DIRECT REVEGETATION TECHNIQUES FOR COAL TAILINGS DAM NO. 3 AT SARAJI COAL MINE CENTRAL QUEENSLAND

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B. App. Sci. (CQU)

MASTER OF APPLIED SCIENCE

2003

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by

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A thesis submitted for the degree of Masters in Applied Science

to

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24.3.2003

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ACKNOWLEDGMENTS

The author is grateful for the financial and technical support that BHP Saraji Mine has offered. Thanks to Dr. Dave Mulligan of the University of Queensland, Centre for the Rehabilitation of Mined Land for assistance in constructing the water release curve, providing literature and advise and reviewing this manuscript where requested. In regard to the establishment of experiments and statistical analyses, input from Dr. Alistair Melzer and Dr. John Sibley of the Central Queensland University was also gratefully appreciated.

I wish to record my sincere gratitude to my supervisor, Dr. Kerry Walsh, whose guidance and light hearted attitude, I would have floundered many times without.

Finally, to my darling wife Jennifer and children, Joshua, Kaitlin and Eloise. I dedicate this project to you, for you have earned it through patients and tolerance.

DECLARATION

I hereby declare that this thesis is my original work and none of the information has been previously submitted for any degree at any University.

Signature Redacted

Bradley John Radloff

Abstract

Coal tailings are produced as a waste product from washing the fine < 2 mm fraction of mined coal to add value to the saleable product. After washing, slurried tailings are pumped to holding dams for disposal and desiccation. Once full the core of these dams dry slowly limiting vehicular access for reprocessing or rehabilitation works. In areas where evaporation exceeds rainfall, a dry surface crust, susceptible to generating wind blown dust, develops during this desiccation phase. A revegetation strategy involving establishing vegetation directly on coal tailings was therefore developed, to reduce wind blown dust hazards whilst maintaining the potential for later coal extraction.

The field studies for the project were conducted on tailings dam number 3 at Saraji Mine in central Queensland. The dam had a storage capacity of approximately 4 Mm^3 (20 m high; 23 ha surface area) and had not been used for tailings disposal since 1985. Substrate characterisation indicated the the tailings consisted of approximately 60 % coal and 40 % inorganics such as inherent clay and pyritic material of predominantly silt particle size. The tailings would only allow the growth of very salt tolerant plants, with an average $EC_{1:5}$ of 2.5 dS m^{-1} at the surface (0-10 cm). The substrate pH was generally in the range 6.5-8.5, except in the immediate area of the discharge points (dam filling points) where the pH was much lower ($pH_{1:5}$ 2-4, c. 2.5 ha). Nutrient analyses indicated a low CEC (< 20 cmol(+) kg^{-1}), with deficiencies in N (0.6 mg NO_3-N kg^{-1}) and P (bicarbonate extract, 6 mg PO_4 kg^{-1}) potentially limiting to plant growth. Plant available water was low in the surface of the dryland but increased to levels acceptable for plant growth at 30 cm in

depth. In the wetland plant available water was adequate for plant growth but the material was poorly aerated where moisture content was high.

Laboratory germination trials were undertaken to establish the salt tolerance of 11 species, using salt extract from the tailings. *Acacia harpophylla* germinated (> 50 %) within four days, even at high salinity (EC 20 dS m^{-1}). In contrast, salinity markedly delayed germination in the other species (eg. *A. salicina*). A glasshouse pot trial was then undertaken to consider the effect of topsoil covering and mulching on the germination and growth of 11 species. No germination was recorded on bare tailings, a result ascribed to salinity and poor aeration. A glasshouse nutrient trial was used to examine the effect of nitrogen, phosphorus and potassium fertiliser on the growth of *Chloris gayana* in tailings substrate. The results found tailings nitrogen and phosphorus levels were limiting to plant growth as indicated by chemical analysis.

Field trials were established with the aim of creating both wetland and dryland zone plant communities, in both cases using species recognised for their salt tolerance. Techniques to decrease surface salinity and increase plant available moisture and nutrients were trialed. In the wetland zone, a factorial experiment (5 replicates) involved three rates of fertilisation (0, 650, 1300 kg ha^{-1} Osmocote™ 14 month plus) and three rates of mulching (0, 10, 20 t sugar cane-tops ha^{-1}). Each plot (2 m by 2 m) was planted with *Vetiveria zizanioides*, *Sporobolus virginicus*, *Typha domingensis*, *Phragmites australis*, *Casuarina glauca* and *Sarcornia* sp. Vetiver grass gave excellent establishment and growth, particularly at the highest fertiliser rate, and is recommended for wetland use. The other species, with the exception of *Sarcornia* sp. that did not survive, were not as vigorous colonisers as Vetiver but may add some diversity to the community over time.

In the dryland zone, a factorial field experiment (3 replicates) considered three mulch conditions (nil, 10 t ha^{-1} cane-tops, plastic horticultural mulch, 2 levels of cultivation (nil, 15 cm depth) and irrigation (nil, T-tape delivering 1 L m^{-2} day^{-1} applied at 3 day intervals) with respect to *C. glauca* tubstock survival and growth. Each plot consisted of a 22 m row fertilised with 1300 kg ha^{-1} Osmocote™ 14 month plus and planted with 30 cm high tubestock every 1 m. *C. glauca* survival and growth was greatest under mulched and irrigated treatments with survival > 90% and growth of 2 m in height, 14 months after planting. The establishment of *C. glauca* by planting in irrigated and mulched rows is therefore recommended for the dryland area to provide windbreaks and potentially dewater the tailings beneath the surface crust through transpiration.

To investigate the potential for the direct seeding of tailings, a randomised complete experiment consisting of 5 mulching treatments (0, 2, 5, 10 t ha^{-1} lucerne hay mulch, 10 t ha^{-1} cane tops mulch) and fertilised with 1300 kg ha^{-1} Osmocote™ 14 month plus was established in the field. The experiment was seeded with six salt tolerant tree, one saltbush and two salt tolerant grass species. Nine months after seeding, the grass *Chloris gayana* was dominant, increasing in projected foliage cover to 54 % under 10 t ha^{-1} lucerne hay mulch and 10 t ha^{-1} cane tops mulch. In bare tailings no germination was recorded. Although the tree and saltbush species *Acacia holosericea*, *A. harpophylla*, *A. salicina* and *Atriplex lentiformis* germinated, all plants were < 5 cm high nine months after sowing and the density of germinants was low (1 per square meter) given the number of viable seeds applied per plot (10 600). The low tree and saltbush growth after nine months was attributed grass competition. The establishment of *C. gayana* by mulching at 10 t ha^{-1} with lucerne hay mulch and direct seeding is therefore recommended as a broad acre ground cover. Further monitoring work on this trial to determine the longer term fate of the tree species, and research into establishing trees by direct seeding without the influence of grasses is recommended.

This thesis demonstrated the establishment of salt tolerant vegetation was possible on tailings dam number three at Saraji Mine and, therefore, revegetation with the view of minimising dust and maintaining access was feasible. Treatments that facilitated vegetation establishment in the field were those that decreased salinity and increased plant available water (mulching and irrigation). Nitrogen and phosphorus fertiliser additions were shown to be necessary in the glasshouse. Given that low plant available water and high salinity were the major limitations plant growth, provided follow up fertiliser is applied, trees and deep rooted vegetation should continue to survive and grow once their roots are have developed sufficiently to access the higher moisture/lower salinity sub-surface tailings. With increased vegetative biomass, the volume of leaf litter produced and dropped onto the tailing surface would increase and "self mulching" could occur. Further monitoring to investigate the longer term "self mulching" potential, *C. glauca* water usage rates and changes in species composition are recommended.

1. INTRODUCTION

The development of a method of vegetation establishment on coal tailings dams in central Queensland is sought to reduce dust, help dewater the tailings material through transpiration and maintain access to a potential future resource. With approximately 1000 ha of un-rehabilitated coal tailings in central Queensland, the need for suitable vegetation establishment techniques is large. Given most tailings dams in central Queensland are at least 10 m deep, it is conservatively estimated that 100 Mt of coal tailings resource could be available for reprocessing should a cost effective method of managing dust emissions and maintaining or improving geotechnical stability be developed so that access to the resource can be maintained whilst reprocessing technologies are developed.

A number of studies have examined the directly rehabilitating coal tailings in America (Nawrot *et al.* 1991, Nawrot and Yaich 1992, Thompson 1998, Warburton *et al.* 1988). The studies utilised standard agronomic techniques to characterise the tailings in terms of plant growth. Salinity, acidity and low plant available nutrients were predominantly identified as the limiting factors to vegetation establishment. The American revegetation efforts were successful for at least four years after planting, with the establishment and spread of the planted wetland vegetation and the immigration of bird, amphibian and mammal species. Although these studies identified that establishing vegetation directly on coal tailings was possible, the techniques were not directly transferable to central Queensland as the American climate was considerably milder and the rehabilitation strategy relied on maintaining a water cover, which does not allow the tailings to dry and improve reprocessing opportunity.

The direct rehabilitation of coal tailings on one tailings dam in Australia has been described (Dwyer 1981). Like the American research, the Australian study identified high salinity, acidity, and low plant available nutrients as impediments to plant growth but also described high surface temperature as a potentially liming factor. As such lime, fertiliser and mulch were used to generate a suitable seedbed for the establishment and growth of *Phalaris* sp. from seed. This trial was deemed as successful 12 months after seeding when the coal mining company reclaimed the tailings for sale. The trial demonstrated that with appropriate establishment techniques, grass can be established on tailings by direct seeding and as such amelioration and direct seeding may prove successful for rehabilitating tailings on a broad area basis.

In 1990, a direct seeding attempt at BHP Saraji tailings dam no. 3 in the Bowen Basin was severely damaged soon after seeding by torrential rain associated with a cyclone. Although much of the mulch and seed was washed away, trees, saltbush and grasses established. As a result of these promising indications BHP Saraji supported the research undertaken in this thesis.

The aim of this thesis was to develop a method of directly (without capping) establishing vegetation on coal tailings dams in central Queensland through characterising the material in terms of plant growth, selecting suitable species and establishment techniques too facilitate plant growth and trialling these species in glasshouse and field trials in coal tailings. The research focused on establishing cover species for the suppression of dust and trees for dewatering the tailings substrate below the surface crust. Coal tailings dam no. 3 at Saraji Mine was the study site for the work within this thesis.

2. LITERATURE REVIEW

2.1 Production, Disposal and Characteristics of Coal Tailings

The majority of coal mined in Australia is black coal from which coking and steaming coals are produced. To produce coal of market specifications, the mined (run-of-mine) ore is often processed within a coal preparation plant. Processing involves crushing, screening and washing the run-of-mine (ROM) ore to separate the combustible organics from inorganic contaminants, thereby lowering the ash content of the coal product and increasing its market value (Williams 1994).

The coarse (typically 2–150 mm) and fine (< 2 mm) wastes from the coal washing process are referred to as coarse reject and coal tailings (tailings), respectively (Williams 1992). Coal tailings typically represent approximately 10 % of the ROM production and contain approximately 50 % of inorganics and coal (Williams 1992, Canibano and Leininger 1987). The exact proportion of tailings to coarse reject and the total mine yield (ratio of saleable to ROM product) however, are dependent on the ROM and product coal characteristics and the technology employed in the washing plant (Gerard, Porteous pers. comm.).

Following production, tailings are typically thickened to a slurry of approximately 35% solids by adding polyanionic flocculents (Shannon and Booth 1980) and pumped to tailings dams of up to 150 ha in area and 30 m in height for disposal (Merritt, Cameron, Porteous pers. comm.). Dam filling is normally conducted from a single discharge point close to the preparation plant to minimise the infrastructure and pumping energy required. Coal tailings dams in the Bowen Basin are typically constructed on the existing landform ("turkey nest" dams) by dumping overburden (spoil) or coarse reject to form the dam walls (Williams 1994). A small number of coal tailings dams have also been constructed by building an earthen wall across a natural valley and diverting natural runoff around the structure with diversion drains.

In the dam, tailings are left to dry through surface evaporation and drainage from the dam walls and base. Surface evaporation is a dominant drying process in central Queensland tailings dams as pan evaporation is approximately three times rainfall (approximately 2000 mm pan evaporation vs 700 mm rainfall, Lloyd 1984). Consequently, central Queensland tailings dams typically establish a consolidated surface crust with wet unconsolidated material beneath (Williams 1992). At this stage energy such as the emplacement of capping material or exposure to evaporative energy needs to be applied to further dam drying and consolidation. Due to the fine nature of the tailings the dry surface material becomes susceptible to wind blown dust generation potentially resulting in off-site environmental contamination.

2.2 The Need for a Tailings Dam Direct Revegetation Strategy in Central Queensland

Current tailings dam rehabilitation strategies involve capping tailings dams with a minimum of 1 m of overburden before establishing vegetation (Johnson 1992, Department of Minerals and Energy 1993). Before capping can commence, the tailings deposit must consolidate sufficiently to support heavy machinery, a process taking up typically two to five years (Merritt, Cameron, Porteous pers. comm). Mine operators are also reluctant to prematurely cap tailings deposits and increase the cost of coal recovery should improvements in technology render reprocessing economically viable (Gerard, Cameron, Merritt pers. comm.). Bell *et al.* (1987) outlined successful tailings rehabilitation practices for Mt. Isa mine tailings (copper, lead and zinc) and bauxite red mud tailings but stated that little work had been done on the rehabilitation of coal tailings dams in Australia. In 1992, approximately 1000 ha of coal tailings dams had been created across the coal mining areas of Queensland, and only approximately 5 % of these had been capped (Cameron pers. comm.). With an increase in the number of mines in the Bowen Basin over the last 10 years and few mine closures it is envisaged that the areas of uncapped tailings have increased.

To reduce the potential for the generation of wind blow dust and maintain access to a potential future resource, an interim tailings rehabilitation strategy involving the establishment of vegetation directly on the tailings surface is sought. Ideally the vegetation structure would consist of grasses for ground cover and trees for wind breaks and water pumps to consolidate the tailings beneath the crust through transpiration. Ideally the vegetation system would be self sustaining to minimise maintenance and management inputs prior to dam capping.

2.3 Alternative Uses for Coal Tailings

The potential exists to use coal tailings beneficially in engineering applications such as road building and pavements (Indraratna *et al.* 1994), and structural fill (Indraratna 1994) after mixing tailings with coarse rejects and preferably cement. The small particle size of the tailings material however, limits it's suitability to structural engineering applications and the volume of tailings material that can be added to these mixes before detrimentally effecting the engineering properties. Thus the volume of tailings that can be disposed of in this manner is relatively limited, particularly when considering the costs of transporting the material from the mine to the construction site.

With a coal content of approximately 50 % (Office of Energy, 1991) the largest potential usage for tailings is in energy production. The energy stored within coal tailings can be released and captured to do work through various methods. Such methods include improvements in coal processing technology such as micro-flotation to improve saleable yield (Welch pers. comm.). The briquetting of the dried tailings from old tailings dams within a double roll press to form a power station feed product has also recently been successfully proven (Kirsten 2001). Combustion of tailings with coarse reject in custom built fluidised bed combustors (Office of Energy 1991) has to date proven the most successful method of tailings use internationally and an Australian plant has been successfully commissioned at Redbank Power Station.

