores of the lake are dominated by erosional processes. They frequently feature cliff outcrops of Archaean and Tertiary rocks, interspersed by deltas where streams disperse into the lake. The southern and eastern lake shores, however, are dominated by depositional processes. The streams that enter the western and northern shores deposit their sediments in small deltas. These sediments are then reworked by aeolian processes to form dunes on islands on the lake or may even be blown across the lake to the opposite side (Clarke, 1994b). Lake Lefroy fills to a depth of about 0.3 m in winter but depths of up to 2 m can occur after flooding (Clarke, 1994a). On average, the lake is probably completely dry only for about 25% of the year, with ephemeral pools forming on parts of the lake between flooding events. Most of the lake surface is covered by a halite crust which, together with the vegetation occurring on the lake shores, prevents major aeolian erosion away from the lake (Clarke, 1994a).

Kambalda has a mean average annual rainfall of 242 mm, slightly lower than that of Kalgoorlie-Boulder (see Chapter 5). Annual evaporation is about ten times that of rainfall. Wind occurs most commonly from the east and south-east but the strongest winds are from the west (during winter and spring) (unpubl. data, Climate and Consultative Services, Bureau of Meteorology; Clarke, 1994a) (Fig. 7.2). Wind is critical to the formation of the lake shores. Winter storms bring water-borne sediments onto the lake and the westerly winds push them in an easterly direction during winter and spring. The sediments dry

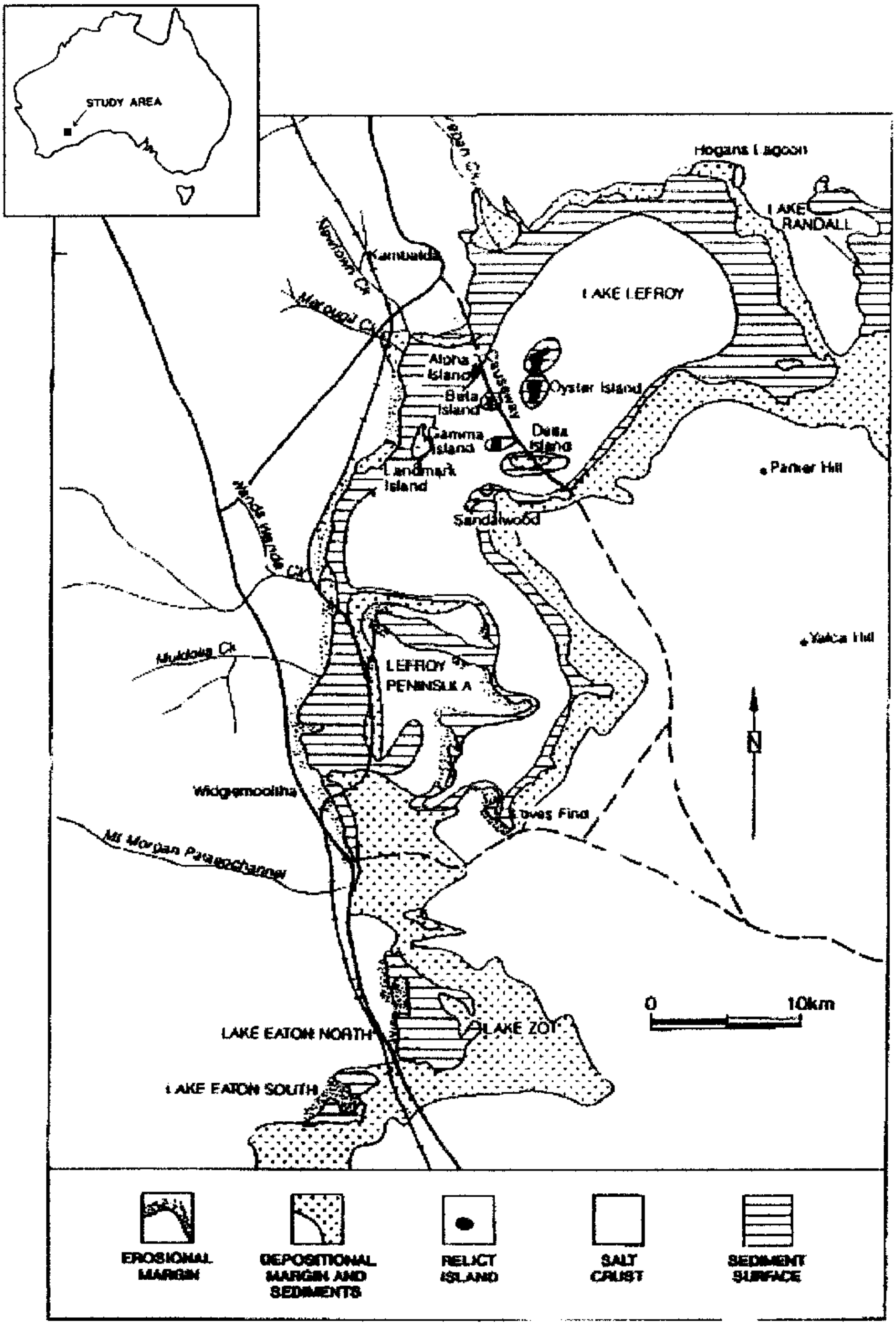


Figure 7.1: Map of Lake Lefroy and surrounding area near Kambalda, Western Australia (31°13'S, 121°40'E). Adapted from Clarke (1994b). Sediment surface indicates material transported by stream flow onto the bare lake surface. Depositional and margin sediments support vegetation and form the southern and eastern lake shores.

over summer and autumn and are available for transport again by westerly winds the following winter and spring. Summer easterlies apparently have less influence. A similar pattern of aeolian deposition has been recorded in Nevada, USA (Young and Evans, 1986) where deposition in sediment traps was typically greater under the influence of winter winds, despite the greater moisture availability.

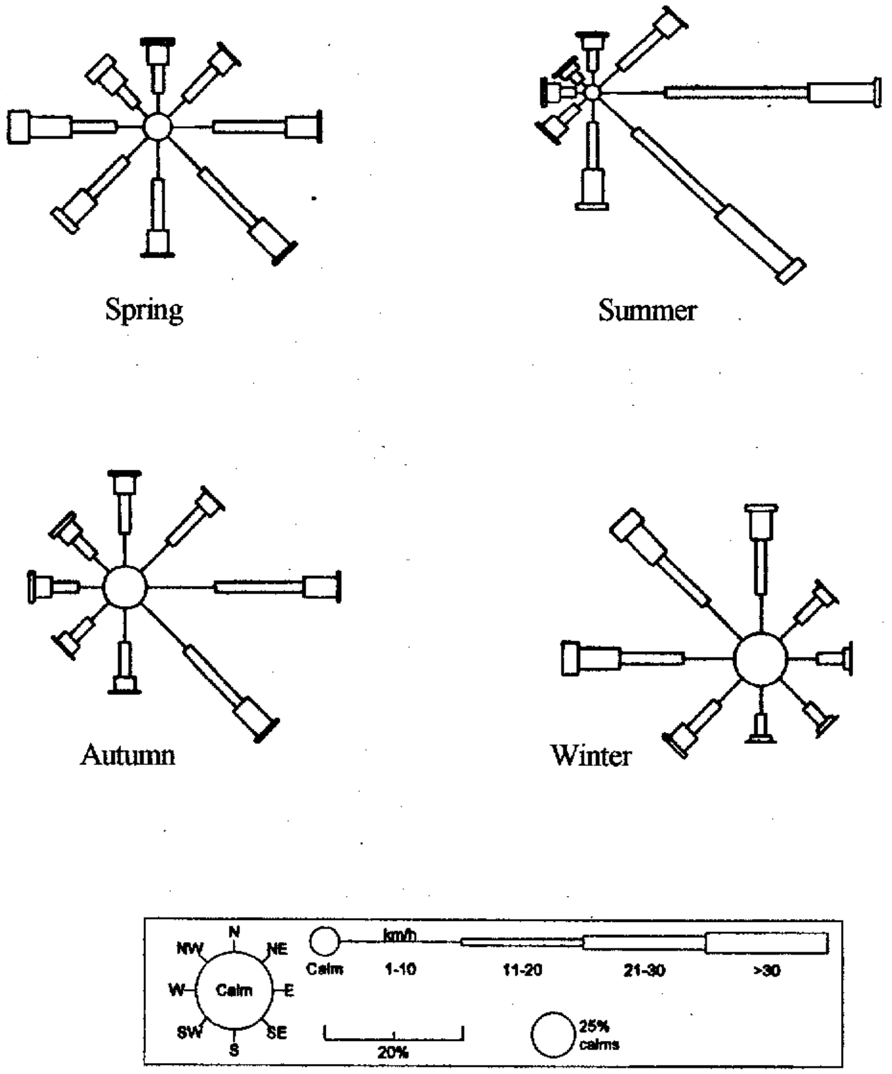


Figure 7.2: Wind roses for each season for Kalgoorlie-Boulder based on mean data for 1961-1990 (unpubl. data, Climate and Consultative Services, Bureau of Meteorology).

A number of lake shore types were identified in the field (Table 7.1) based on the observations of Clarke (1994a). The shores were identified from areas accessible by road and were not necessarily a comprehensive review of all shore formations. Unvegetated rocky cliffs along the western and northern lake shores were not studied. Only shores supporting some form of vegetation in a gradient from the lake surface were considered. Within each shore, two or three distinct zones were observed, as described in Table 7.2.

During a preliminary assessment at 18 sites around the lake (Figure 7.3), data on soil and groundwater characteristics were obtained (Table 7.3). All lake shore types had highly saline soils (as EC_e values) in Zone I ranging to very low salinity in Zone III. Almost all winter soil EC_e values were markedly lower than summer values. All sodium adsorption ratios were less than the critical value of 13 (Sumner, 1995). Soil pH and available P varied between lake shore types, while soil NO_3, NH_4 and organic C content were all low. The mean minimum depth to groundwater in the vegetated portion of the lake shores ranged from 0.52 to 1.08 m below ground level. All groundwater was highly saline (typically ~150 g L^{-1} total dissolved solids) with pH ranging from acidic (3.4) to neutral or mildly alkaline.

Table 7.1: Lake shore types observed at Lake Lefroy. Classification based on lake physiography as described by Clarke (1994a,b) and on distinct vegetation types recognised in the field during this study.

Type	Characteristics
Siliciclastic dunes	Large (> 5 m above lake bed) dunes usually underlain by gypsum but may be underlain by outcropping silcrete or ferricrete Tertiary duricrust in south-western part of lake.
Dune swales	Small (< 2 m above lake bed) interdune swales, small islands or narrow lake shores lying across prevailing winds. They are usually dominated by siliciclastic material and often occur along the shores of lake estuaries.
Gypsum dune beds	Lake shores with gypsum dune beds exposed by eastward movement of sand dune; common along, but not limited to, the eastern shore of the lake.
Scree slopes	Variable shore type dominated by rock scree. Predominantly consist of mafic or ultramafic Archaean rocky ridges observed in estuaries in south-western part of lake. In several other small areas, a narrow lake shore is formed of coarse (> 2 mm diameter) and broken fragments of weathered duricrust (Tertiary sediments), ranging from gravel (2-20 mm) to boulders (> 256 mm), trapping mobile sand and pelletised clay particles.

Table 7.2: Characteristics of zones within lake shore types observed by me at Lake Lefroy.

Zone	Characteristics
I	"Littoral" zone. Lowest elevation at which vegetation occurs. Widespread salt crusting over surface with very low plant cover and diversity. Plants usually restricted to succulent halophytes.
II	"Sub-littoral" zone. Higher elevation than Zone I. Intermittent salt crusting and staining of surface. Plant cover and diversity markedly greater than Zone I.
III	Dune sands. Higher elevation than Zone II. No salt crusting or staining on surface. Plant cover greater than Zones I or II.

7.2.2 Field work

Following a review of the preliminary data, five sites were selected for detailed study. The sites studied were a siliciclastic dune (1), two dune swales (13 and 14), an exposed gypsum dune bed (15) and a scree slope (11) (see Fig. 7.3). At each site, parallel transects were established 5 m apart and perpendicular to the lake shore. Two transects were used at each site except Site 1 where four transects were used due to the steeper slope providing relatively fewer samples. Each transect commenced at a point below which the lake surface was completely unvegetated and rose to an elevation of 1.2 m above this point. This elevation was selected from field observations suggesting that vegetation associations specifically related to the lake shores at most sites ended at that point. The lengths of transects, therefore, varied with the slope of the lake shores and ranged from 8 m at site 1 to 135 m at site 14.

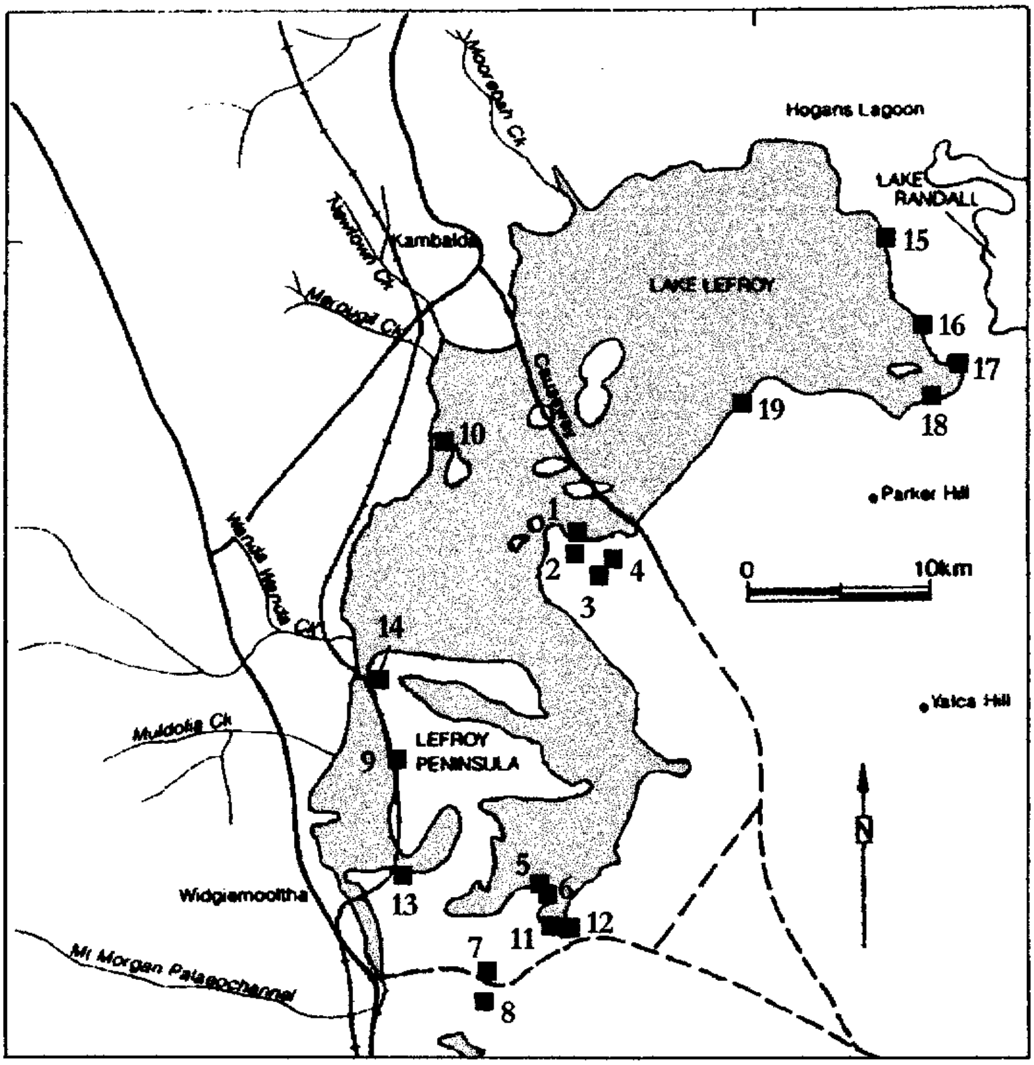


Figure 7.3: Location of lake shore study sites (1-19) selected around Lake Lefroy (in grey) for preliminary assessment. Sites 2-4, 7-8 and 19 occur on lake estuaries connected to the main lake body but not detailed on the map. No soil data were collected at site 10.

Table 7.3: Mean values from preliminary sampling and analyses of soil and groundwater characteristics of lake shores around Lake Lefroy. n.d. = no data.

Characteristic	Zone	Siliciclastic dunes ($n = 5$)	Dune swales ($n = 7$)	Gypsum dune beds ($n = 4$)	Scree slopes ($n = 2$)
EC_e (dS m^{-1}) (summer)	I	86.4	80.0	55.3	138.4
	II	9.1	20.3	32.9	52.0
	III	1.2	12.1	4.7	n.d.
EC_e (dS m^{-1}) (winter)	I	32.7	48.6	74.8	62.9
	II	1.6	13.1	21.5	7.3
	III	1.0	2.9	11.3	n.d.
SAR (summer)	I	3.3	2.4	3.9	5.2
	II	1.1	0.7	2.8	3.9
	III	0.4	0.5	2.2	n.d.
SAR (winter)	I	8.3	8.8	18.3	13.3
	II	0.7	2.8	4.6	3.0
	III	0.4	0.7	2.0	n.d.
pH	I	6.6	7.7	8.0	6.4
	II	6.4	7.2	8.5	6.3
	III	6.2	7.0	8.7	n.d.
Organic C (%)	I	0.27	0.21	0.27	0.43
	II	0.32	0.22	0.16	0.53
	III	0.39	0.17	0.20	n.d.
NO_3 (mg kg^{-1})	I	1.3	1.3	6.4	1.5
	II	1.4	1.2	2.9	1.5
	III	2.6	1.3	1.8	n.d.
NH_4 (mg kg^{-1})	I	2.5	1.6	2.3	2.5
	II	1.9	1.4	1.3	4.5
	III	2.9	1.4	1.0	n.d.
Available P (mg kg^{-1})	I	2.7	4.5	16.1	3.8
	II	2.6	3.6	12.3	6.0
	III	2.9	3.2	11	n.d.
Minimum depth to groundwater (m)		0.53	0.70	1.08	0.51
Total dissolved solids (g L^{-1}) in groundwater		156.4	139.6	150.3	n.d.
pH of groundwater		6.1	7.2	7.0	n.d.