The extraction of coal from tailings by hydrophobic mineral oils with the mixture used as fuel for power generation has also recently been trialed (Duong *et al.* 2000). Other methods of tailings usage are as rudimentary as re-excavating dried tailings dams and blending with saleable coal should product specifications and economics allow such opportunity (Cornock pers. comm.). The use of tailings for energy generation is currently highly dependent on the availability of local power generation infrastructure or a mass of suitable tailings and rejects to enable the cost effective construction of infrastructure such as was the case at Redbank. However with improvements in reprocessing and usage technologies, tailings deposits of no current value may be reworked at some time in the near future.

2.4 Major Constraints on the Direct Revegetation of Coal Tailings

Extensive work has been undertaken on Australian tailings to understand engineering properties relevant to their disposal and rehabilitation (Williams and Morris 1987, Williams and Morris 1988, Williams and Morris 1990). However, there are few reports in the literature of attempts to establish vegetation directly into tailings within Australia. Dwyer (1981) successfully established grasses and legumes on a tailings dam in the Western Coalfields of NSW after characterising the parameters limiting to plant growth and implementing appropriate amelioration techniques. Vegetation establishment directly on tailings within Indiana and Illinois America has been successfully demonstrated (Nawrot and Yaich 1982, Thompson 1988, Warburton *et al.* 1988). These authors from the Co-operative Wildlife Research Laboratories of Illinois established vegetation directly on 550 ha of tailings over a 10 year period and propose the technique for dust suppression and tailings dam decommissioning as an alternative to capping.

A 4 ha revegetation trail involving direct seeding was established on the dryland tailings surface in December 1990 by BHP staff (Cameron pers. Comm.). The trial evaluated the establishment of native shrubs and trees, saltbush and exotic grasses in gypsum and mulching treatments. The treatments consisted of gypsum (unknown quantity) and gypsum in combination with lucerne hay mulching (20 t ha^{-1}). A native shrub and tree seed mix of *Acacia concurrens*, *A. holosericea*, *A salicina*, *Cassia nemophila*, *Casuarina stricta*, *Melaleuca amillaris*, *M. nodusa* and *Atriplex amnicola* was sown at a combined rate of 4 kg ha^{-1}. *Chloris gayana* cv. Pioneer (Rhodes grass) and *Cenchrus ciliaris* cv Biloela (buffel grass) were sown at a rate of 15 kg ha^{-1} per species. The trial was destroyed by torrential rain associated with cyclone Joy in January 1991. Evidence of the trial remained in late 1993 in the form of scattered *A. salicina*, *A. holosericea*, *C. stricta* trees, the saltbush *A. amnicola* and the grasses *C. gayana* and *C. ciliaris* which established within the mulched area.

Tailings mineralogy studies indicated that the major inorganic constituents of tailings are the clay minerals kaolinite, illite, illite/montmorillite and sulphide minerals such as pyrite and siderite in Australian (Williams and Morris 1987), German (Canibano and Leininger 1987), and American (Warburton *et al.* 1988) tailings. A result attributed to the common association of these minerals with coal deposits. The proportions of these minerals was highly variable however, reflecting the mineralogy of the parent coal material, washing methods and the desired characteristics of the final coal product.

Williams (1994) described tailings as predominantly silt classification having a particle size mostly in the range of 0.002-0.06 mm (Unified Soils Classification Scheme). However 40 % of the material may be clay (< 0.002 mm) or as much as 30 % sand (Williams and Morris 1990). Between tailings dams, particle size distribution varied with the parent material mined and washery sophistication, with maximum topsizes between 2.0-0.06 mm being obtained (Williams and Morris 1990). Williams and Morris (1990) report physical characters for West Morton, Hunter Valley and Bowen Basin Coalfields tailings some of which are relevant to plant growth (Table 1).

Table 1. Synopsis of tailings physical characteristics relevant to plant growth.

Parameter	Typical Values
particle size	50% passing 0.002-0.06 mm sieve
specific gravity	1.8 g cm^{-3}
bulk density	1.0 g cm^{-3}
hydraulic conductivity (sat)	10^{-7} cm s^{-1}
crust depth	0.1-1.0 m
Unified Soil Classification	low plasticity silt-high plasticity clay

After Williams and Morris (1990).

Williams and Morris (1987) and Nawrot and Yaich (1982) independently concluded that particles within the tailings slurry separated due to differential sedimentation once in the dam resulting in a gradient of particles deposited on the basis of their specific gravity and particle size. Heavy, large particles beached closer to the discharge (filling) point whilst the smaller or lighter particles remained in suspension and beached at the decant point where pooled water accumulated. Between the discharge and decant points were particles beached in accordance with a gradient of particles sizes and specific gravities. For example, Nawrot and Yaich (1982) reported that the percentage of sand and clay sized particles was 75 % and 10 %

respectively at the discharge point and 28 % and 49 % respectively 500 m away at the decant point. Similarly the authors reported that pyrite, due to its high specific gravity, accumulated at the discharge point.

After characterising tailings in agronomic terms Nawrot and Yaich (1982) found that this differential sedimentation process had profound implications on the direct establishment of vegetation. The differential settling of tailings particles in relation to their specific gravity and dam topography (sloping at 1:300-1:100 from discharge to decant point) created by the dam filling process, generated three distinct management zones with specific amelioration and species selection requirements (Nawrot and Yaich 1982, Warburton *et al.* 1998). These management zones were typically termed the discharge, intermediate and low zones (Nawrot and Yaich 1982, Warburton *et al.* 1998).

The discharge zone was in the proximity of the discharge point where pyrite and therefore potential acidity were dominant, resulting in acid conditions of as low as pH 2 being produced within 1-2 years of ceasing to fill the dam. In newly filled dams, pyrite contents of up to 13 % and resultant net neutralisation deficits of 150-200 t $CaCO_3$ ha^{-1} (0-10 cm incorporated) of tailings were common (Nawrot and Yaich 1982, Thompson 1988, Warburton *et al.* 1988). The low pH values indicated that pyrite oxidation by *Thiobacillus ferrooxidans* was the dominant acid generation process (Kleinmann and Crerar 1979).

Low discharge zone nutrient levels were attributed to the low cation exchange capacity of the sand sized particles, whereas, potentially phytotoxic metal ion (eg. Al, Fe; Mn) concentrations were considered to be a result of the acidity of the substrate (Nawrot and Yaich 1982, Warburton *et al.* 1988). Due to the combined effects of discharge zone being the highest point on the dam surface and the area being dominated by larger sand sized particles, low plant available water was recognised as an impediment to vegetation establishment (Nawrot and Yaich 1982, Warburton *et al.* 1988). Due to the high adverse chemical and moisture relations of the area the authors concluded that as a dam decommissioning strategy, the direct rehabilitation within the discharge zones was generally considered not feasible. The authors recommended liming the discharge tailings surface (0-10 cm) with c. 100 t $CaCO_3$ ha^{-1} and capping the area with 1-2 m of overburden as traditionally undertaken across the entire dam. The only discharge zones where vegetation was directly established in tailings, were those of older dams (c. 10-20 years) where pyrite concentrations had been reduced to below c. 4 % by uncontrolled oxidation (Nawrot and Yaich 1984).

Given the coal washing and tailings settling process concentrate pyrite in the discharge zone of tailings dams filled from a single point it is likely that high potential acidity discharge zones are relatively common and, therefore, need to be considered in the generation of direct revegetation strategies for tailings dams.

In contrast to the discharge zones, silt and clay particles predominated in the low zones and little pyrite was detected (Nawrot and Yaich 1982, Thompson 1988, Warburton *et al.* 1988). With distance from the discharge point neutralisation potentials decreased less dramatically than acid producing potentials resulting in a negligible net acid producing potential and circum-neutral pH values within the decant zones of all dams examined (Nawrot and Yaich 1982, Thompson 1988, Warburton *et al.* 1988). The higher cation exchange capacity and circum-neutral pH of the low zones resulted in the wetland having higher plant available nutrients than the remainder of the dam. In conjunction with high clay content, a characterising feature of the low was the presence of water, with the area being permanently or seasonally inundated. Consequently, the direct establishment of vegetation in the low zone was pursued.

The intermediate zone was characterised as a zone of transition between the discharge and wetland zone (Nawrot and Yaich 1982). The higher areas of the intermediate zone were more typical of the discharge zones whereas the lower areas were similar to the low zone. Key features of the intermediate zone included droughty surface conditions and net neutralisation deficits of 50-100 t $CaCO_3$ ha^{-1} (Nawrot and Yaich 1982, Thompson 1988, Warburton *et al.* 1988). Salinity was evident as indicated by surface (0-10 cm) $EC_{1:5}$ measurements of 3-10 dS m^{-1} however salinity was not considered a barrier to vegetation establishment provided salt tolerant vegetation species were used. Vegetation establishment was considered feasible within these areas and was pursued.

Nawrot *et al.* (1981) found the Montery Coal Co. no. 1 tailings dam to be sodic as indicated by the average ESP of 20 %. The majority of the tailings characterised in America however, were not sodic as calcium was the dominant cation bound to cation exchange sites (Nawrot and Yaich 1982, Warburton *et al.* 1988).

Direct vegetation establishment in tailings of low and intermediate zones was undertaken (Nawrot and Yaich 1982, Warburton *et al.* 1988). Prior to the establishment of vegetation, the substrate is characterised in terms of acidity, net neutralisation potential, salinity, nutrient availability and metal iron toxicity (where material was acidic). Appropriate amelioration techniques, species and establishment techniques were then defined. Nawrot *et al.* 1981 initially commenced directly establishing *Phragmites australis* on tailings due to its tolerance of low pH, high salinity wetland environments. *P. australis* was planted with 14 g of 12N:12P:12K fertiliser as 30-50 cm rhizomes in a vertical hole dug with a soil sampling T-bar. At the time of planting the pH of the tailings surface was circum-neutral as filling of the dam was only recently completed. Despite the acidification of the surface tailings, *P. australis* proved to be a successful species for establishment on tailings with a habitat used by migrating water foul created over 4 years.

The tailings direct revegetation effort described by Thompson (1988) relied on the liming of the intermediate and low zones with 30 and 20 t ha^{-1} of agricultural lime respectively, fertiliser addition and the sowing of a cover crop of grasses and legumes at 109 and 70 kg ha^{-1} respectively. The following year both zones were re-limed at previous rates to account for further acid generation and an extensive planting effort consisting of 12 500 trees incorporating 20 species and 46 000 wetland plants incorporating 22 species was undertaken. Between one year after dam abandonment and the time of tree and wetland plantings the surface pH of the area was raised approximately three to seven.

Four years after planting the vegetation cover across the tailings surface was 70-100 % and the plants well established. The area considered of significantly beneficial wildlife habitat with 11 vertebrate mammal and frog, 17 aquatic bird, nine terrestrial bird and four fish native or naturalised species identified. The species identified included small omnivores such as mice (*Peromyscus* sp.), herbivores such as deer (*Odocoileus virginianus*) and carnivores such as Coyote (*Canis latrans*) and Fox (*Vulpes fulva*).

After characterising the tailings in terms of agronomic properties, Dwyer (1981) established vegetation directly on a tailings dam at the Wallerawang Colliery near Lithgow in New South Wales, Australia. Dwyer (1981) identified acidity (pH 3.3-3.5), salinity ($EC_{2:5}$ 3.35-5.38 dS m^{-1}), low plant available moisture, low plant available nutrient (N, P, K) levels and the daytime temperature (c. 50 °C) of the substrate surface (0-10 cm) as the factors impeding plant growth. This study did not identify any marked difference in agronomic properties across the surface of the tailings dam.

Under a treatment of agricultural lime (21 t ha^{-1}), fertiliser (750 kg ha^{-1} 11N:34P:11K) and wheaten straw mulch (1 t ha^{-1}), *Phalaris* sp. colonised the tailings surface (c. 50 % cover) from seed. Unfortunately the long term viability of the vegetation cover was not studied as the mining company reclaimed the tailings dam 12 months after the trial was established for blending and sale with product coal.

The success of the Illinois Co-operative Wildlife Research Laboratories in regard to vegetation establishment on tailings rehabilitation may be attributed to the high water levels within the tailings dams during the establishment and monitoring periods. Indeed the more successful tailings dams revegetation attempts (Nawrot *et al.* 1981, Thompson 1988) were on dams rehabilitated soon (1-2 years) after, or just prior to the cessation of filling when moisture contents were high as evidence by the presence of water tables. Thompson (1988) refers to the raising and lowering of the spillway to manage water levels and the establishment of a wetland of c. 60 % of the dams area and the raising and lowering of the spillway to generate fluctuations in water height. It could easily be envisaged that a tailings dam with a high water table might be more conducive to the establishment of vegetation as plant available water would be more abundant and pyrite oxidation low.

In the case of central Queensland where many tailings dams exist in excess of two years from filling and evaporation is 3 times rainfall, the establishment of vegetation directly on the tailings surface may not be as portrayed for Indiana and Illinois. Further, the different ROM material quality, product specifications, washery feed water and washing technologies would result in a different tailings product. Consequently work on tailings undertaken in other coal basins, or even other mines may not be directly applicable to the direct tailings revegetation problem at hand.

Bell (1990) reported that sodicity was a factor that could affect the rehabilitation of overburden spoils in the Bowen Basin by producing a surface crust that was detrimental to water infiltration and seedling establishment. As sodicity was has been found associated with tailings and is common at Saraji mine (Cameron pers. comm.) there is potential for high sodicity within the tailings.

2.5 Methods of Ameliorating Acidic, Saline or Sodic Substrates

Acid Substrates

The optimum pH range for plant growth species is generally in the range of 6.5-8.5 depending on the plant species. Substrates with a pH < 5.5 are generally problematic in terms of plant growth under agronomic conditions (Aitken *et al.*1984). Highly acidic soils (pH < 4) have proven very difficult to revegetate as the high concentration of hydrogen and metal metal irons (predominantly Mn and Al), in combination with induced nutrient imbalances, are detrimental to plant survival and growth (Russell 1973, Koch and Bell 1983). Extreme acidity in coal mining wastes are generally a result of the oxidation of pyrite (Kleinmann and Crerar 1979). Bell (1986) reported that acidic spoils occurred in association with some from Hunter Valley and Bowen Basin Coal Mines, however, the occurrence of spoil acidification and acid mine drainage was not nearly as great as that in north America.

Soils low in pH are regularly ameliorated with the addition of lime (Mc Lean 1982, Rayment and Higginson 1992). Amelioration with lime is not considered appropriate at liming rates greater than 100 t ha^{-1} due to a high potential of re-acidification from residual pyrite and the cost of lime application (Bell 1990). In these cases the substrate may be capped with clean fill (Department of Minerals and Energy 1993) or acid tolerant species selected if a permanent solution is required (Bell 1990). In applying clean fill, precautions need to be taken to ensure that acid produced from the underlying material does not acidify the applied capped through capillary rise. Consequently a capillary barrier of gravel particle size is often installed between the acid parent material and the cap.

Promac™ is a commercially available pelletised surfactant that inhibits the production of acid from pyrite by dissolving the cell membrane of *Thiobacillus* sp. bacteria largely responsible for the generation of sulphuric acid from pyrite (Masters pers. comm.). It is through the oxidation of pyrite by these bacteria that the acid soils below approximately pH 4 are generated (Kleinmann and Crerar 1979). Promac™ and lime addition has been used to raise the pH and prevent further pyrite oxidation in acid mine spoils at the Pelton Colliery in NSW, Australia (Burns pers. comm.). The time frame over which this treatment is effective however must be questioned as the pellets have a finite life and current trials of the product are only 10 years old.

The most appropriate way to address acid mine drainage from mining activities is to not let the situation occur by taking potential acidity into account in mine planning operations (Bell 1993). Where potential acid forming material occurs the material should be buried deeply in the strata during mining operations (Bell 1993). As such a potentially good approach to the disposal of tailings may be to pump the material to a final void where the material can be thickly capped after tailing emplacement has ceased. A deep void for tailings emplacement is not always available, however, as the void is normally a central part of the mining operation and not available for alternate uses until mining has ceased.

The testing of soil pH is relatively simple and standard methods are well established (Rayment and Higginson 1992). Methods for the determination of potential acidity, neutralisation potential and lime requirement however, are more complex. Where the pyrite content and pH are low, lime requirement determined by the SMP single buffer method (Shoemaker *et al.* 1962), rather than from potential acidity based on pyrite content (Sobek *et al.* 1978) are recommended (McLean 1982). In such situations the SMP single buffer method is more accurate than total potential acidity as substantial pyrite oxidation has occurred and the acidity present, rather than the potential acidity, needs neutralisation (McLean 1982).

Saline Substrates

Badawy (1992) characterised severely salt affected lands as areas having a $EC_{1:5} >$ 1.4 $dS.cm^{-1}$ stating that salinity of this severity was difficult to ameliorate as the osmotic water potential was high and consequently plant available water low. Shaw (1988) stated that the survival and yield of salt tolerant crops was severely reduced in soils having an $EC_{1:5} > 2.0$ $dS.cm^{-1}$. Hoy *et al.* (1994) found that survival and growth of saline tolerant genotypes from the central Queensland area (eg. *Casuarina glauca*) was reduced by c. 50 % at an $EC_{1:5} > 3.0$ $dS.cm^{-1}$. Germination under saline conditions has been studied less extensively than survival and growth. Tanji (1990) however, found considerable variability in the effect of salinity on germination. The response of germination to salinity was complex with many salinity sensitive species germinating effectively at high salinities ($EC_{1:5}$ c. 2 $dS.m^{-1}$). The germination of some salt tolerant halophytes however, was retarded at a comparable salinity.

Dryland salinity has been combated by the use of salt tolerant native trees to decrease water tables and thus prevent saline groundwater impacting the surface (George 1990, Schofield 1991). In central Queensland, the *Causuarina glauca* trees established on a saline site have resulted in water table draw down (Walsh *et al.* 1995). Consequently, if established on tailings dams, trees could increase the rate of dam dewatering by transpiring water from beneath the surface crust, thus enabling the material to be easily worked using conventional earthmoving machinery. The ability to work on tailings with conventional machinery would be extremely beneficial for reprocessing or capping the tailings deposit in the future.

Sodic Substrates

In the classification scheme of Northcote and Skene (1972) soils were termed sodic when exchangeable sodium percentages (ESPs) were > 6 %, and highly sodic when ESPs were > 14%. Sodic soils contain excess exchangeable sodium on the cation exchange sites rendering them dispersive in nature (Russell 1973). Sodic soils are problematic for plant growth as they are typically crust forming, reducing water infiltration, gas exchange and germination (Russell 1973). The high crust strengths of sodic soils impede germination and epicotyl emergence. The reduction in germination and early seedling growth has been attributed to the high resistance to epicotyl and hypocotyl extension (Hillel 1980) a phenomenon observed in Bowen Basin spoil (Emmerton 1983).

Sodic soils can be ameliorated with the incorporation of the calcium cation to displace sodium from the cation exchange complex, reducing the repulsive forces between soil particles and stabilising soil structure (Russell 1973). Gypsum, dolomite or lime may be used as a source of calcium however gypsum has been commonly used in sodic soils. The gypsum requirement (GR) can be calculated theoretically via the following relationship:

$$GR(cmol^{(+)}\,kg^{-1}) = \frac{CEC(\text{initial ESP - final ESP})}{100}$$

2.6 Climate

The climate of the Saraji area has been categorised as sub-humid and sub-tropical with high seasonal variability in temperature, rainfall and evaporation (Lloyd 1984). Annual pan evaporation rates of 1500-2000 mm greatly exceed the 600-700 mm annual summer dominant rainfall (Lloyd 1984). Rainfall, which may pose a major limitation to plant growth in rehabilitation areas (Kelly 1979), is often temporally and spatially erratic with dry period often broken by summer cyclones or storms (Lloyd 1984). Mean temperatures range from 14-19 °C in winter to 23-26 °C in summer. The winter mean daily minimum is 3-7 °C with frosts having greater than a 50 % probability of occurring (Lloyd). The mean daily summer maximum is 34-36 °C (Lloyd 1984) and with Saraji Mine daily maximums were likely to exceed 38 °C for 27 days between November and March (Kelly 1987).

2.7 Summary

The crusting process associated with the desiccation of coal tailings in environments where evaporation exceeds rainfall can result in off-site wind erosion and environmental contamination effects. These potential environmental effects in combination with the desire to maintain access to the tailing resource for future reprocessing and difficulty associated with capping the dams generate the need for establishing a vegetation cover directly in tailings. There have been a number of successful revegetation attempts with this as the focus. Many of these studies identified substrate acidity, salinity, low nitrogen, phosphorus and potassium nutrient status and plant water availability as the primary barriers to vegetation establishment and growth. Due to differences in ROM ore properties, minesite water, washery technology, product coal specifications, tailings dam construction, filling history and local climate however, the requirements for establishing vegetation on tailings will vary between dams.

3. METHODS AND MATERIALS

3.1. SITE DESCRIPTION

Saraji open-cut coal mine (latitude 22° 23' 52"; longitude 148° 16' 23") is situated in the Bowen Basin of central Queensland approximately 180 km south-west of Mackay and 270 km north-west of Rockhampton (Fig. 1). Coal tailings dam number 3 at Saraji was located adjacent to the northern haulroad, approximately 2 km from the preparation plant and industrial area. The tailings dam was a "turkeys nest" dam, 20 m in height and 23 ha in area with the major axis 880 m in length (Fig. 2) which had not been used for tailings disposal since 1985 and was considered "drained".

The tailings dam was filled from two distinct discharge points (Fig. 2). The primary discharge point, located in the south-west corner, was used to fill ca. 95 % of the tailings dam. A second discharge point, situated approximately 370 m from the primary discharge point along the western dam wall (Fig. 2), was briefly used to increase the dam's holding capacity. As the primary discharge point was positioned at the southern end of the dam a topographical gradient of 1:300 from south to north resulted. The higher southern end formed a catchment and runoff area for an ephemeral waterbody (wetland) in the north where the tailings surface was 2 m below the top of the dam wall. To prevent the wetland overtopping after rain, an overflow pipe was installed in the dam wall.

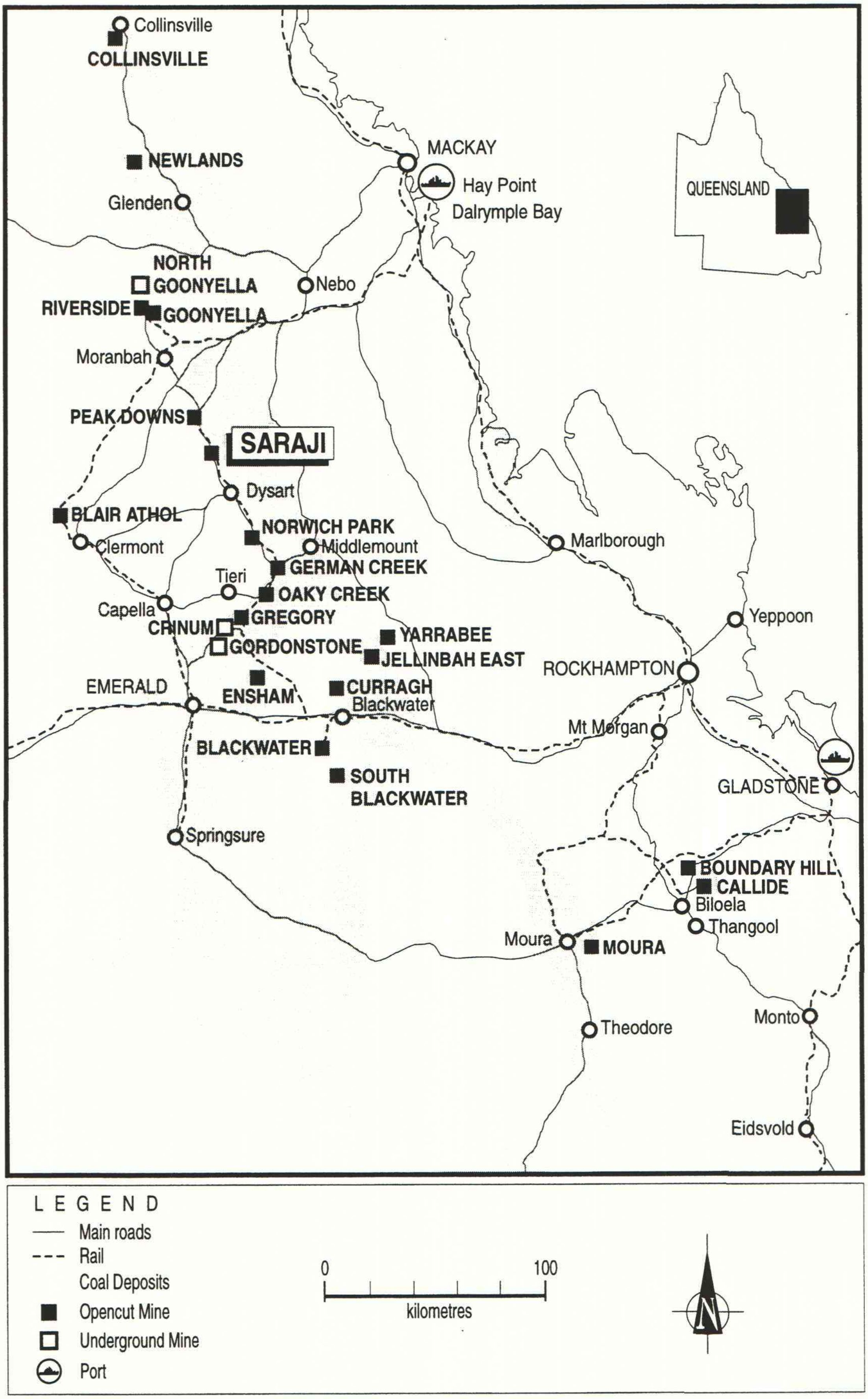

Figure 1. Location of Saraji Mine in the Bowen Basin of Central Queensland.

After: Queensland Department of Mines and Energy (1996).

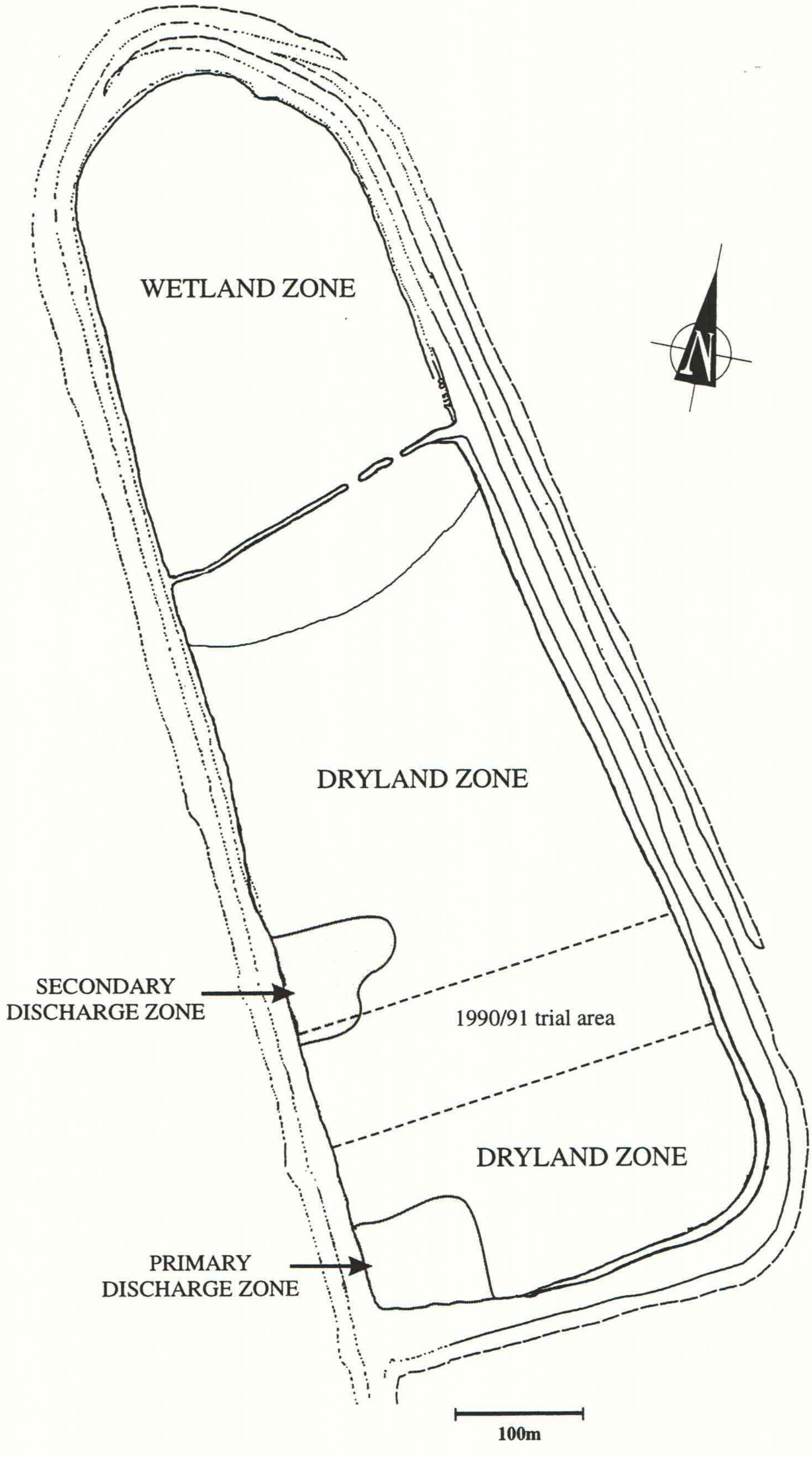

Figure 2. Layout of Saraji coal tailings dam no. 3 showing the dryland, wetland and discharge zones.