At each site, one or two boreholes were established during the preliminary assessment to determine depth to, and quality of, groundwater. Drilling of the boreholes was carried out using a hand auger for shallow water tables and a 4WD-mounted mechanical auger, where ground conditions permitted, for the deeper holes. The boreholes were cased with 20 mm electrical conduit scored at regular intervals with a hacksaw and wrapped in a geotextile (Bidim™) to prevent ingress of sediments. Water levels were taken in winter and summer using a 50 m Solinst™ water level probe. Elevations of boreholes and slopes along transects perpendicular to the lake shore were determined using a dumpy level and staff.

Starting from the lake edge, a 1 m^2 plot was placed along each transect at each successive point where the elevation changed by 0.1 m. Where changes in elevation of 0.1 m or greater occurred over a distance of 1 m or less, contiguous plots were used. A total of 140 plots were sampled. Soil samples (0-0.1 m depth) were collected on a standardised grid pattern of three subsamples within each plot. Salt crusts, if present, were removed prior to soil sampling. At selected points at each site, excavations were made to inspect soil profiles to 0.5 m for the presence of gypsum (a common precipitate) or other hardpans or marked changes in soil horizons, and to make opportunistic observations of root distributions. Soil samples were also collected from these excavations.

The range of environmental data collected is given in Table 7.4. Groundwater quality was not included as an environmental variable as groundwater at all sites was hypersaline (> 50 g L^{-1} TDS). Soil nutrient status and soil sodicity were also not considered as, despite the preliminary sampling indicating some differences between sites, other variables were believed to be more likely to play a direct role in determining plant distributions. Other data were collected but not used in subsequent analyses due to their high correlation with other variables.

Within each plot, the cover for each vascular plant species was classified according to the following Braun-Blanquet scale, as given in Kershaw (1974):

1 = sparsely or very sparsely present; cover very small
2 = plentiful but of small cover value
3 = very numerous, or covering at least 1/20 of the area
4 = any number of individuals covering ¼ to ½ of the area
5 = any number of individuals covering ½ to ¾ of the area
6 = covering more than ¾ of the area

Dead shrubs of *Melaleuca thyoides*, *Frankenia desertorum* and *Halosarcia halocnemoides* occurred in some plots. They were included in the species score. The cover of gelatinous and crustaceous lichens was also recorded (terminology follows Eldridge and Rosenstreter, 1999). Vascular plant specimens were identified using a field herbarium compiled during preliminary studies of lake shores, a reference herbarium at WMC Resources Ltd, Kambalda, the Goldfields Reference Herbarium in Kalgoorlie-Boulder and the Western Australian Herbarium in South Perth, Western Australia. Nomenclature follows Green (1985). Life forms of vascular plant species were classified after Raunkiaer (1934).

7.2.3 Soil analyses

CSBP & Farmers Ltd, Bayswater, Western Australia, performed all soil chemical analyses. Electrical conductivity (EC) and pH for each sample were determined as a 1:5 dilution in deionised water. Soils were also analysed for Ca (acid digestion, atomic absorption spectrophotometry) and S (lecofurnace, infrared cell) to determine gypsum content. All $EC_{1:5}$ values were converted to EC_e (saturated extract equivalents) using the conversion factors calculated by Slavich and Petterson (1993) on the basis of soil texture and the inferred saturation percentages. The factors used were 13.8 (sandy clay loam-sandy loam) and 22.7 (loamy sand-sand). Soil texture was determined by sorting samples into common groups and undertaking particle size analyses for each group (minimum of ten samples per group) using the hydrometer method (Bouyoucos, 1962).

Table 7.4: Environmental data collected in each plot at five sites along the shores of Lake Lefroy. Variable types are continuous (C) or ordinal (O).

Variable	Code	Variable type	Details
Soil EC_e	SOILEC	O	Value determined for each plot and then sorted into groups of ecological significance based on plant tolerance data from Richards (1954) and Chapter 5. Scores were 1 (< 4 dS m^{-1}), 2 (4-8), 3 (8-16), 4 (16-50), 5 (50-100) and 6 (> 100).
Soil pH	SOILPH	O	Value determined for each plot and sorted into groups of ecological significance. Scores were 1 (< 5.5), 2 (5.5-6.5), 3 (6.5-7.5), 4 (7.5-8.5) and 5 (> 8.5).
Soil texture	SOILTX	O	Value assigned to each plot based on particle size analysis of soil types observed in field. Values were ranked by decreasing clay content: sandy clay loam (1), sandy loam (2), loamy sand (3) and sand (4). Soil types confirmed by the hydrometer method (Bouyoucos, 1962).
Subsoil gypsum	SOILGY	O	A score for each plot was allocated dependent upon the gypsum content of two subsoil samples from each site. Scores were 1 - low (Ca, S < 1%), 2 - moderate (Ca, S 1-5%), 3 - high (Ca, S > 5%).
Mean depth to groundwater	MEANGW	C	Mean depth to groundwater from summer and winter measurements to nearest 0.01 m. Corrected for each plot from survey data.
Rock cover	ROCKCV	O	Each plot scored as absent (1) if cover < 10%. If cover ≥ 10%, scored as 2 (quartz or ironstone gravel, 2-75 mm diameter), 3 (angular rock fragments, 2-75 mm), 4 (cobbles, 75-256 mm) or 5 (stones, > 256 mm).
Aspect	ASPECT	O	Scored on the basis of influence of the predominant spring and winter winds. Lake shores facing WNW, W or WSW were scored as 2 and other aspects were scored as 1.
Microtopography	MICROT	O	Degree of intraplot topographical variability. Each plot scored as 1 (uniform) or 2 (variable) if there was > 0.15 m variation in elevation within plot, usually in the form of small vegetated mounds.

7.2.4 Data analysis

Data were analysed using multivariate data reduction methods. A principal components analysis (PCA) was used to detect similarity of the sites based on environmental characteristics (Kent and Coker, 1992). Input for the PCA were Pearson correlation coefficients determined for all environmental variables with all values standardized so that they ranged over 0-1 (Hill, 1979). Species distributions in relation to environmental variables at each site were analysed by canonical correspondence analysis (CCA) (ter Braak, 1987). Plots containing no plants and rare species (single occurrences) were discounted. Environmental variables were removed where they did not contribute to explaining variation or were strongly correlated with other variables. All variables were standardised as for the principal components analysis. The variance explained by the axes was the proportion of the calculated eigenvalue to the 'inertia' value, or total variance (ter Braak, 1990). The statistical significance of the variances and the correlation coefficients was assessed by Monte Carlo tests (100 runs) with the null hypothesis that there was no relationship between the environmental and species matrices. Differences between species distribution in respect of soil EC_e and depth to groundwater were assessed by one-way ANOVA and LSD tests. Statistical significance was at the 0.05 level unless otherwise indicated. All analyses were undertaken using PC-ORD v.3.17 (MjM Software, Gleneden Beach, Oregon, USA) and Analyse-It v.1.5 (Analyse-It Software, Leeds, UK).

7.3 Results

Differences between summer and winter groundwater levels were small (~0.2 m) and the mean values were used in the subsequent analyses. All groundwater samples were hypersaline (> 50 g L^{-1} TDS) except one borehole at site 14 in which the groundwater was 41.4 g L^{-1} TDS. Samples obtained from boreholes at the edge of the bare lake surface were consistently more saline than samples from boreholes within vegetated areas further from the body of the lake (Table 7.5). No hardpans were observed at any site so groundwater levels were considered the soil depth limit.

Table 7.5: Total dissolved solids (TDS) (g L^{-1}) of groundwater sampled from boreholes located at different distances along five transects from the unvegetated lake edge.

Site	First borehole			Second borehole		
	Dist. from lake (m)	Depth to water (m)	TDS (g L^{-1})	Dist. from lake (m)	Depth to water (m)	TDS (g L^{-1})
1	0	0.12	106.3	11.0	1.88	70.3
11	0	0.20	84.6	-	-	-
13	0	0.24	117.7	44.1	1.11	55.7
14	0	0.06	97.8	196.9	3.74	41.4
15	0	0.56	115.5	32.5	1.62	107.8

Soil EC_e was high (>70 dS m^{-1} and up to 300 dS m^{-1}) at all five sites at the start of each transect and declined with increasing elevation. The rate and degree of decline varied between sites with the differences being less evident at site 15. Soil EC_e at the higher elevations in dune sands and swales was typically less than 5 dS m^{-1}. No strongly acidic or alkaline soils occurred but site differences appeared to be influenced by the groundwater table. The most acidic soils occurred at site 11 (scree slope) where the groundwater was strongly acidic (3.4). Soil texture at most sites was loamy sand or sand, with loams only occurring at site 15 (exposed gypsum dune bed) with this likely to have had a bearing on the soil EC_e values recorded at that site. Soil surfaces were stabilised by rock cover at some sites. At sites 13 and 14, quartz pebbles occurred at the base of the transects and more commonly at site 15. The scree slope (site 11) had substantial rock cover of increasing particle size with elevation. Towards the base of the transects at sites 13 and 14 and more commonly at site 15, vegetated mounds up to 0.3 m in height occurred. Spaces between the mounds were often bare or partially covered by therophytes or, at site 13, gelatinous lichens. During the excavations, significant root development was not observed at depths greater than 0.4 m. At site 15, a crystalline deposit likely to be gypsum had precipitated at a depth of about 0.3 m.