For the purpose of delineating suitable species and vegetation establishment strategies for Saraji tailings dam number 3, a classification system based on that of Nawrot and Yaich (1982) was used. The classification system was modified, however, to reflect the fact that Saraji tailings dam no. 3 was substantially drier than any of those revegetated by the American authors. Consequently the management zone terminology was changed from the discharge, intermediate and low zone to discharge, dryland, and wetland zones for the purpose of this study (Fig. 2, Plates 1 and 2).

Plate 1. Saraji tailings dam number 3 dryland zone.

Plate 2. Saraji tailings dam number 3 wetland zone.

The discharge zones were identified as those areas where the $pH_{1:5}$ (see section 3.2.4) was < 5.5, resulting from the oxidation of pyrite which, due to its high specific gravity, concentrated at the discharge points (Nawrot and Yaich 1982). The dryland zone was defined as the area having a $pH_{1:5}$ > 5.5 and being above the level of the dam decant pipe and thus not susceptible to long periods of water inundation. The wetland zone was defined as that area inundated at the height of the overflow. The overflow limited the depth of the wetland to 1 m and its area to 7 ha. The area covered by free standing water was variable, expanding during periods of rainfall and contracting throughout the dry. After drying to the extent where no free standing water remained in the wetland, approximately 300 mm of rainfall would be required to fill the wetland to capacity. Preliminary $pH_{1:5}$ analysis indicated that each discharge zone represented approximately 1.2 ha and were concentrated in the immediate proximity of the discharge points (Fig. 2). The dryland and wetland zones encompassed approximately 13.5 and 7.0 ha respectively (Fig. 2).

Several native and two exotic plant species volunteered within the wetland area. The most successful of these, *Typha domingensis*, had colonised approximately 1 ha of the wetland. *Cynodon dactylon* was also found in the wetland zone, growing in isolated scattered tufts. The fringes of the wetland zone were colonised by sparsely scattered individuals of *Atriplex muelleri*, *Salsola kali*, *Enchylaena tomentosa* and *Sesbania cannabina*.

3.2. SITE CHARACTERISATION

3.2.1. Climatic Monitoring

Throughout the period when field trials were established and monitored (July 1994-April 1996), records of average monthly maximum and minimums, and total monthly rainfall were recorded by BHP 2 km from the tailings dam at the Saraji Administration building. Maximum and minimum temperatures were recorded with a maximum/minimum thermometer within a Stevenson Screen and rainfall with a Nylex™ 1000 rain gauge.

To monitor the temperature that plants were exposed to when growing on the tailings, a Campbell Scientific Inc. weather station was installed on the tailings dam. The weather station consisted of a CR 10 data logger and Vaisalla Inc. HPM35C air temperature and relative humidity probe (with radiation shield), and a Texas Instruments Inc. HSMM02 tipping bucket rain gauge (0.2 mm tip^{-1}, 600 mm hr^{-1}).

3.2.2. Substrate Characteristics: Sample Collection and Preparation

0-30 cm Bulk Samples

To represent the predominant plant root zone, triplicate 0.2 m^3 (0-30 cm) tailings samples were collected from the dryland, and triplicate 0.05 L m^3 (0-30 cm) samples from the wetland and primary discharge zones for use in characterisation studies and glasshouse trials. Sampling positions for the triplicate samples were obtained by subdividing each zone into three equal cells from east to west and collecting 10 subsamples of equal weight within each cell. The 10 subsamples were collected randomly further dividing each cell into 30 equal parts and selecting sampling sites from a random number table. Wetland zone material was not gathered from the area covered by free standing water at the time of sample collection (c. 1.5 ha).

Tailings samples for determining site characteristics were derived by homogenising 10 × 500 g subsamples (air dried) from each management zone cell. Each 5 kg sample (nine in total) was representatively subsampled and sieved where necessary, before being subjected to chemical and physical analyses. Tailings for use in glasshouse experiments were obtained by mixing the remaining dryland bulk sample in a conventional cement mixer.

Core Samples

A depth profile sample was randomly collected (as described above) for each management zone cell (three cores per zone) to determine tailings specific gravity, gravimetric water content (GWC), $pH_{1:5}$ and electrical conductivity ($EC_{1:5}$, defined in section 3.2.4). The profile samples were collected with a hand auger (100 mm in diameter) to 6 m in the dryland and wetland zones, and 4 m in the primary discharge zone. Each profile was divided into 10 cm increments to 3 m in depth, below which increments of 50 cm were collected. The auger contents were transferred to 600 mL polypropylene containers, stored in a cool humidified environment, and transferred to the laboratory and analysed within three days. Samples from individual depth increments were mixed and representatively subsampled by pooling 10 randomly selected subsamples of equal weight.

Surface Samples

Surface samples (0-10 cm) were collected for determining GWC, $pH_{1:5}$, $EC_{1:5}$, pyrite content and *Thiobacillus ferrooxidans* density. All 0-10 cm samples were collected with a sampling tube 10 cm in length and 5 cm in diameter by driving the tube to the collar with a mallet. The contents of the tube were then transferred to 600 mL polypropylene containers, stored in a cool humidified environment and transferred within 3 d to the laboratory and analysed.

3.2.3. Tailings Physical Characteristics

Particle Size Analysis

Particle size distribution between 0.05 μm and 875.00 μm diameter was determined using a Malvern Mastersizer™ S Ver. 2.14. Particle Size Analysis System. Particle size analyses were performed on 1 g subsamples obtained from the mixed 0 - 30 cm cell samples from each management zone (see section 3.2.2). Particle size was classified as percentage fine clay (particles < 0.2 μm in diameter), clay (particles 0.2-2 μm), silt (particles 2-20 μm), fine sand (particles 20-200 μm) and coarse sand (200-2000 μm) in accordance with the classification scheme of Graze and Hamilton (1991).

Water Holding Characteristics

Tailings water holding characteristics in the primary discharge and dryland zones were characterised in terms of field capacity, permanent wilting point and plant available water. All measurements were made in triplicate on material from the 0-30 cm mixed bulk samples from each management zone. Each sample was sieved to pass a 2 mm sieve, packed in 1 cm high, 5 cm diameter rings and prewet on a tension table prior to pressure plate analysis (Klute 1965). Moisture release curves were constructed by measuring GWC at matrix potentials of -0.1 (field capacity), -3.0, -7.0 and -15.0 bar (permanent wilting point) using a pressure plate apparatus (Klute 1965). Plant available water was defined as the difference in GWC between field capacity and permanent wilting point. GWC analyses were performed by oven drying the sample at 105 ^{o}C in a fan forced oven until a constant weight was obtained (Gardner 1965).

Atterberg limits (liquid and Plastic limits)

Plastic and liquid limits were determined to characterise the tailings under the Unified Soil Classification System. Analyses were performed on the 0-30 cm mixed bulk cell sample from the dryland zone in accordance with the method of Sowers (1965). Liquid limit was taken as the GWC at which the material started to flow in a Casagrande Apparatus (Sowers 1965). Plastic limit was defined as the GWC at which the material could be rolled into a 3 mm continuous thread (Sowers 1965). GWC was determined as outlined by Gardner (1965).

Specific Gravity

Specific gravity was determined by pycnometer in accordance with the method of Blake (1965). Triplicate 10 g samples were obtained at 0-10 cm and 140-150 cm in depth from each management zone by representatively subsampling the cores dug (see section 3.2.2). Each sample was transferred to a pycnometer and weighed, before half filling with distilled water. Entrapped air was removed by slowly boiling for several minutes with frequent agitation. After cooling, the pycnometer was filled with distilled water (preboiled to remove excess gas), thoroughly dried, weighed, and the temperature of the internal mixture recorded (Blake 1965).

Bulk Density

Bulk density (BD) was determined at 0-10 cm and 140-150 cm depths in the dryland, wetland and primary discharge profiles (see section 3.2.2) in accordance with the method of Blake (1965). Before auguring the 100 mm diameter cores at each sampling depth, undisturbed samples 10 cm in length and 3.8 cm in diameter were gathered using a cylindrical stainless steel sampling tubes of 1.5 mm wall thickness. Samples from 140-150 cm in the profile were obtained by attaching a 2 m extension to the sampling tube, and slowly pushing the sampler (under body weight) into the tailings. The point at which the 10 cm sampling tube filled was detectable by a rapid increase in penetration force. Dry weight was obtained by weighing the sample after oven drying at 105 °C to a constant weight (ie. 48 h). Sample volume was calculated from the dimensions of the sampling tube. Bulk density was calculated as follows:

BD = sample dry weight / sample volume (including pore spaces).

Gravimetric Moisture Content

GWC was assessed by measuring the weight loss after oven drying to constant weight at 105 °C (Gardner 1965). The drying time to constant weight for a 150 g sample was 48 h. Subsamples of approximately 150 g were obtained from each depth increment of the dryland, wetland and primary discharge zone cores (see section 3.2.2). Additional cores to 1 m in depth were dug in triplicate at randomly selected positions 1 m from the wetland. Sample wet weights were recorded no later than two days after sample collection and storage in 600 mL polypropylene containers in a cool, humidified environment.

Porosity and Pore Saturation

Porosity (P) and pore saturation (PS) were calculated for each management zone from the results of BD, SG, and GWC measurements, following the protocols of Vomocil (1965) and Craig (1987) respectively.

Saturated Hydraulic Conductivity

The saturated hydraulic conductivity of *in situ* tailings material was measured with a Guelph Permeameter (model 2800KI). Saturated hydraulic conductivity was determined by measuring infiltration through a plastic covered well 4 cm in diameter and 250 cm in depth. Infiltration was measured for 15 min under constant head steady state conditions. Flow was considered as steady state when the standard error of five consecutive recordings occurred within 5 % of the mean. Within each management zone 3 measurements were performed at randomly selected points.

3.2.4. Tailings Chemical Characteristics

Acidity and Salinity

To assess surface $pH_{1:5}$ and salinity, 0-10 cm samples were collected at 50 m centres across the surface of the dam (see section 3.2.2). Further 0-10 cm samples were collected from plumes of discharge zone like material (c. 1 m in width and 100 m in length) radiating from the primary discharge point (Plate 1). To examine $pH_{1:5}$ and salinity profiles, three random core samples were obtained from each management zone (section 3.2.2).

Subsamples for $pH_{1:5}$ and $EC_{1:5}$ analyses were obtained by representatively subdividing each sample. The subsamples were air dried, and sieved (to pass a 2 mm sieve) before $pH_{1:5}$ and $EC_{1:5}$ were measured in a 1:5 soil:water extract (Rayment and Higginson 1992). pH was measured with a Hanna, Piccalo Auto Temperature Compensation pH meter, and EC with a TPS LC81 conductivity meter. pH and EC meters were calibrated against pH 4.0 and 7.0, and 0.05 M KCl standards respectively, before each batch of thirty analyses. Throughout the remainder of this thesis, EC and pH refer to 1:5 soil:water extract determinations unless otherwise stated.

To assess if oxidation of potentially pyritic discharge zone material occurred between sample collection and analysis, a 1.5 m core sample was augured from the primary discharge zone and pH determined immediately after sample collection and 14 d later in the laboratory.

The data were compared with a paired Student t Test. Throughout this thesis data analyses were performed using SYSTAT™ Version 5.0 and a level of significance of 5 % was used for hypothesis testing. All binomial data expressed as a fraction (eg. percentages) were arc-sin transformed prior to data analyses in order to normalise variances (Montgomery 1997).

Organic Carbon, Soluble Salts, Nutrient Status, Cation Exchange Capacity and Exchangeable Sodium Percentage

Organic carbon, soluble salts, nutrient status, cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) were assessed from the 0-30 cm bulk sample material (see section 3.2.2). Nine mixed, sieved (2 mm) and air dried 0-30 cm cell samples (three per management zone) were subjected to chemical analyses as follows by Incitec Ltd:

1. pH and EC were determined on 1:5 soil/distilled water suspensions mixed for 1 h (Rayment ane Higginson 1992).
2. Organic carbon was analysed by the Walkley-Black method (Allison 1965).
3. Nitrate-nitrogen was determined by the Griess-Ilosvay method (Bremner 1965) using a 1:5 ratio of soil/distilled water as the solvent.
4. Bicarbonate extractable phosphorus (0.5 M $NaHCO_3$) was determined by the method of Olsen and Sommers (1982).
5. Potassium, calcium, magnesium and sodium were extracted with 1 M NH_4OAc (pH 7) (Chapman 1965). K, Ca and Mg were determined by atomic absorption spectrophotometry and Na by flame photometry.
6. Chloride was extracted with a 1:5 soil/water suspension, filtered and quantified with Cotlove automatic chloride titrator.
7. Sulphate-sulphur was analysed by the method of Sobek *et al.* (1978) which employs 0.01 M $Ca(H_2PO_4)_2$ as the solvent.

8. Copper, zinc, manganese and iron were extracted with 0.05 M diethylenetriaminepentacetic acid (DPTA), 0.1 M triethanolamine (TEA) and 0.01 M $CaCl_2$ before quantification by atomic absorption spectrophotometry.

9. 1 M KCl extractable aluminium was determined in accordance with the method of Barnhisel and Bertsch (1982).

10. Boron was determined by spectrophotometry (azomethine-H method), after extraction with 0.01 M $CaCl_2$ and 0.05 M Mannitol (Bingham 1982).

11. Approximations of CEC and ESP were derived from the cation determinations conducted (CEC by summation of basic cations; ESP from sodium content/CEC × 100). Samples were not pretreated to remove soluble salts before measuring ion exchange properties.

Pyrite Content, Total Potential Acidity and *Thiobacillus ferrooxidans* *Enumeration*

To assess the total potential acidity and study the tailings acidification process, pyrite content and *Thiobacillus ferrooxidans* density were determined within each management zone. Pyrite content was determined by boiling representative 5 g samples of ground material (< 120 μm) with 50 mL of 5N HCl (to solublise all iron except that bound in FeS_2). After filtering, the samples were boiled with 2N HNO_3 to solublise pyritic iron. Iron content of the 2N HNO_3 filtrate was determined by atomic absorbance spectrometry (372 nm) and the total pyrite content calculated

(Sobek *et al.* 1978). Total potential acidity (TPA) was determined from the total pyrite content via the following equation:

$$\text{TPA } (CaCO_3/1\,000 \text{ t material}) = \%\ FeS_2 \times 14.54 \text{ (Sobek } et\ al. \text{ 1978).}$$

T. ferrooxidans density was assessed using the Most Probable Number method (Alexander 1965). Triplicate 5 g samples were obtained by representatively subsampling the 0-10 cm surface samples collected for pyrite and potential acidity measurements. Samples were air dried and subdivided in a laminar flow cabinet to ensure aseptic sample preparation. Throughout the sample collection, preparation and inoculation phases, aseptic techniques were adopted to prevent sample contamination.

Each subsample was ground to pass a sterile 150 μm sieve and 0.5 g of the material suspended in 9 mL of sterile distilled water. To act as controls, 0.5 g subsamples from the discharge and wetland zone (three per management zone) were autoclaved (15 min at 120 °C, 15 psi) before suspension. For each subsample (autoclaved and un-autoclaved) serial dilutions of the 0.5 g in 9 mL suspension were performed and a dilution series to 10^{-7} of the original concentration obtained. A 0.1 mL aliquot from each dilution series was added to 0.9 mL of *Thiobacillus ferrooxidans* medium (Atlas 1993) in 5 mL sterile culture tubes. Uninoculated culture tubes containing 1 mL of *Thiobacillus ferrooxidans* medium were included to act as blanks. Each culture tube was stoppered with cotton wool to allow gas exchange and exclude contaminants. Cultures were incubated at 25 °C and inspected at 30, 60 and 90 days, at which time 0.2 mL of sterile reverse osmosis water was added to replace evaporative loss. The presence of *T. ferrooxidans* was scored when a yellow precipitant formed.

Liming Requirement

The quantity of lime ($CaCO_3$) necessary to increase the pH of the acidic (pH 2.8) primary discharge zone tailings to a level favourable to plant growth (pH 6.5) was determined by the lime incubation method of Dunn (1943). Air dried 10 g subsamples were obtained from each primary discharge zone 0-30 cm mixed bulk sample (see section 3.2.2). Each 10 g sample was sieved to pass a 2 mm sieve and representative subsamples of c. 1 g obtained. Each 1 g subsample was incubated in a stoppered 250 mL Erlenmeyer flask at 25 ^{o}C and -0.1 bar water potential for 68 days. Adding distilled water gravimetrically to the flask generated the –0.1 bar water potential (Dunn 1943). Liming rates of 0, 10, 20, 30, 40, 50, 60, 70, 80, 100, 125, 150, 175 and 200 kg t^{-1} tailings were attained with $Ca(OH)_2$. addition. After incubation the material was air dried and pH determined.

3.3. GLASSHOUSE AND LABORATORY TRIALS

3.3.1. Species Selection

Species were selected for their ability to colonise saline waterlogged substrates (eg. *Acacia stenophylla*, Marcar *et al.* 1995; *Eucalyptus camaldulensis*, Marcar 1992; *Vitiveria zizanioides* (cv Monto), Truong and Roberts (1992); *Casuarina glauca*, Hoy *et al.* 1994) or as halophytes (eg. *Atriplex lentiformis*). Grass species were selected on the basis of previous establishment and growth success on saline central Queensland mine spoils (Silcock 1991). The tree and shrub species used in dryland trials were *A. harpophylla, A. salicina, A. holosericea, A. stenophylla, E. camaldulensis, C. glauca, C. cristata* and *Melaleuca bracteata.* The saltbushes *Atriplex lentiformis*, *A. amnicola* and *A. lindleyi* and the grasses *Cynodon dactylon* and *Chloris gayana* (cv Pioneer) were included. Tree seed was obtained from Queensland Tree Seeds (Moura, Queensland) and grass seed from Selected Seeds (Biloela, Queensland). All tree and shrub species were collected from the Leichardt provenance, except for *C. glauca* and *M. bracteata* which were from Port Curtis.

In the wetland *Vetiveria zizanioides, Sporobolus virginicus, Phragmites australis, Typha domingensis* and *Sarcocornia quinqueflora* were trialed. All planting material, except for *V. zizanioides* stock was collected from the lower reaches of the Fitzroy River. *V. zizanioides* stock was obtained from P. Truong of the Queensland Department of Primary Industries, Myers Road, Brisbane.

3.3.2. The Effect of Tailings Salt Extract on Tree and Saltbush Seed Germination

The effect of tailings salt extract on the germination of the tree and saltbush species selected from use in the dryland (see section 3.3.1) was studied in Petri dishes. The salt extract was obtained from a representative sample of dryland surface material collected for substrate characterisation analyses. A 1 kg tailings sample was mixed with 5 L of deionised water and stirred for 1 h at 25 °C. The supernatant was collected by filtering, under vacuum, through Whatmann number 5 filter paper and concentrated allowing to evaporate at 30 °C until a stock solution (EC 20 dS m^{-1}) was obtained. Aliquots of the stock were diluted to obtain solutions of EC 2.5, 5 and 10 dS m^{-1}.

Seeds were placed in Petri dishes on filter paper over vermiculite and 20 mL of salt solution (0, 2.5, 5,10, 20 dS m^{-1}) or deionised water added. Thirty seeds of each *Acacia* species and 100 seeds of each other species were placed in each Petri plate with three replicates per salt treatment (13 species × 5 salt treatments × 3 replicates). *Acacia* species were pretreated (except for *A. harpophylla*) with boiling water (20 seconds) and left to imbibe for 24 h before sowing. The Petri dishes were randomly placed in 40 cm × 40 cm metal trays filled with 3 mm of distilled water, covered with Glad Wrap™ to reduce evaporation. The trays were incubated for 60 d at 25 °C with a photoperiod of 12 h light/12 h dark. Germination was assessed at 2 d intervals for the first 14 d and 5 d intervals thereafter. At each counting, the dishes were re-randomised and the water replenished as required. Seeds were scored as having germinated when the radical reached twice seed length. Data analyses for germination and time to 50 % germination (intraspecies comparisons only) were performed using the completely randomised ANOVA and Kruskall-Wallis tests, respectively. Before statistical analysis, germination data were arcsin transformed.

3.3.3. Tree and Saltbush Germination and Growth Trial

A 60 d glasshouse trial was undertaken to study dryland tailings as a medium for germination and growth and the effect of topsoiling and mulching on these parameters. The trial examined the germination and growth of the tree and saltbush species identified as having potential for establishment in the dryland (see section 3.3.1), and topsoil and mulching treatments. Species and amelioration procedures were selected after the examination of substrate characterisation results.

The experiment was designed as a randomised complete block with five replicates, being 20 cm pots and seven treatments including:

1. tailings.
2. tailings with 10 t ha^{-1} lucerne hay mulch.
3. tailings with 5 cm topsoil capping.
4. tailings with 5 cm topsoil and 10 t ha^{-1} lucerne hay mulch.
5. tailings with 5 cm 50 % topsoil/50 % tailings capping.
6. topsoil alone (control).
7. topsoil with 10 t ha^{-1} lucerne hay mulch surface cover.

Each pot was divided into thirds and species randomly assigned to each position to constitute a replicate. Eleven tree species including *Acacia stenophylla, A. harpophylla*, *A. salicina*, *A. holosericea*, *Casuarina cristata, C. glauca*, *Atriplex lindleyi*, *A. lentiformis*, *A. amnicola*, *Melaleuca bracteata* and *Eucalyptus* *camaldulensis* were trialled. Twenty five *Acacia* seeds and 50 seeds of the other genera selected for trial in the dryland were sown at approximately twice the depth of the seed diameter. *Acacia* species were pretreated as in the tailings salt extract germination trial (see section 3.3.2).

Tailings and topsoil were fertilised with the equivalent of 1300 kg ha^{-1} (incorporated to 10 cm in depth) Osmocote™ 14 month plus (ie 195 kg N ha^{-1}, 45 kg P ha^{-1} and 120 kg K ha^{-1}). This relatively high rate of slow release fertiliser was used in all growth trials, except the nutrient addition trial, so that nutrient status was not limiting on plant growth. As each pot contained 7.2 kg of material, 8 g of Osmocote™ 14 month plus was added before thorough mixing. Lucerne hay mulch was trialed in an attempt to reduce evaporation and thus surface salination. All pots (140 in total of size 20 cm in diameter × 20 cm height) were filled to the same height by adjusting the height of tailings to allow for the capping depth.

Tailings substrate was derived from the 0-30 cm mixed dryland bulk sample (see section 3.2.2). The tailings were sieved to pass a 2 mm sieve and approximately 3 kg of air-dried tailings packed to uniform bulk density by dropping each pot five times from a height of 5 cm. Preliminary investigations indicated that by dropping the pots five times from 5 cm, an equilibrium bulk density approximating that of *in situ* tailings (1 t m^{-3}) was attained. 'Topsoil" consisted of 5 parts medium river sand, 2 parts perlite and 1 part coir fibre peat.

Pots were "bottom watered" by placing in plastic lined level bays 3 m in length, 2 m in width and 150 cm in height (Plate 3). To block possible differences in microclimate within the polyhouse, the bays were blocked into five replicates, each 50 cm in width and running parallel to the polyhouse wall. The water level in the bays was refilled with distilled water to 50 mm in depth every two days. Throughout the trial, average minimum and maximum temperatures within the polyhouse varied between 20-35 °C, respectively.

Plate 3. Tree and saltbush germination and growth trial. Photograph taken before seeding and randomisation.

Germination was assessed every two days for the first 14 days, and every five days thereafter until day 29. Germination was scored when the epicotyl was visible. After 10 days, seedlings were thinned to three per species and growth assessed at 60 days by measuring height. Pots were re-randomised within blocks very two weeks.

Germination data were analysed as in the salt extract germination trial (see section 3.3.2) and growth by a randomised complete block ANOVA (intra-species comparisons only).

3.3.4. Nutrient Rate Trial

The response of *C. gayana* grown in tailings to the addition of four rates of nitrogen (0, 35, 70, 140 kg N ha^{-1} as NH_4NO_3), three of phosphorus (0, 35, 70 kg P ha^{-1} as $Ca(H_2PO_4)_2.H_2O$) and two of potassium (0, 70 kg K ha^{-1} as K_2SO_4) were examined in a factorial glasshouse trial of eight weeks duration. The experiment was designed as a completely randomised block involving twenty four treatments and four replicates. In each replicate a control treatment of washed and sterilised medium river sand, fertilised with 140 kg N ha^{-1}, 70 kg P ha^{-1} and 70 kg K ha^{-1} was included for comparison with tailings treatments.

All nutrients, with the exception of N, were applied by pipetting known quantities of nutrient solution evenly over 1 kg of tailings (predetermined pot contents) spread at a thickness of 5 mm on a plastic sheet. N was applied in three equivalent doses, the first pipetted on spread tailings and the second and third added with irrigation water after three and six weeks growth. Micronutrients (Table 2) were pipetted (as above) into all treatments to avoid confounding between micronutrient and macronutrient responses (Bell 1985).

Table 2. Nutrient source and weight applied in nutrient rate trial.

Nutrient	Nutrient Source (Salt Stock)	Fertilisation Rate ($kg\ ha^{-1}$)*	Salt Added ($mg\ kg^{-1}$)
nitrogen (N)	NH_4NO_3	140	400.4
phosphorus (P)	$Ca(H_2PO_4)_2.H_2O$	70	285.5
potassium (K)	K_2SO_4	70	156.1
manganese (Mn)	$MnCl_2.4H_2O$	1	3.60
zinc (Zn)	$ZnSO_4.7H_2O$	1	4.40
copper (Cu)	$CuSO_4.5H_2O$	1	3.93
iron (Fe)	$C_{10}H_{12}O_8N_2FeNa.H_2O$	1	6.89
boron (B)	H_3BO_3	0.1	0.57
molybdenum (Mo)	$Na_2MoO_4.2H_2O$	0.05	0.13

Note: For N, P and K the weight of salt is given for highest fertilisation rate.

* application rate calculated on nutrient addition to surface 10 cm of *in situ* tailings material (bulk density = 1.15 $t\ m^{-3}$).

Tailings substrate was derived from the 0-30 cm mixed dryland bulk sample material, air dried and sieved to pass a 2 mm sieve. Pots were lined with plastic bags and 1 kg of treated tailings packed in each pot (100 pots in total, 10 cm diameter × 12 cm height) by dropping the pot (see section 3.3.2).

Approximately 50 *C. gayana* seeds were germinated in a 1 cm medium river sand seedbed (washed and sterilised) over prewatered (field capacity) tailings. After one weeks growth, seedlings were thinned to five germinants per pot. Throughout the experiment, glasshouse minimum and maximum daily temperature was maintained at 15 and 28 °C respectively. Pots were maintained at field capacity by watering (to a predetermined weight) with distilled water every two days. At two weekly intervals, all pots were re-randomised within experimental blocks. After eight weeks growth shoots were harvested 1 cm above the surface of the growing medium and dried at 65 °C until a constant weight was attained (four days). Statistical analysis was performed by randomised complete block factorial ANOVA.

3.4. FIELD TRIALS

3.4.1. Wetland Species and Amelioration Techniques

To screen plant species and amelioration techniques for the wetland zone, a field trial was established in August 1994 (Fig. 3). The trial was planted three weeks later in September 1994 and monitored for 12 months. Plant species were selected as ephemeral wetland species with salt tolerance. Amelioration techniques to potentially decrease EC, increase GWC and increase plant nutrient availability were selected. The experiment evaluated three levels of cane-top mulching (0, 10 t ha^{-1}, 20 t ha^{-1}) and three levels of Osmocote™ 14 month plus fertiliser (0, 650 kg ha^{-1}, 1300 kg ha^{-1}). Fertilisation at 1300 kg ha^{-1} equated to 195 kg N ha^{-1}, 45 kg P $ha^{-1}$and 130 kg K ha^{-1}. Treatments were arranged in a factorial design (producing nine treatments) as a randomised complete block with five replicates (45 plots).