The first two axes of the PCA of environmental variables explained 36.6 and 62.2% respectively of the cumulative variance. Pearson correlation coefficients used in the PCA are given in Table 7.6. The resulting plot of the PCA (Fig. 7.4) showed that the measured values for environmental variables associated with the exposed gypsum dune bed and the rock scree were different from each other and from those of the siliciclastic dunes and dune swales. The Pearson correlation coefficients indicated significant correlations between a number of the variables. For example, soil EC_e showed positive correlations with soil gypsum and rock cover and negative correlations with soil texture, depth to groundwater, microtopography and aspect. The soil EC_e values for site 15 could have been affected by dissolved gypsum, thus the relative contribution to EC_e from Na^+ and Cl^- may have been less at that site than at the other sites.

The presence and absence of vascular plant species at each site are shown in Table 7.7. The best represented families were the Chenopodiaceae (11 species), Asteraceae (10), Aizoaceae (4), Poaceae (4), Portulacaceae (3) and Frankeniaceae (3). Two morphological groups of lichens were also recorded. A total of 50 vascular plant species was recorded of which almost half (48%) were therophytes (annuals). The dune swales had the greatest species richness with 23 and 29 for sites 13 and 14 respectively and the scree slope was the poorest with only four species.

The CCA ordinations showed (Fig.s 7.5-7.7) between 15.4 and 54.1% of the variance explained by the first two axes. The first axes in each case were statistically significant (Table 7.8). Zone I species at all sites consisted of succulent, highly salt-tolerant species including the perennial shrubs *Halosarcia halocnemoides* (sites 13 and 14) and *H. syncarpa* (site 1), and annuals *Gunniopsis septifraga* (sites 1 and 13) and *Mesembryanthemum nodiflorum* (site 15). Other perennial species occurring in Zone I included *Frankenia pauciflora*, *F. desertorum* and *F. setosa*. On the dune and the dune swale sites, soil EC_e and depth to groundwater were the most important correlates with species distributions whereas microtopography (site 15), and soil texture and depth to groundwater (site 11) were the most important at other sites. Soils in the latter sites were also saline but they were more consistently so in each zone of vegetation. Zone II at most sites was markedly more species-rich. Where present, Zone III was the richest. This applied particularly to the dune swales (13 and 14) while the dune at site 1 (Fig. 7.8) had a narrow band of comprised of *Melaleuca thyoides* shrubs only. Zone III species occurred at the lowest soil EC_e values and the greatest depths to groundwater. Rankings of the 34 most common plant species in relation to soil EC_e and depth to groundwater are given in Figures 7.9 and 7.10. The perennial succulent halophyte, *Halosarcia syncarpa* (Fig. 7.8), occurred at significantly higher soil EC_e values and closer to the groundwater table than any other species.

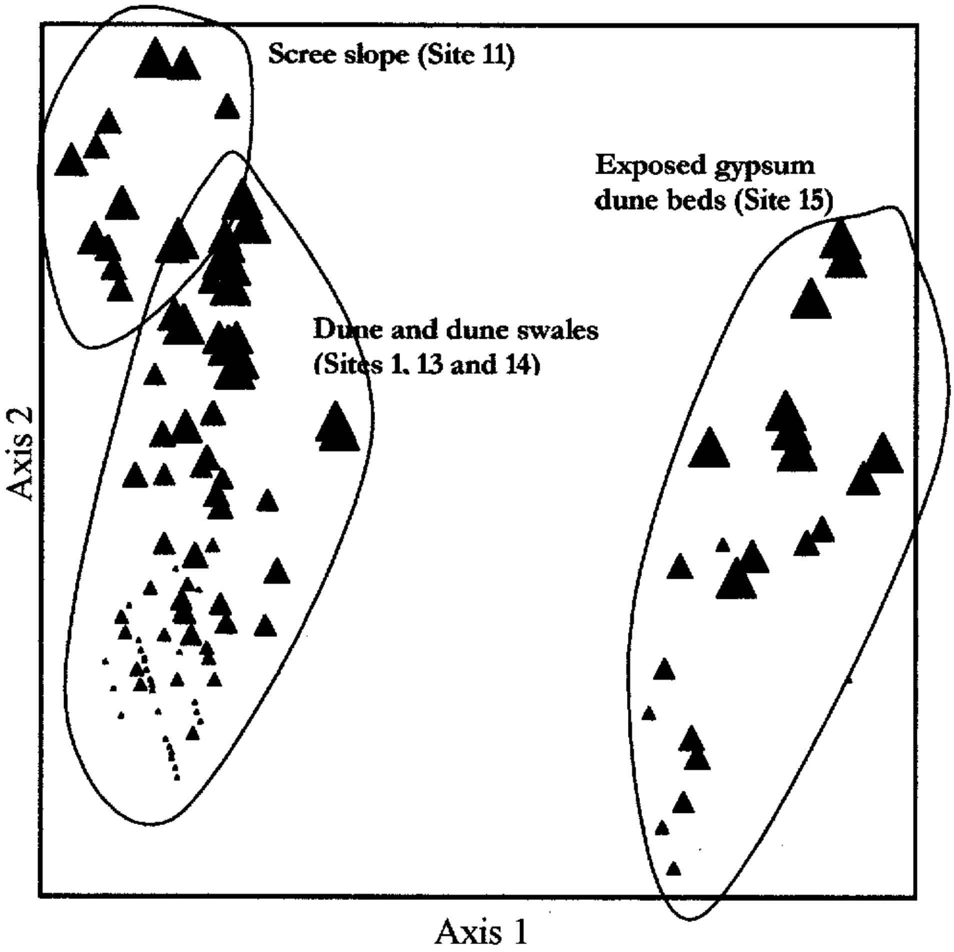


Figure 7.4: Principal components analysis (PCA) of data set of eight environmental variables (Table 7.4) from a total of 140 plots around Lake Lefroy. Symbol size indicates relative plots score for soil EC_e (see Table 7.4). The first two axes explain a cumulative amount of 62.2% of the variance.

Table 7.6: Pearson correlation coefficient matrix of data on environmental variables from 140 plots around Lake Lefroy. Environmental variable codes are as given in Table 7.4. Asterisks indicate significant correlations (* - $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$).

	SOILEC	*SOILPH*	*SOILTX*	*SOILGY*	*MEANGW*	*ROCKCV*	*ASPECT*	*MICROT*
SOILEC	1.00							
SOILPH	0.15	1.00						
SOILTX	-0.39***	-0.22**	1.00					
SOILGY	0.28**	0.55***	-0.67***	1.00				
MEANGW	-0.51***	0.09	0.00	0.34***	1.00			
ROCKCV	0.38***	-0.40***	-0.11	-0.06	-0.16*	1.00		
ASPECT	-0.28**	-0.55***	0.67***	1.00***	-0.34***	0.06	1.00	
MICROT	-0.20*	0.10	0.69***	-0.01	0.05	0.32***	0.01	1.00

Table 7.7: Species presence/absence data for lake shores around Lake Lefroy. Life forms of vascular plants are microphanerophyte (Mi), nanophanerophyte (N), chamaephyte (Ch), hemicryptophyte (H), geophyte (G) and therophyte (Th); exotic species are marked with an asterisk.