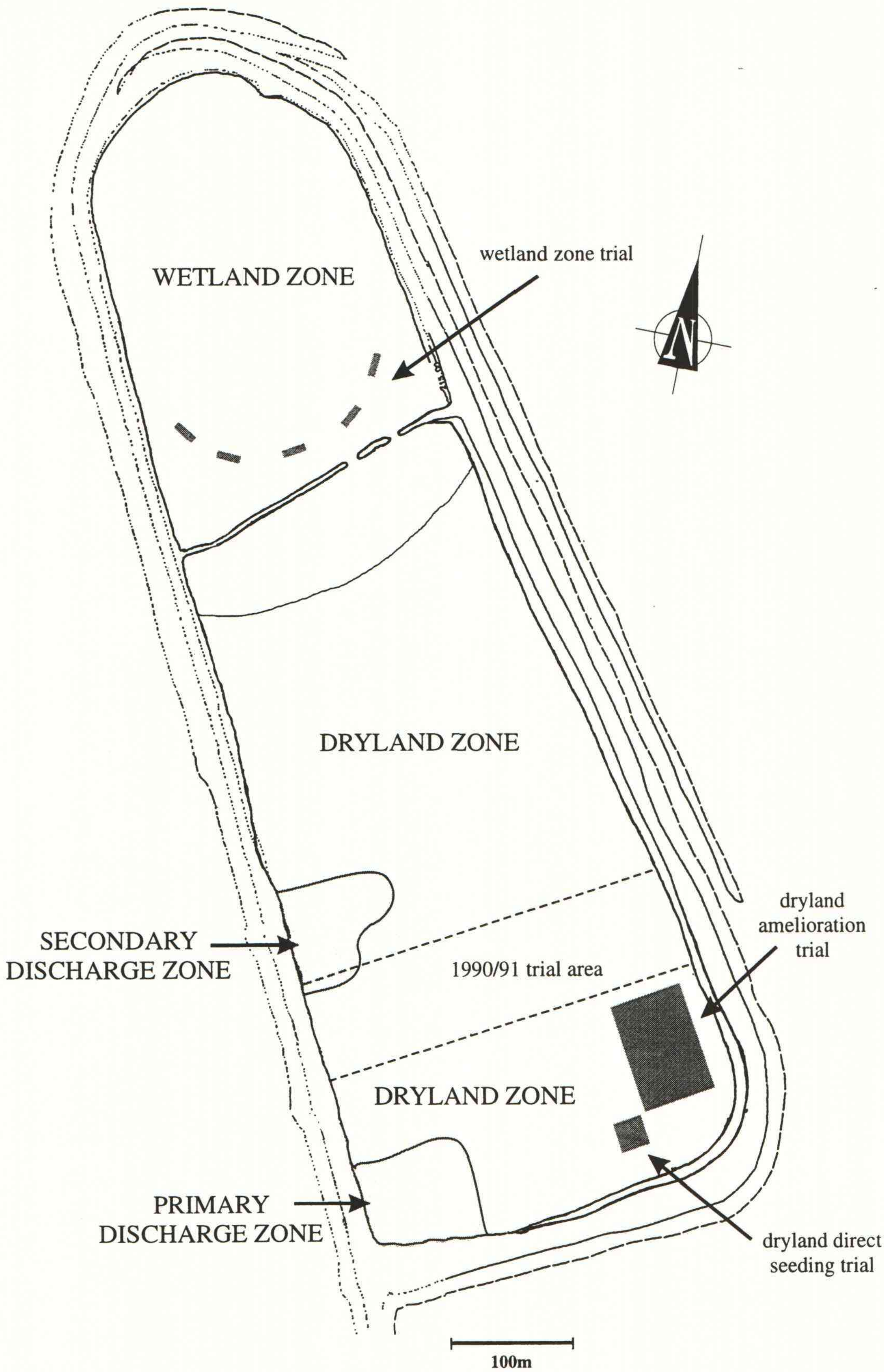

Figure 3. Layout of Saraji coal tailings dam no. 3 showing the position of the wetland, dryland amelioration and dryland direct seeding trial.

Each treatment was imposed over a 2 m × 2 m area, with the internal 1 m^2 planted to minimise edge effects on the small plantlets. Blocks (2 m × 18 m) were arranged parallel to, and 1 m from, the water edge at trial establishment. Blocks were orientated in this manner to maximise substrate water at planting and maintain a similar moisture regime between blocks.

Cane tops mulch, derived from sugar cane tops cut during the sugar harvesting process, were bailed in 350 kg round bales and delivered to site form Sarina (central Queensland). Mulch was spread manually by pulling the material from the bale and weighting into a plastic rubbish bin. The mulch was evenly spread over the plots at the corrects weights and fixed in position with stakes and bailing twine.

The trial species *Vetiveria zizanioides, Sporobolus virginicus, Phragmites australis, Typha domingensis* and *Sarcocornia quinqueflora* were randomly assigned to grid positions (30 cm centres) and planted. *V. zizanioides* and *T. domingensis* were planted as 30 cm high slips, each with 5-7 roots of 4-7 mm in diameter. *S. virginicus* was planted as 10 cm by 10 cm blocks, *P. australis* as rhizomes with eight nodes and *S. quinqueflora* as 20 cm high plants with associated root material. All planting material, except for *V. zizanioides*, was collected from the lower reaches of the Fitzroy River three days prior to planting and stored in a cool (15 ^{o}C) humidified environment. *V. zizanioides* was sourced from stocks obtained from the Queensland Department of Primary Industries held at the Central Queensland University.

Plant survival and growth, and surface (0-10 cm) substrate GWC, pH and EC, were assessed at four monthly intervals. Three GWC, pH and EC samples were collected per plot. Sample collection and analyses were as described for substrate characterisation studies (see section 3.2.2). *V. zizanioides* and *S. virginicus* growth was assessed by determining cross sectional area (maximum height × maximum width/2, when viewed parallel with the ground surface) and total area (length × breadth, when viewed perpendicular with the ground surface), respectively. Twelve months after planting *V. zizanioides* shoots were harvested 3 cm above the tailings surface and dry weight determined after drying at 65 °C for seven days.

Survival data were analysed using the Kruskal-Wallis test for randomised complete blocks. Growth, GWC, pH and EC were analysed using a randomised complete block factorial ANOVA. Where data was collected over time a Kruskal-Wallis test on each sampling date was undertaken to determine significant differences. Where such data has been graphed the LSD value for the last sampling date is presented.

3.4.2. Dryland Amelioration Trial

To screen amelioration techniques in the dryland zone, a field trial of 14 months duration was established in December 1994 and planted with *C. glauca* tubestock in January 1995 (Fig 3). Amelioration techniques were selected to decrease surface EC and increase GWC and nutrient availability. Eleven treatments involved mulching

(10 t ha^{-1} cane tops, 26 μm silver horticultural polythene plastic), cultivation (0, 15 cm) and irrigation (0, 1 L m^{-2} d^{-1} applied at three day intervals) were trialed. The treatments included:

1. tailings.
2. 10 t ha^{-1} cane tops mulch.
3. cultivation (15 cm in depth).
4. 10 t ha^{-1} cane tops mulch and cultivation.
5. plastic mulch (5 cm deep trough along tree planting line) and cultivation.

6-10. As above with irrigation (1 L m^{-2} d^{-1} applied at 3 d intervals).

11. plastic mulch (no trough) with cultivation and irrigation.

All plots received a fertiliser application of 1300 kg ha^{-1} Osmocote™ 14 month plus which was evenly spread on the surface after cultivation. Fertiliser rates were calculated on the basis of a row being 1.5 m wide and the fertiliser not being incorporated.

The experiment was constructed as a randomised complete block with three replicates (33 plots). Plots consisted of rows 1.5 m wide and 22 m long. The experiment was arranged factorially with respect to cane tops mulch, cultivation and water. Plastic mulch, however, was not used without cultivation as the mulch could not be secured.

Cultivation to a depth of 15 cm was performed with a Kubota AT70-S rotary hoe. Five passes along the row were necessary to cultivate and mix the material. The first and second pass were used to dig to 10 cm and 15 cm depth, respectively. The third, fourth and fifth passes mixed the cultivated material in an attempt to reduce the surface EC.

Preparation plant feed water (c. pH 8, EC 3-6 dS m^{-1}) was delivered along treated rows through 515-40-250 T-Tape™. A LEGO™ LC4 timer was used to control irrigation scheduling. To minimise evaporative concentration of surface salts, plots were irrigated every third day from 8.00 pm-10.30 pm. Irrigation water was available 30 m from the site at a pressure of 620 kPa through a 100 mm pipe. The pipe was reduced to 31 mm and a pressure reducing valve used to decrease the pressure to 275 kPa. The water was filtered with a 2 μm disc element filter before passing through a solenoid switched timer valve. Water was piped to the plots through 30 m of 31 mm rural poly pipe and a second pressure reducing valve used to decrease the pressure to 55 kPa for use in the T-Tape™. A 31 mm header pipe was used as an interface with the T-Tape™. Two parallel T-Tape™ lines per plot, placed 20 cm either side of the row centre line, were used to apply irrigation. Each T-Tape™ line was buried at a depth of 2 cm to reduce evaporative concentration of salts blocking water flow at the irrigation pores. To ensure the irrigation rate was equal between and within rows, the irrigation system was designed by T-Tape Australia Pty. Ltd. (Rockhampton supplier: Aqua Industrial-BP Solar). To ensure the irrigation system was functioning as designed, mine staff inspected the trials at weekly intervals.

The irrigation controller solenoid developed a fault 2.5 months into the trial which resulted in a period of two weeks continuous watering before the solenoid was replaced. The fault re-occurred seven months into the trial and was remedied after 1.5 weeks by dismantling, cleaning and reassembling the solenoid. If using the saline water for future irrigation therefore, it is recommended that a filtration system to further reduce suspended solids in the irrigation water, and a solenoid resistant to corrosion be trialed to increase reliability.

Cane tops were sourced and spread as in the wetland species and ameliorant trial (see section 3.4.1). Plastic mulch treatments were constructed by laying the 1.2 m wide 26 μm silver horticultural polythene plastic over the cultivated tailings. A 5 cm central depression (to harvest rainfall and deliver to the seedlings) was formed along the central length of the cultivated row before laying the plastic. The plastic was layed and secured by covering the edges with cultivated tailings. The central depression (trough) was weighted with ca. 10 cm in diameter sandstone rocks, placed at 1 m intervals. A plastic mulch treatment with no central trough (treatment 11) was included to determine the effect of the water harvesting properties of the trough.

The survival and growth of six month old *C. glauca* tubestock (seed source and provenance as given in 3.3.1) was assessed in all treatments. Seedlings were raised at the Central Queensland University in 50 mm (diameter) × 100 mm (height) plastic pots and held in full sunlight on outside benches. The potting mix consisted of 5 parts medium river sand, two parts perlite and one part coir fibre peat and 1 g Osmocote™ (14 month plus) kg of air dried potting mix. Before planting in the field the seedlings were hardened by water stressing. Water stress was imposed three times by droughting the seedlings until the apical region wilted. After hardening, the c. 60 cm high seedlings were trimmed to 30 cm before planting. The centre of each plot was planted with 20 seedlings per row (660 in total) at 1 m intervals. At planting each seedling was given approximately 2 L of irrigation water (preparation plant feed water) through a hand held hose.

C. glauca survival and growth (height), surface GWC, pH and EC were assessed at four month intervals. At each sampling 20 GWC, pH and EC samples were collected at 1 m intervals along each row. GWC, pH and EC were analysed as in the substrate characterisation studies (see section 3.2). Data analyses were performed by randomised complete block ANOVA on each sampling interval. Where this data was graphed, the LSD for the final sampling date was displayed on the graph.

3.4.3. Dryland Direct Seeding Trial

To determine optimum mulching rates for the direct seeding of grasses, trees and saltbush in the dryland zone, a trial of nine months duration was established in June 1995 (Fig. 3). The experiment, which was designed as a completely randomised block with five replicates, consisted of five treatments (two plots):

1. tailings.
2. 2 t ha^{-1} lucerne hay mulch.
3. 5 t ha^{-1} lucerne hay mulch.
4. 10 t ha^{-1} lucerne hay mulch.
5. 10 t ha^{-1} cane tops mulch.

Each plot was 5 m × 5 m and the treatment and seeding imposed over the entire area. To guard against edge effects only the internal 4 m × 4 m was sampled. All plots were manually fertilised with 1300 kg ha^{-1} Osmocote^{TM} (14 month plus) and seeded prior to mulching. After seeding the trial area was given a light sprinkling of water with hand held hose to minimise seed loss during the lucerne hay mulch blowing process.

Lucerne hay mulching was undertaken with 40 kg bales and a mulch blower driven by a petrol motor. The mulch blower shredded the lucerne hay bales with a series of chainsaw belts in parallel, before mixing with fan blown air for dispersal through a 150 mm (diameter) × 30 m in length flexible pipe. Cane tops mulch was not spread with the blower as the bales were too large. The cane tops mulch were spread manually as in the wetland species and ameliorant trial (see section 3.4.1).

The species sown were those selected for trial in the dryland zone, with the exception of *A. stenophylla, C. cristata, A. lindleyi and A. amnicola*. One hundred viable seeds of each *Acacia* species (2 kg ha^{-1} of *A. harpophylla and A. salicina,* 0.75 kg ha^{-1} of *A. holosericea* and 2500 *C. glauca* (1.3 kg ha^{-1}), 800 *A. lentiformis* (0.45 kg ha^{-1}), 4000 *M. bracteata* (0.57 kg ha^{-1}), 3000 *E. camaldulensis* (4.45 kg ha^{-1}) and 6 kg ha^{-1} of each *C. gayana* and *C. dactylon* were sown per plot. The seed was broadcast directly on the tailings surface immediately prior to the application of mulch.

In each plot the number of tree and salt bush seedlings, and grass projected foliage cover was determined at three monthly intervals. Tree and saltbush seedlings were determined by identifying and counting individuals of each species. Projected foliage cover was determined using 2 $\times$ 600 cm square polyvinylchloride (PVC) quadrats. Each quadrat was drilled at 10 cm intervals and bailing twine taughtly tied to form a grid with 25 intersections. A PVC frame held the quadrats 35 cm and 70 cm above the ground with the grid intersections between quadrats vertically aligned. Projected foliage cover was scored by visually aligning the intersections between quadrats and recording the number of intersections under which *C. gayana* foliage lay.

During each three monthly site visit, one randomly positioned profile sample (0-150 cm in 10 cm increments) was obtained from each plot for GWC, pH and EC determinations. Surface GWC, pH and EC samples were collected and analysed as in the substrate characterisation studies (see section 3.2). Data analyses were performed using a randomised complete block ANOVA for each sampling date. Where this data was graphed, the LSD for the last sampling date was displayed on the graphs.

4. RESULTS

4.1. SITE CHARACTERISATION

4.1.1. Climatic Monitoring

During the field trial period, mean monthly maximum and minimum temperatures at the Saraji Administration building reached 35 °C in summer and 10 °C in winter, respectively (Fig. 4). Mean monthly maximum temperatures on the tailings dam were approximately 10 °C above those recorded at the Administration building, whereas mean monthly minimum temperatures were similar.

During the field trial period (August 1994-April 1996) the average yearly rainfall for Saraji was 486.7 mm which was less than the 53 year average for Dysart (25 km to the south) of 601.7 mm (Fig. 4), with rain predominantly received through summer thunderstorms.

4.1.2. Tailings Physical Characteristics

Particle Size Analysis

Tailings particle size for the 0-30 cm mixed bulk sample was, as found for other Australian tailings (Williams and Morris 1990), predominantly in the range of silt and fine sand (Table 3). Particle size decreased with distance from the primary discharge point. In the dryland and wetland zones the coarse sand proportion was low. The clay proportion was not greater than 14 % in any management zone. (Table 3). Only the primary discharge zone contained particles > 875 μm in diameter.