Species	Key	Life form	Siliciclastic dune (Site 1)	Dune swales		Gypsum dune bed (Site 15)	Scree (Site 11)
				Site 13	Site 14		
Angianthus preissianus (Steetz)Benth.	ANGPRE	Th	-	+	+	-	-
Atriplex codonocarpa Paul G. Wilson	ATRCOD	Th	-	-	-	+	-
Atriplex nana Parr-Smith	ATRNAN	Ch	-	+	+	+	-
Brachyscome sp.	BRACHY	Th	-	-	+	-	-
Calandrinia eremaea Ewart	CALERE	G	-	+	+	-	-
Calandrinia granulifera Benth.	CALGRA	G	+	-	-	-	-
Calandrinia polyandra Benth.	CALPOL	G	-	-	+	-	-
Calotis hispidula (F. Muell.) F. Muell.	CALHIS	Th	-	+	-	-	-
Centrolepis polygyna (R.Br.) Hieron.	CENPOL	Th	-	+	+	-	-
Crassula sieberiana (Schultes and J.H. Schultes)	CRASIE	Th	-	+	+	-	-
Cuscuta australis R.Br.	CUSAUS	G	-	-	-	+	-
Darwinia diosmoides (DC.) Benth.	DARDIO	N	+	-	-	-	-
Disphyma crassifolium (L.) L. Bolus	DISCRA	Ch	-	+	+	+	-
Dodonaea viscosa Jacq.	DODVIS	Mi	-	-	+	-	-
Eragrostis dielsii Pilger ex Diels & Pritzel	ERADIE	H	-	+	+	+	-
Eragrostis falcata (Gaudich.) Benth.	ERAFAL	Th	-	-	+	-	-
Frankenia desertorum Summerh.	FRADES	Ch	-	-	-	+	-
Frankenia pauciflora DC.	FRAPAU	Ch	-	-	+	-	+
Frankenia setosa W.Fitzg.	FRASET	Ch	-	+	+	-	-
Gnephosis angianthoides (Steetz)Anderb.	GNEANG	Th	-	+	+	-	-
Gnephosis tenuissima Cass.	GNETEN	Th	-	-	+	-	-
Grevillea acuaria F.Muell. ex Benth.	GREACU	N	-	+	-	-	-
Gunniopsis quadrifida (F. Muell.) Pax in Engl. &	GUNQUA	Ch	-	+	-	-	-
Gunniopsis rodwayi (Ewart) C.Gardner	GUNROD	Th	-	-	+	-	-
Gunniopsis septifraga (F.Muell.)Chinn.	GUNSEP	Th	+	-	+	-	+
Halosarcia halocnemoides (Nees) Paul G. Wilson	HALHAL	Ch	-	+	+	-	-
Halosarcia indica (Willd.) Paul G. Wilson	HALIND	N	-	-	+	-	-
Halosarcia lylei (Ewart & J.White) Paul G. Wilson	HALLYL	N	-	-	-	-	+
Halosarcia syncarpa Paul G. Wilson	HALSYN	N	+	-	-	-	-
Hemichroa diandra R.Br.	HEMDIA	N	-	+	+	-	-
Hordeum leporinum Link	HORLEP	Th*	-	-	-	+	-
Hyalochlamys globifera A. Gray	HYAGLO	Th	-	+	+	-	-
Jacksonia spinosa (Labill.) R.Br. in W.T.Aiton	JACSPI	N	+	+	+	-	-
Lepidium phlebopetalum (F. Muell.) F. Muell.	LEPPHL	Th	-	+	+	-	-
Maireana amoena (Diels) Paul G. Wilson	MAIAMO	Ch	-	+	-	-	-
Maireana carnosa (Moq.) Paul G. Wilson	MAICAR	Th	-	-	-	-	+
Maireana eriosphaera Paul G. Wilson	MAIERI	Th	-	+	-	-	-
Maireana glomerifolia (F.Muell. & Tate) Paul G.	MAIGLO	N	-	+	+	-	-
Melaleuca thyoides Turcz.	MELTHY	Mi	+	-	-	-	-
Mesembryanthemum nodiflorum L.	MESNOD	Th*	-	-	-	+	-
Pentzia suffruticosa (L.) Hutch. ex Merxm.	PENSUF	Th*	-	-	-	+	-
Podotheca gnaphalioides R.A. Graham	PODGNA	Th	-	-	+	-	-
Rhagodia drummondii Moq. in DC.	RHADRU	N	-	+	-	-	-
Rhodanthe floribunda (DC.) Paul G. Wilson	RHOFLO	Th	-	-	-	+	-
Scaevola spinescens R.Br.	SCASPI	N	-	+	-	-	-
Senecio glossanthus (Sonder) Belcher	SENGLO	Th	-	-	+	+	-
Stenopetalum sphaerocarpum F.Muell.	STESPH	Th	-	-	+	-	-
Triglochin calcitrapa Hook.	TRICAL	Th	-	-	+	-	-
Trisetaria cristata (L.) Kerguelen	TRICRI	Th	-	+	-	-	-
Wurmbea dioica (R.Br.) F.Muell.	WURDIO	G	-	-	+	-	-
Crustaceous lichens	CRULIC	-	-	-	-	-	+
Gelatinous lichens	GELLIC	-	-	+	+	-	-

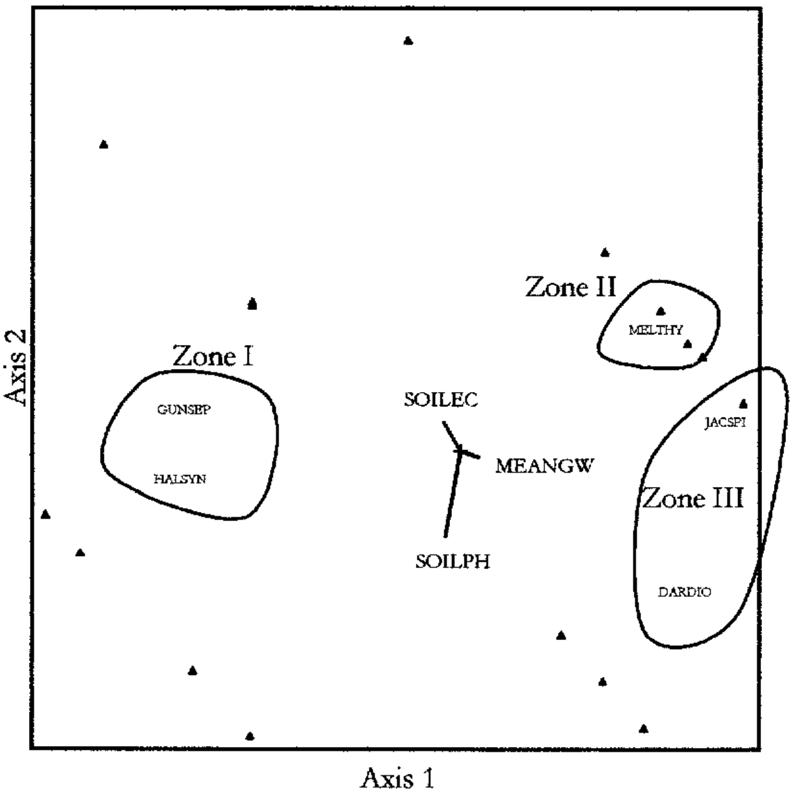


Figure 7.5: CCA ordination of siliciclastic dune (site 1). Zones are as described in Table 7.2. Environmental and species variable codes are as given in Tables 7.4 and 7.6 respectively.

Table 7.8: Cumulative variance explained (%) and species-environment correlation for each axis in CCA ordinations shown in Figs. 7.5-7.7. Statistical significance of each axis, as determined by Monte Carlo tests, is shown as an asterisk ($P < 0.05$) or ns (not significant).

Site	No.	Fig.	Cumulative variance explained (%)			Species-environment correlation		
			Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3
Siliciclastic dune	1	7.5	31.8 *	38.9 ns	39.6 ns	0.966 *	0.542 ns	0.175 ns
Dune swale	13	7.6	19.2 *	26.3 *	31.1 *	0.834 *	0.668 *	0.724 *
	14	7.6	10.3 *	15.4 ns	19.3 ns	0.892 *	0.711 ns	0.685 ns
Gypsum dune bed	15	7.7	26.1 *	35.9 ns	42.1 ns	0.938 *	0.615 ns	0.690 ns
Scree slope	11	7.7	35.1 *	54.1 ns	67.3 *	0.981 *	0.871 ns	0.877 *

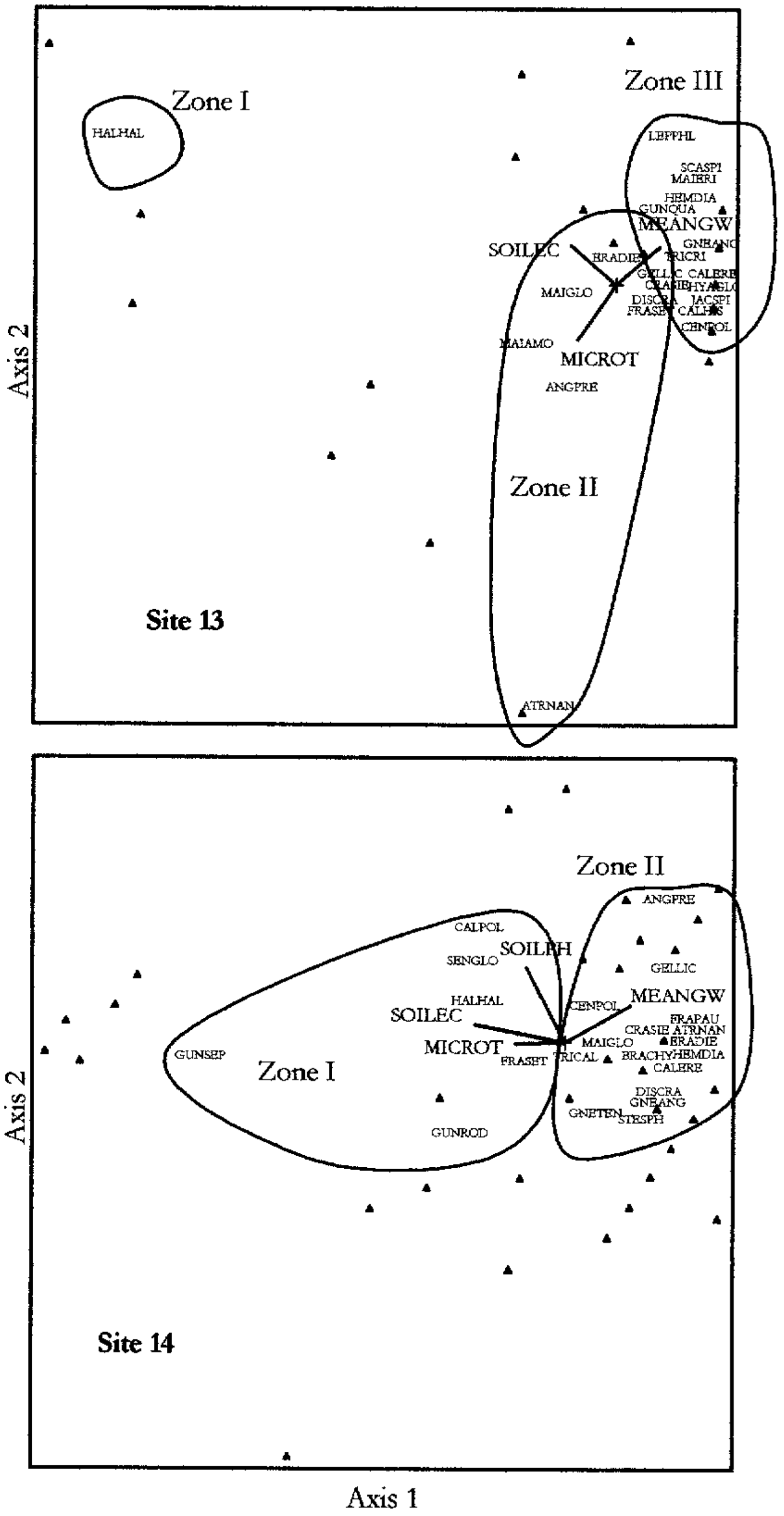


Figure 7.6: CCA ordination of dune swales (sites 13 and 14). Annotation as per Fig. 7.5.

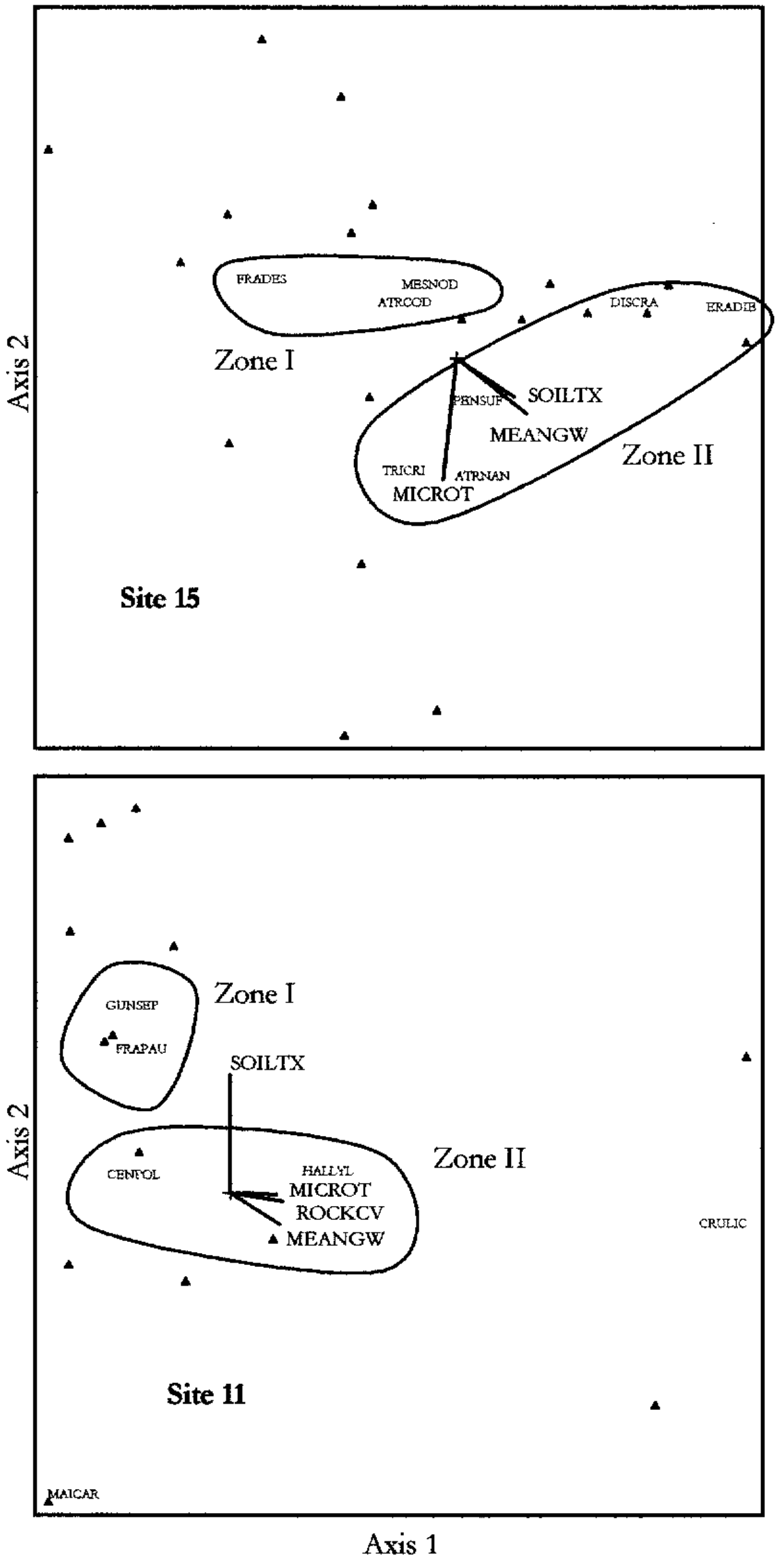


Figure 7.7: CCA ordination of exposed gypsum dune beds (site 15) and scree slope site 11). Annotation as per Fig. 7.5.

Figure 7.8: a) Lake shore at Site 1 with *Halosarcia syncarpa* shrubs along lake edge and *Melaleuca thyoides* (live plants and dead stumps further up dune); b) *M. thyoides* shrub (2 m tall) near lake edge; c) *H. syncarpa* shrub (0.8 m tall) at lake edge (bar = 100 mm).

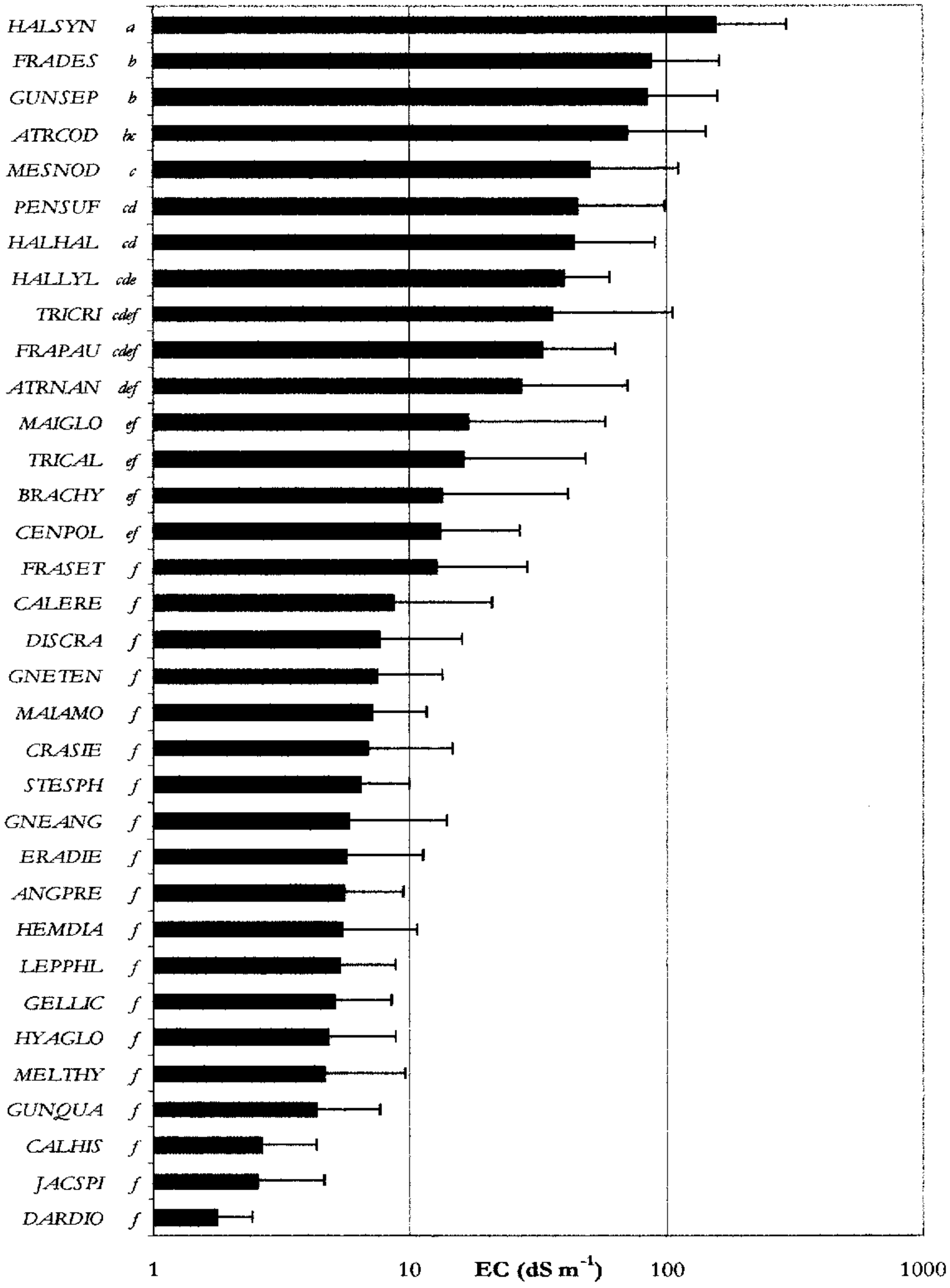


Figure 7.9: Log plot of mean ±SE soil EC$_e$ values for each species. Letters indicate groups of significantly different ($P < 0.05$) EC$_e$ values as determined by ANOVA with LSD to separate groups. Species codes are as per Table 7.7.