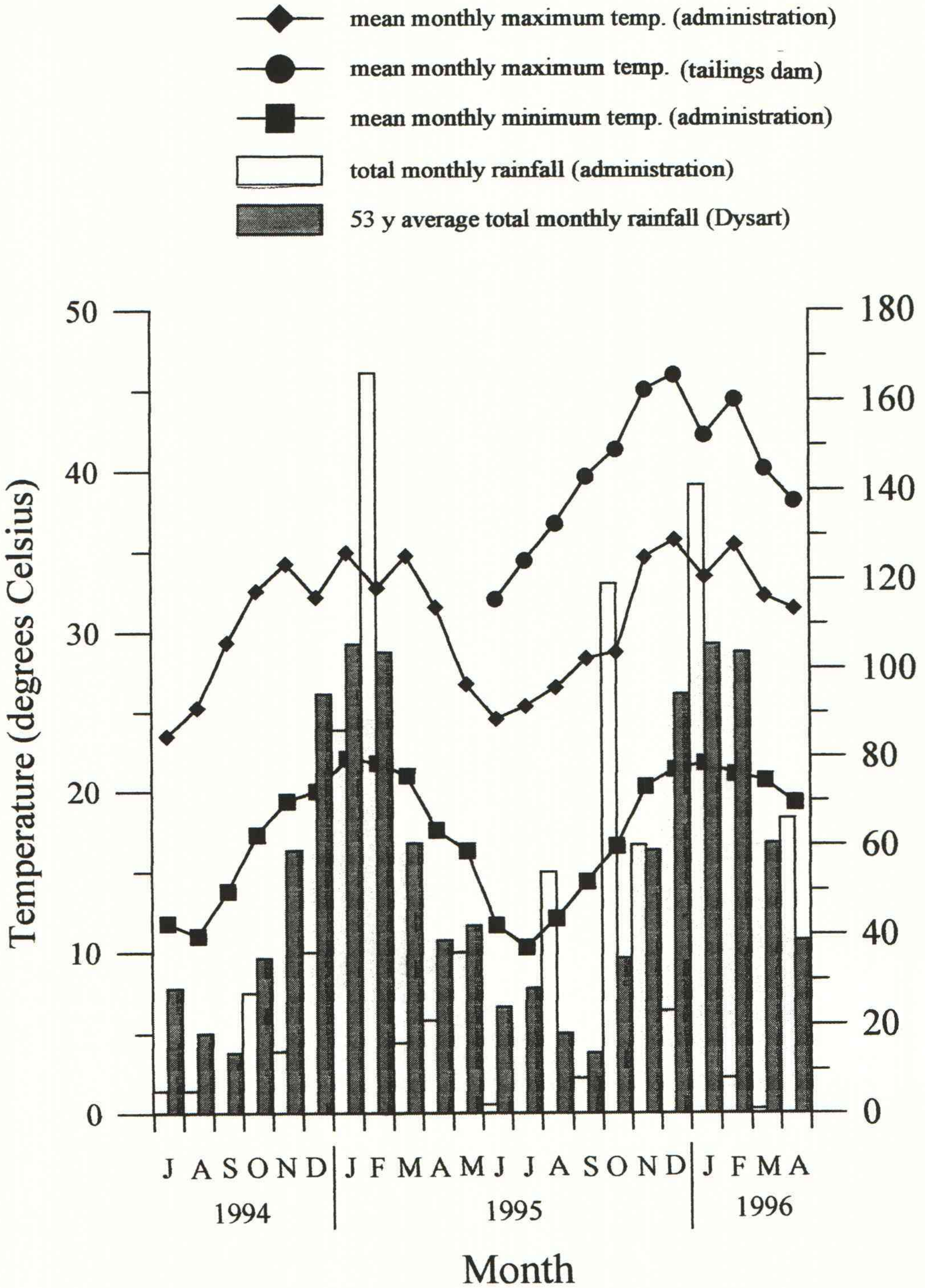

Figure 4. Average monthly maximum, minimum air temperature and total monthly rainfall at Saraji Mine (administration weather station) from July 1994 - April 1996 (period of field trials). Average monthly maximum air temperature 1 m above tailings surface given from June 1995 - April 1996. Dysart 53 y (1956-1989) total average rainfall provided.

Table 3. Physical characteristics of relevance to vegetation establishment on Saraji coal tailings dam no. 3.

Characteristic	Dryland zone	Wetland zone	Primary Discharge zone
Particle Size Analysis			
coarse sand 200-2000 μm (%)	1	0	31 (4)
fine sand 20-200 μm (%)	51 (6)	42 (2)	35 (6)
silt 2-20 μm (%)	38 (4)	44 (4)	20 (1)
clay 0.2-2 μm (%)	10 (1)	14 (1)	14 (2)
Water Holding Characteristics			
field capacity (%, -0.1 bar)	41 (0.1)	–	27 (0.6)
wilting point (%, -15 bar)	10 (0.0)	–	9 (0.1)
plant available moisture (%)	31	–	16
Atterberg Limits			
plastic limit (%)	26 (0.3)	–	–
liquid limit (%)	37 (0.5)	–	–
Specific Gravity (t m^{-3})			
0-10 cm	1.7 (0.12)	1.6 (0.03)	2.1 (0.18)
140-150 cm	1.6 (0.10)	1.6 (0.04)	2.0 (0.21)
Bulk Density (t m^{-3})			
0-10 cm	1.0 (0.08)	1.0 (0.03)	1.3 (0.12)
140-150 cm	1.0 (0.09)	1.0 (0.03)	1.4 (0.16)
Moisture Content (%)			
0-10 cm	12 (4)	40 (2)	11 (3)
140-150 cm	30 (2)	34 (1)	14 (2)
Porosity (%)			
0-10 cm	44	36	38
140-150 cm	38	37	30
Pore Saturation (%)			
0-10 cm	25	113	33
140-150 cm	81	95	56
Saturated Hydraulic Conductivity (cm s^{-1})	10^{-7}	10^{-8}	10^{-5}

Data represent means with one standard error given in parentheses (n=3). Water holding characteristics taken from water release characteristic curves (Fig. 5, see section 3.2.2). Specific gravity, bulk density and gravimetric water content were derived from 3 cores augured in each management zone (see section 3.2.2).

Water Holding Characteristics

The relationship between matrix potential and GWC in the dryland (pressure plate analysis) indicated could be described by the equation GWC = -6.39 log(matrix potential) + 26.8 (R^2 = 0.98) (Fig. 5). For the primary discharge zone y = -3.77 log(matrix potential) + 19.0 (R^2 = 0.99) described the soil water release characteristic. The water release characteristics were typical of soils of similar particle size and the coarser discharge zone sample had higher plant available water than the finer dryland zone sample.

In the dryland zone, field capacity and permanent wilting point (-0.1 and -15 bar, respectively, assuming no contribution of the osmotic component of water potential to total water potential) occurred at 41 % and 10 % moisture respectively (Table 3). In the primary discharge zone, field capacity occurred at a soil moisture of 27 % and wilting point at 9 % (Table 3). Soils in the dryland and discharge zones therefore possessed 31 % and 16 % potential plant available water (field capacity – wilting point), respectively.

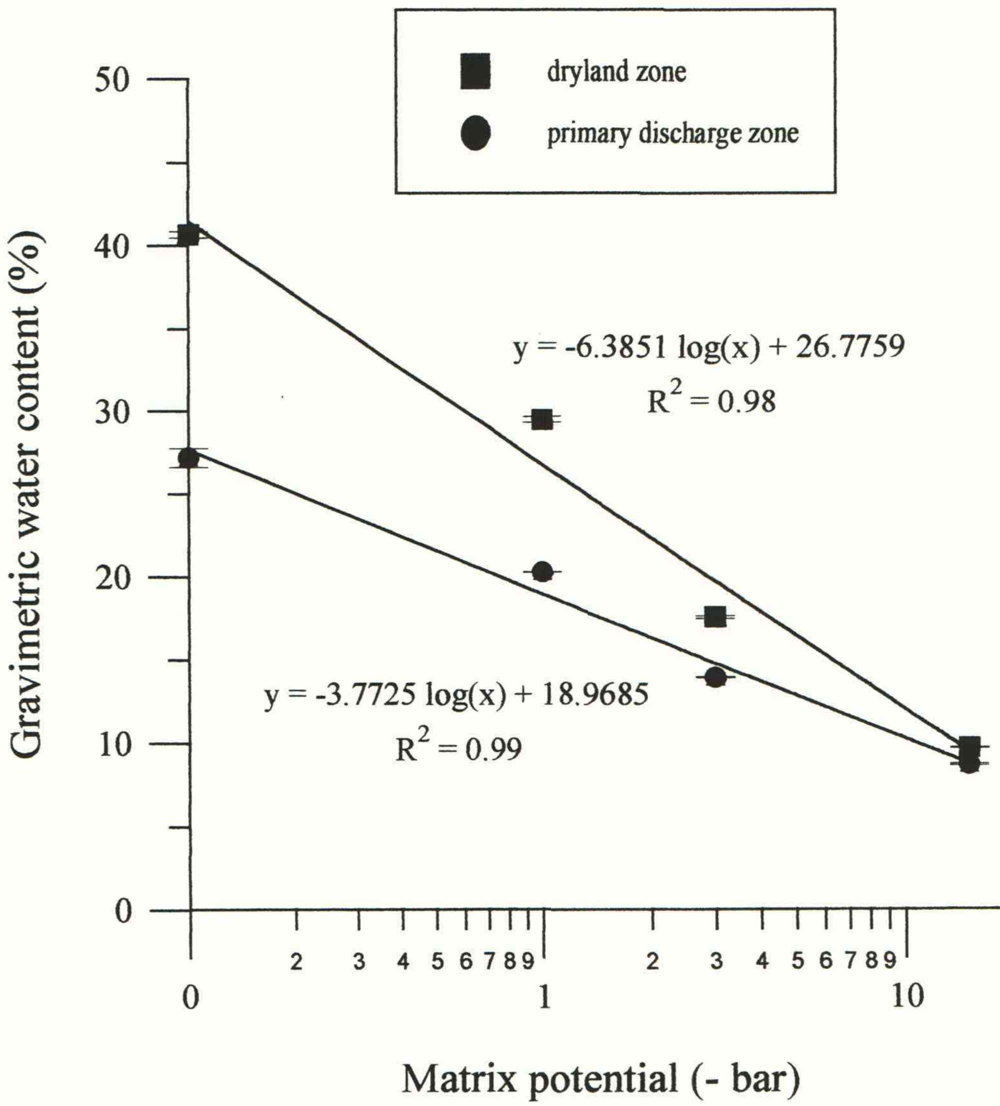

Figure 5. Water release characteristics of dryland and primary discharge zone tailings from Saraji coal tailings dam no. 3. Water release characteristics determined by pressure plate apparatus at -0.1 (field capacity), -1.0, -3.0 and -15 bar (wilting point). Data represent the mean and standard error of triplicate determinations on 0-30 cm bulk sample material. X-Axis logarithmic scale from 0 to -20 bar.

Atterberg Limits (liquid and plastic limit)

Within the dryland zone the average plastic and liquid limits occurred at 26 and 37 % moisture, respectively (Table 3). From the liquid and plastic limits the plasticity index was calculated (by subtraction) as 11. With the material having a liquid limit below 50 % and plotting above the A-Line the material was classified as CL (low plasticity clay) under the Unified Soil Classification System (Hicks 1991). Liquid and plastic limit results were comparable to those of other Australian tailings (Williams and Morris 1990).

Specific Gravity

Tailings specific gravity ranged between 1.85 g cm^{-3} and 1.58 g cm^{-3} which is between the specific gravity of coal (1.3 g cm^{-3}) and clay (2.65 g cm^{-3}) (Graze and Hamilton 1991) indicating a high coal content in the tailings (approximately 60 %). There was no significant difference in specific gravity between management zones, although specific gravity tended to decrease with distance from the primary discharge area (Table 3). The lower standard error associated with the wetland specific gravity, relative to the dryland and primary discharge zones (Table 3), suggested higher substrate homogeneity within the wetland.

Bulk Density

Bulk density was lower than that of a clay or silt soil, due to the lower specific gravity of the coal fraction. Tailings bulk density did not vary significantly between management zones or with depth (Table 3). The lower standard error for bulk density in the wetland relative to that of the other zones, supported the observation that tailings homogeneity increased with distance from the primary discharge area.

Gravimetric Water Content

GWC approached permanent wilting point (Table 3) in the dryland surface (0-10 cm) and primary discharge zone tailings material (Fig. 6). In the dryland, GWC increased from 12 % in the surface material, to 33 % at 165 cm in depth (Fig. 6), indicating that plant available water in the surface material may be limiting to vegetation establishment. At 20 cm depth, however, enough soil moisture was available to allow plant growth. Thirty metres from ponded water in the wetland, surface GWC was 25 %, increasing to 32 % by 25 cm in depth (Fig. 6). Within 1 m from free standing water however, surface GWC was 40 %, decreasing to 32 % at 105 cm in depth (Fig. 6), indicating the water was perched on the tailings surface. Below 115 cm depth, GWC was similar in the dryland and wetland zones. The lower GWC in the discharge zone was lower than elsewhere in the dam, presumably, due to the larger particle size of the material deposited around the discharge (Fig. 6).

Porosity and Pore Saturation

Porosity, as calculated from specific gravity and bulk density measurements, averaged 38 % (v/v), ranging from 44 % in the dryland to 30 % in the primary discharge zone (Table 3). Tailings pore saturation, as calculated from porosity and GWC values, differed markedly between management zones (Table 3). Within the dryland zone, pore saturation increased from 49 % at the surface (0-10 cm), to 81 % at 140-150 cm in depth. In the wetland, the substrate was saturated at the surface

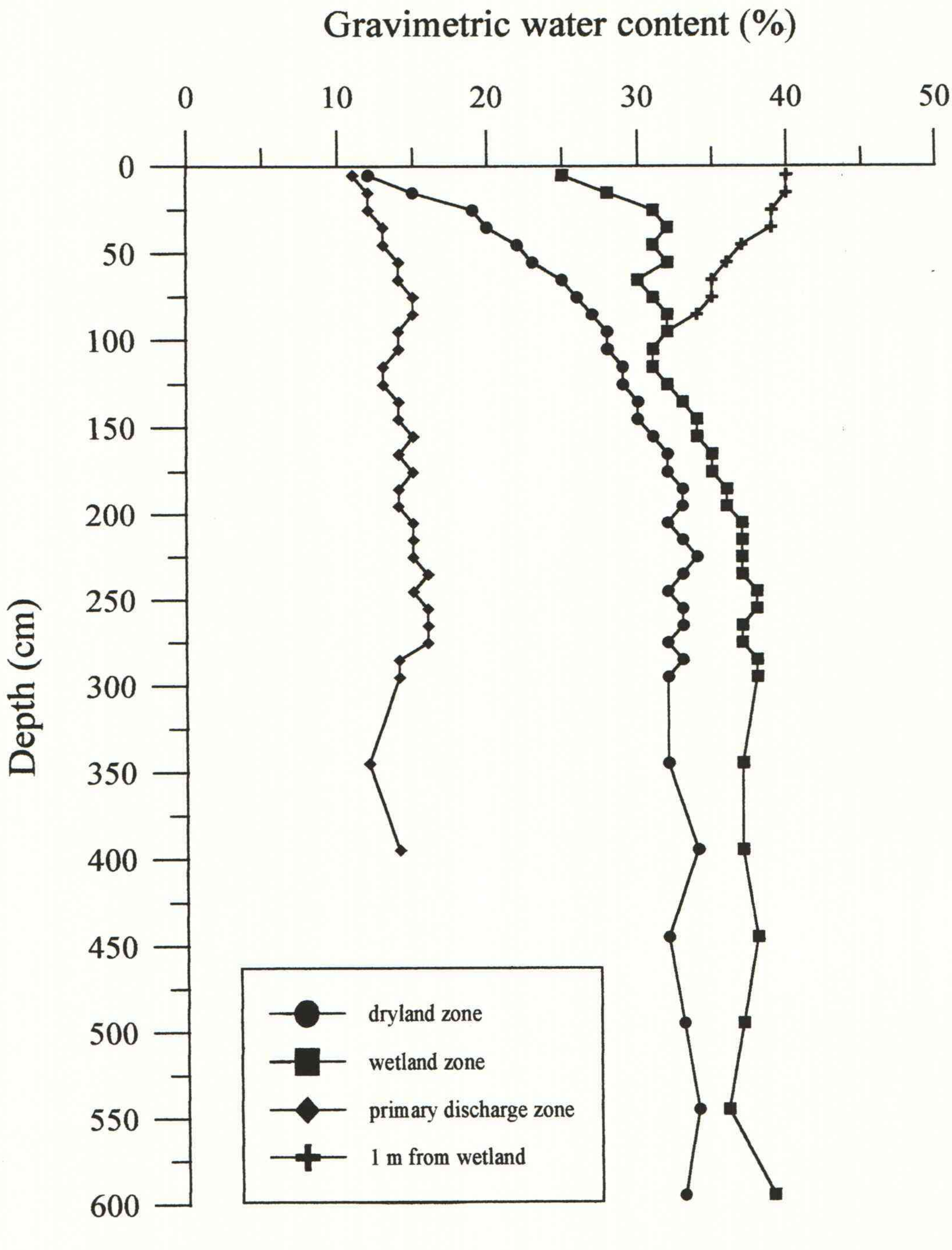

Figure 6. June 1994 gravimetric water content profiles of the dryland, wetland and primary discharge zones of Saraji coal tailings dam no. 3 (lsd=2.16, n=3). Wilting point was 10 % and 9% GWC in the dryland and primary discharge zones respectively. Field capacity was 41 % and 27 % GWC in the dryland and primary discharge zones respectively.