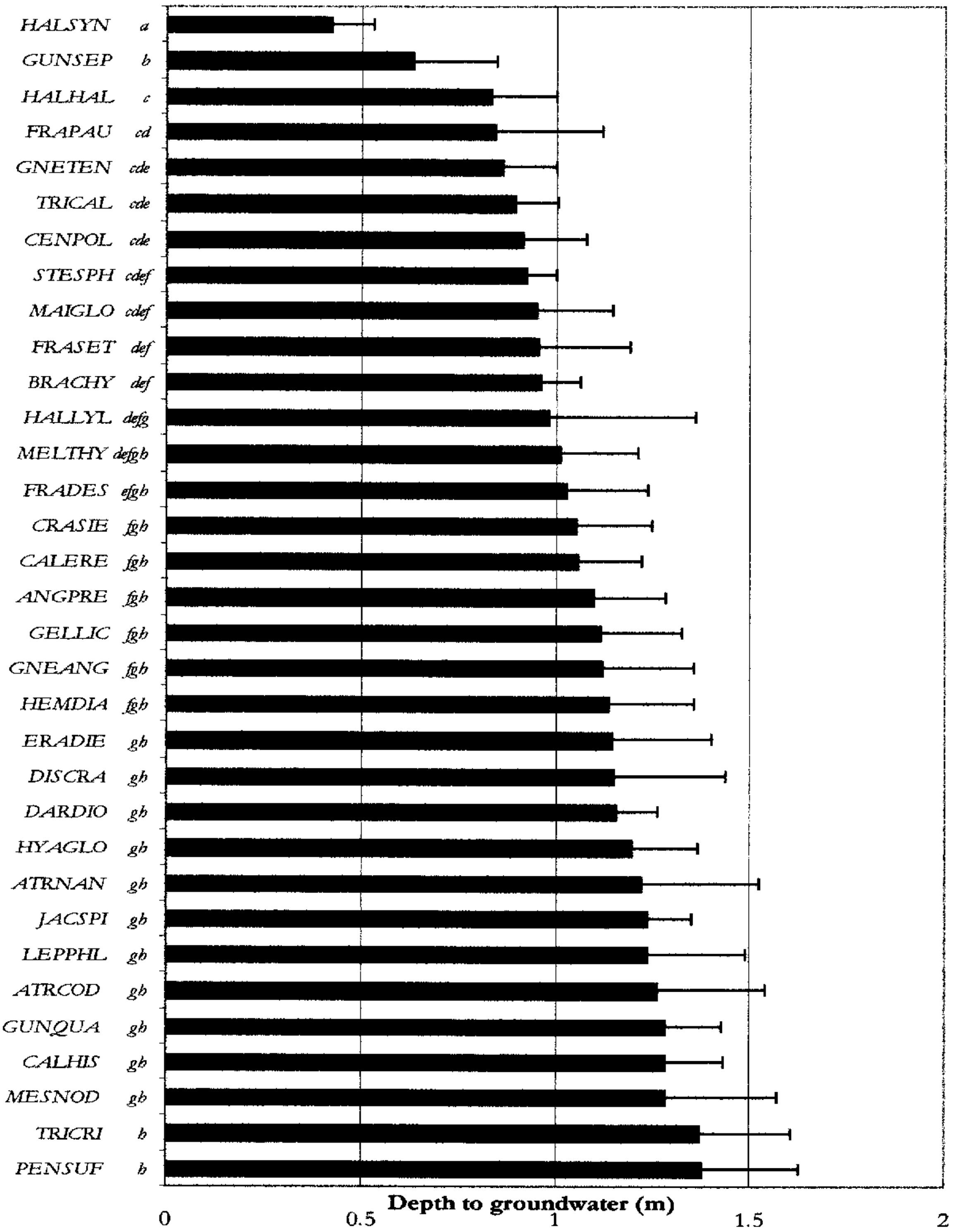


Figure 7.10: Plot of mean ± SE depth to groundwater (m) for each species. Letters indicate groups of significantly different ($P < 0.05$) values as determined by ANOVA with LSD to separate groups. Species codes are as per Table 7.7.

7.4 Discussion

The vegetated southern and eastern lake shores of Lake Lefroy show a wide range of environmental and floristic characteristics. These characteristics are strongly influenced by aeolian processes, in particular the strong northerly winds that can occur during summer (Clarke, 1994a). Westerly winds that occur during winter also have an impact by moving sandy material occurring along the eastern lake shores further eastwards such that the dune formations occur away from the lake shore, exposing the base of former dunes. An assessment of eight important environmental variables showed that they could be grouped according to aspect in particular (Fig. 7.3).

Vegetation plays a modifying role in stabilising lake shores such that miniature dunes are formed, similar to those described by Brown and Porembski (1997, 1998) in Kuwait. These miniature dunes occur on dune swales and on the exposed gypsum dune beds around Lake Lefroy. They may indicate a tolerance by certain species of burial by aeolian material, a characteristic viewed as important in determining zonation in coastal dunes (Maun and Perumal, 1999). These miniature dunes are also likely to act as resource islands for other plant species. This is an aspect of the ecology of the lake shores of Lake Lefroy that deserves further investigation.

Another important determinant of the structure and zonation in vegetated lake shores is groundwater. As all groundwater is highly saline, it is likely to be a strongly limiting factor for plant growth and development. This is particularly so along the vegetated margins of the lake as these are believed to be the main zone where evaporation of groundwater occurs freely, in contrast to the dry lake surface where evaporation of groundwater is inhibited by salt crusts and very low hydraulic conductivity in lake sediments (Malek *et al.*, 1990; Thorburn *et al.*, 1992) and by a substantial soil cover as the elevation of the lake shore increases. Determinations of groundwater quality conducted in this study tended to support this assessment. The vegetation that occurs in this zone, therefore, must be tolerant not only of high groundwater levels but of saline groundwater further concentrated by evaporation processes within the salt lake system. Perennial plant species occurring in this zone included several species in the genus *Halosarcia*, chenopods often associated with salt lakes and very saline conditions (Chapter 3). *Halosarcia* spp. are able to take up substantial quantities of salts within their tissues (Chapter 3). They are likely to be able to counteract the strong osmotic effects by compartmentation of solutes at the cellular level (Short and Colmer, 1999). Other species occurring in this zone use different mechanisms to survive. For example, *Gunniopsis septifraga* is a succulent therophyte that can complete its life cycle during winter while conditions are at their most favourable. Other perennial species, such as the *Frankenia* spp., survive through active excretion of salt through glands on the leaf surface (Thomson, 1975).

At most sites, an increase in elevation of 0.2-0.3 m was sufficient to permit the establishment and growth of numerous other plant species (Zone II). These included a range of perennial halophytes, such as *Atriplex nana, Halosarcia lylei* and *Maireana glomerifolia. Melaleuca thyoides* on the dune sands, and several species associated with Zone 1, including *Halosarcia halocnemoides,* also occurred in Zone II. The dominance of the latter was reduced as, although the environmental conditions were more favourable, other species were able to compete successfully for the available resources. With further increases in elevation, soil EC_e was reduced to low levels (<5 dS m^{-1}) and shrubs such as *Jacksonia spinosa* could establish and become dominant. This competitive relationship has been observed in other habitats where zonation is apparent and relates to the displacement of competitive subordinates to the more abiotically stressful habitats (Bertness, 1991) although competition alone is unlikely to explain the distribution of the Zone I halophytes. They are likely to have, to some degree at least, physiological and morphological characteristics restricting them to areas of high moisture availability. A further factor that may influence zonation that was not considered in this study is episodic inundation of lake shores. Extensive flooding of Lake Lefroy occurred in 1992 (Clarke, 1994a) and this may have led to the death of some *Melaleuca thyoides* woody shrubs at site 1 (see Fig. 7.8a). Other plant species, e.g. *Halosarcia* spp., are tolerant, to some degree, of inundation (Chapter 5) and may be better able to withstand occasional inundation and maintain their position at the lower elevations. Episodic inundation, thus, may play a role in determining plant distribution within zones.

This study highlighted the effects aeolian processes have on the formation of salt lake shores. These effects occur at the 'macro' level with zonation at particular lake shores controlled by other factors including depth to groundwater and soil EC_e. Relatively small differences in elevation produced large differences in species composition and soil characteristics. The design of land rehabilitation programs for disturbed areas with features in common with salt lakes would need to take account of these factors. Indeed, the findings of this study have direct application for the increasing occurrence of disturbance of salt lake surfaces by mining activity, including substantial developments on Lake Lefroy itself (Dames & Moore, 1999). The recreation of sustainable landforms on the surface of salt lakes will depend on an understanding of the processes governing them. In this study, important factors were the direction of the prevailing wind, depth to ground water and soil texture. The study also highlighted a number of species with potential for use in saline land rehabilitation, particularly in areas where saline groundwater occurs close to the surface.

8.0 SUMMARY AND CONCLUSIONS

8.1 Introduction

The purpose of this thesis was to help broaden existing approaches to the rehabilitation of saline land after mining in the semiarid Eastern Goldfields region of Western Australia. Existing guidelines (Department of Minerals and Energy, 1996a), although not intended to be prescriptive, have been closely followed in many instances, even where alternatives that may have provided a better outcome should have been considered. Innovation in approaches to land rehabilitation issues in recent years has been limited (Cannon, 1996). This thesis examined aspects of the ecophysiology of halophytes that might lead to the more efficient use in land rehabilitation programs of halophytes generally, and the more widespread use of selected halophytes with potential to play important roles. It also examined some possible alternative approaches to rehabilitating highly saline landforms.

8.2 Ecophysiology of halophytes

8.2.1 Germination of halophytic seeds

An understanding of the ecophysiology of halophytes is critical for the successful and cost-efficient revegetation of severely salt-affected land after mining. This is particularly so at the germination stage which most dictates whether these revegetation efforts will be successful. While the seeds of halophytes have evolved strategies for survival in saline environments (Ungar, 1995), the specific responses between species need to be considered to ensure seed collection and/or purchase is undertaken in a manner in which the outcomes are optimised.

In the experiments on germination response to NaCl conducted in Chapters 2 and 3, seeds of all halophytic species were able to germinate in NaCl solutions up to 20 g L^{-1} and also showed an ability to recover and germinate after exposure to higher NaCl concentrations. Other physiological responses were noted during the course of the experiments. These responses included:

- Distinct patterns of germination among the native chenopods where salt-induced dormancy was more marked among the perennial species; and
- More rapid germination in some species after induction of dormancy by high NaCl solutions and subsequent return to low NaCl solutions.

The latter has practical implications whereby seed could be 'primed' prior to sowing to accelerate germination in the field and the physiological mechanism by which this response occurs warrants further investigation. An hypothesis developed here (Chapter 2) suggests that germination is accelerated because the solutions with high NaCl concentrations (> 20 g L^{-1}) may dissolve salts contained within the seed while still preventing germination occurring. Subsequently, germination occurs more rapidly when the seeds are transferred to solutions with lower NaCl concentrations because the salt contained within the seeds has already been reduced or removed.

Another possible tool for use by revegetation practitioners is the Tolerance Index (TI) described in Chapters 2 and 3. The TI, based on the fundamental characteristics of halophytes seeds described by Ungar (1995), provides a means by which the germination responses to NaCl by different species can be assessed and compared. This potentially can be used to tailor seed mixes for particular revegetation scenarios and to determine the level of salt tolerance of particular species, or of particular provenances of the same species.

With respect to field establishment, the responses recorded here suggest that colonising annual and short-lived perennial species will establish first, especially in more saline situations, while allowing the subsequent germination of the seeds of perennial species. More needs to be known about seed bed conditions in saline soils. Future research should focus on the impact of rainfall on seed beds and what actual levels of salinity occur at the soil-seed interface.

8.2.2 Seed dormancy in *Halosarcia pergranulata* subsp. *pergranulata*

Halosarcia pergranulata subsp. *pergranulata* is a succulent halophyte with potential for use in revegetation programs where saline land is involved. Research conducted in this thesis showed that only about half of the viable seeds of this taxon, however, germinate freely. This is due to the crustaceous testa present in this taxon and a number of other *Halosarcia* spp. In *H. pergranulata* subsp. *pergranulata*, this testa-induced dormancy could be relieved by removing a small portion of the testa. This was most effective when done at the distal, or micropylar, end of the seed – thus, the micropyle appears to be the key structure in controlling ingress of water and oxygen. Physical dormancy of the seed itself, however, is rare in halophytes (Baskin and Baskin, 1998) and it does not appear to have been recorded previously in the Chenopodiaceae. Further study of the permeability of the micropyle is required to understand the factors controlling germination and to permit the reliable use of this species in land rehabilitation. The findings of this study have implications for the germination requirements of other *Halosarcia* spp. with a crustaceous testa.

8.2.3 Early growth in *Halosarcia* spp.

Early growth under saline conditions was studied in *H. halocnemoides* subsp. *halocnemoides* and *H. pruinosa*. Both taxa demonstrated substantial salt-tolerance during early growth. Accumulation of shoot organic matter for both was slow but continued at the highest NaCl treatment (40 g L^{-1}). Root growth, however, was reduced by 40 g L^{-1} NaCl in both taxa and shoot:root ratios were sharply higher at this concentration. This response suggests that growth and survival in the longer term will be reduced at this NaCl concentration.

Other than the continued accumulation of organic matter, salt-tolerance in these taxa was characterized by the:

- Ability of shoots to make osmotic adjustments under increasing external NaCl concentrations.
- Lack of evidence of ion toxicity.
- Reductions in π_{sap} corresponding with the increasing ash content of shoots.

Increasing succulence, a common strategy used by halophytes to cope with increasing salinity, was not observed. At the cellular level, it is assumed an osmotic balance is made possible by the presence of unidentified organic solutes within the cytoplasm to counter NaCl in the vacuole. Further work could concentrate on determining the organic solutes present and understanding the mechanisms by which they assist these taxa to make the necessary osmotic adjustments.

8.3 Alternative approaches to rehabilitation

8.3.1 In-situ treatment of saline substrates

Chapter 5 described the rehabilitation treatments of the land surface after old gold mine tailings had been removed for retreatment using high pressure hypersaline water. This exposed the underlying alkaline silt loam soil after up to 60 years of coverage by the tailings and left them highly saline ($EC_e > 50$ dS m^{-1}) and resistant to revegetation.

The main experimental treatment involved ponding good quality waste water behind small embankments and allowing it to infiltrate into the soils. While this treatment significantly enhanced the establishment and growth of vegetation compared with areas which received rainfall only, it did not lead to a decrease in soil EC_e after 2.5 years and, of other soil parameters measured, only P was significantly increased by the treatment. These findings suggests that, even in highly saline soils, if revegetation is being carried out with highly salt-tolerant species, it may not be necessary to leach or otherwise remove the salts from the soil. Indeed, in finely-textured soils, it may not be possible to leach much of the salt contained within the soil as ponded water infiltrates the soil along preferred pathways and may not sufficiently permeate the aggregates to dissolve and convey salts downwards. The successful establishment of vegetation is believed attributable to the additional water that would have temporarily reduced the EC of soil water, effectively elevating and prolonging the P/E_p ratio during the critical period, such that germination and establishment could occur widely.

The better-performed plant species included *Atriplex amnicola* and *Halosarcia pergranulata* subsp. *pergranulata,* two species that are also suitable for the revegetation of salt-affected agricultural land in Western Australia (Malcolm and Swaan, 1989). While water ponding was not conducted continuously within experimental plots, it was evident that deeper (50-100 mm), more frequent (continuous standing water for periods of 3-5 days) ponding favoured establishment of *H. pergranulata* subsp. *pergranulata* while shallow, less frequent ponding favoured establishment of *Atriplex* spp. and others. This should be a consideration should this approach be adopted elsewhere and the ponding conducted should be aligned with the revegetation outcome desired.

8.3.2 Surface covers

The value of soil cover over a hypersaline tailings surface was studied in Chapter 6. The capillary 'breaks' tested here were very effective in preventing the rise of salts into the overlying topsoil layer, significantly reducing salinity and sodicity. The salinity levels in the topsoil only cover, in particular, were likely to severely limit the establishment and survival of even highly salt-tolerant vegetation. The source of this salinity was in water rising by capillary action from the tailings below. Where the moisture content of tailings is low, it may not be necessary to use capillary breaks but their use should be considered in any areas likely to accumulate water.

Although plant survival in the soil covers tested here was favourable, long-term survival without supplementary water was not tested. Any cover in a semiarid area must be able to maintain a reasonable level of soil moisture to ensure plant survival through hot, dry periods. The typical rooting patterns for different species, where known, should be considered when selecting species for use on covers and, indeed, root competition may be a limiting factor for above ground biomass.

8.3.3 Ecology of salt lake shores

In Chapter 7, the biological and environmental characteristics of an ecosystem where high salinity is a naturally occurring feature were examined. The lake shores of a salt lake, Lake Lefroy, show a range of environmental and floristic characteristics, strongly influenced by aeolian processes, in particular the prevailing westerly winds that can occur during winter. Following preliminary studies, a group of eight important environmental variables was selected for analysis at five sites. Using multivariate analysis, the variables could be clearly grouped according to aspect (predominant wind direction). This, in turn, affected other important shoreline characteristics such as soil texture and soil EC_e, and depth to groundwater.

An important aspect of this study was the relationship between these environmental variables and the vegetation occurring on the salt lake shores. The zone of vegetation closest to the bare salt lake surface (Zone I) occurred on highly saline soils with a very shallow saline groundwater table. The species occurring within this zone exhibited the necessary physiological characteristics to cope with saline soils and water, and an elevated water table. At most sites, an increase in elevation of 0.2-0.3 m was sufficient to permit the establishment and growth of numerous other halophytic and glycophytic plant species (Zone II) in the loamy sands and sands comprising the lake shores. Additionally, on dune swales and exposed gypsum dune beds, miniature dunes (0.2-0.3 m tall) occurred which became foci for numerous plant species not occurring in the interdune intervals. This phenomenon is a result of the interaction between aeolian processes and certain key plant species, and has implications for the construction of landforms for disturbed areas around the lake. It is worthy of further investigation.

The recreation of sustainable landforms on the surface of salt lakes will depend on an understanding of the processes governing them with prevailing wind direction, depth and salinity of groundwater, and soil texture all likely to play critical roles. Lessons learnt from this study have implications for approaches to rehabilitation of disturbed saline land as salt lake shores provide an illustration of plant establishment and survival across a range of environmental conditions where soil and groundwater salinity are important factors.

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