with pore saturation values decreasing to 95 % at 150 cm (Table 3). Pore saturation within the primary discharge increased from 33 % in the surface material to 56 % at 140-150 cm in depth (Table 3). Where the surface substrate was saturated in the wetland, species adapted to these conditions would be required due to the waterlogged nature of the substrate.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity was 10^{-7} cm s^{-1} in the dryland zone, 10^{-8} cm s^{-1} in the wetland zone and 10^{-5} cm s^{-1} in the primary discharge zone (Table 3). Saturated hydraulic conductivity decreased with distance from the primary discharge zone, which was consistent with a decrease in particle size from the discharge point (Table 3). Saturated conductivity values were low in comparison with those for soils of similar particle size (Hicks 1991) but comparable with other coal tailings (Williams and Morris 1990).

4.1.3. Tailings Chemical Characteristics

Acidity

Surface pH analyses indicated pH was grouped into zones of acidic (average pH 2.8) and neutral (average pH 7.0) tailings (Fig. 7, Table 4). The acidic areas (pH < 5.5) lay adjacent to the discharge points and were termed the discharge zones (Fig. 7). Although the primary discharge point was used to fill > 90 % of the dam's tailings volume, the primary and secondary discharge zones each covered 1.2 ha or 4 % of the dam's surface area (Fig. 7). The pH profiles indicated the primary discharge zone was acidic to a minimum depth of 4 m (average pH 2.8; n=33) (Fig. 8).

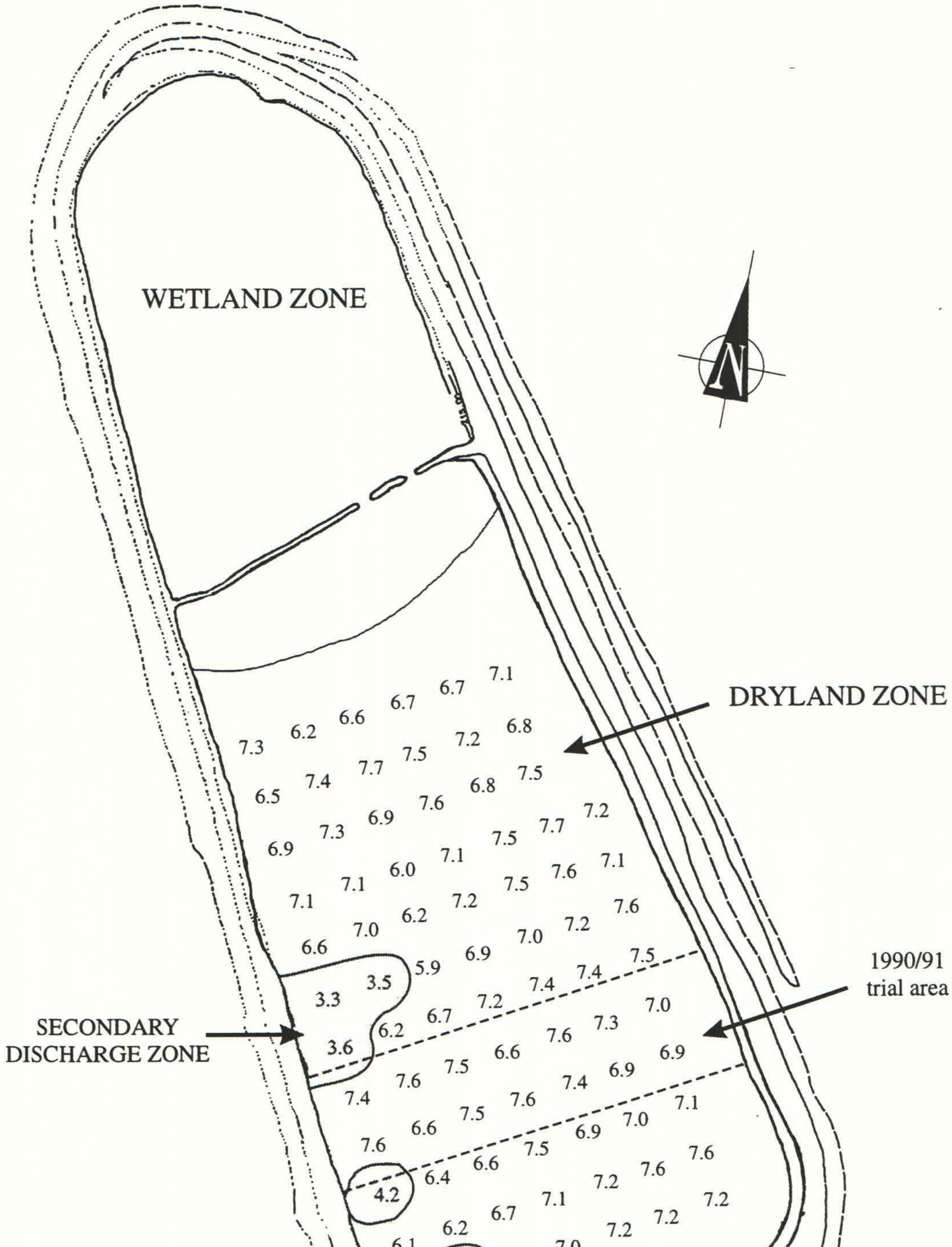

Figure 7. Saraji tailings dam no. 3 surface (0-10 cm) $pH_{1:5}$ survey at 50 m centres. Shading indicates $pH_{1:5} < 5.5$.

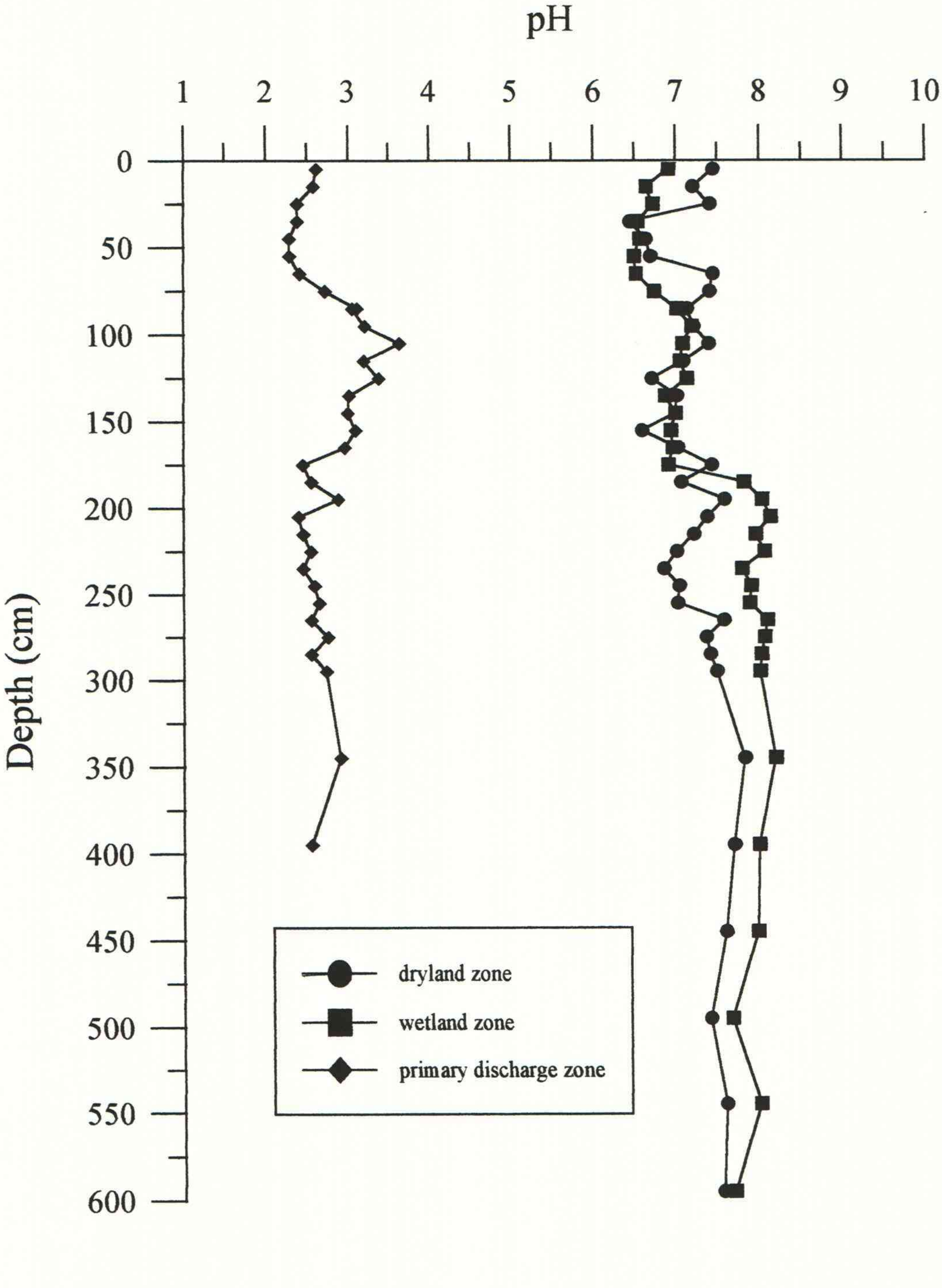

Figure 8. June 1994 pH(1:5) profiles of the dryland, wetland and primary discharge zones of Saraji tailings dam no. 3 (lsd=0.36, n=3).

Table 4. Chemical characteristics of relevance to vegetation establishment on Saraji coal tailings dam no. 3.

Characteristic	Extractant	Dryland zone	Wetland zone	Primary Discharge zone	Critical level*
$pH_{1:5}$	1:5 H_2O	7.2 (0.2)	7.9 (0.1)	2.6 (0.1)	5.5-8.5
$EC_{1:5}$ (dS m^{-1})	1:5 H_2O	3.21 (0.51)	1.35 (0.12)	3.35 (0.41)	< 0.4
Organic Carbon (%)	$K_2Cr_2O_7/H_2SO_4$	5.0 (0.0)	5.0 (0.0)	5.0 (0.0)	< 1.0
Nitrate Nitrogen (mg kg^{-1})	1:5 H_2O	0.4 (0.1)	0.9 (0.2)	0.2 (0.1)	–
Phosphorus (mg kg^{-1})	0.05 M $NaHCO_3$	4 (0.3)	9 (0.3)	125 (8.1)	30
Potassium (cmol(+) kg^{-1})	1 M NH_4OAc	0.41 (0.04)	0.34 (0.04)	0.01 (0.02)	0.2-0.3
Calcium (cmol(+) kg^{-1})	"	5.84 (0.27)	5.38 (0.50)	17.47 (0.34)	1.2
Magnesium (cmol(+) kg^{-1})	"	9.23 (1.38)	5.10 (0.45)	7.66 (0.52)	0.75-1.5
Sodium (cmol(+) kg^{-1})	"	11.16 (2.12)	4.42 (0.41)	0.01 (0.00)	–
Chloride (mg kg^{-1})	1:5 H_2O	585 (195)	315 (5)	5 (1)	200-600
Sulphate Sulphur (mg kg^{-1})	0.01M $Ca(H_2PO_4)_2$	3106 (499)	1096 (136)	6600 (430)	15
Copper (mg kg^{-1})	0.005 M DTPA 0.1 M TEA 0.01 M CaCl	0.9 (0.03)	1.4 (0.15)	2.4 (0.11)	0.2
Zinc (mg kg^{-1})	"	2.4 (0.5)	3.4 (0.3)	6.6 (0.5)	0.5-1
Manganese (mg kg^{-1})	"	2 (0.3)	2 (0.3)	210 (14.1)	2
Iron (mg kg^{-1})	"	7 (1.4)	10 (0.6)	2400 (110)	4.5
Aluminium (cmol(+) kg^{-1})	1 M KCl	–	–	20.00 (2.40)	
Boron (mg kg^{-1})	0.01 M CaCl 0.05 M Mannitol	0.95 (0.10)	0.74 (0.02)	5.90 (0.39)	0.15
CEC (cmol(+) kg^{-1})	calculated	26	15	45	–
ESP (% cations)	"	41	29	0.02	< 15

* critical levels represent values below which the addition of nutrient might reasonably be expected to improve plant response in improved crop and pasture

species; for Cl, EC and ESP the critical level is the value above which growth will be retarded (Aitken *et al.* 1984).

Data are means with one standard error given in parentheses (n=3). Replicates were derived from the 3 0-30 cm cell samples gathered for each management zone (see section 3.2.2). Cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) were calculated from the total number of exchangeable (1 M NH_4OAc) cations 100g tailings^{-1}, and the % saturation of the available exchange sites (CEC) by sodium respectively.

Average surface pH in the dryland zone and wetland zones was circum-neutral (Table 4, Fig. 7). Profile examinations in these zones indicated that pH did not vary significantly with depth (Fig. 8).

Eight plumes of discharge zone material (possibly containing pyrite) were observed radiating through the dryland from the primary discharge zone. These plumes were acidic (average pH 3.6; n=5) (Fig. 9). The plumes were approximately 1m wide, 600 m long and occupied about 3 % of the dam's surface area. Due to their small area, these were not detected in the 50 m grid sampling.

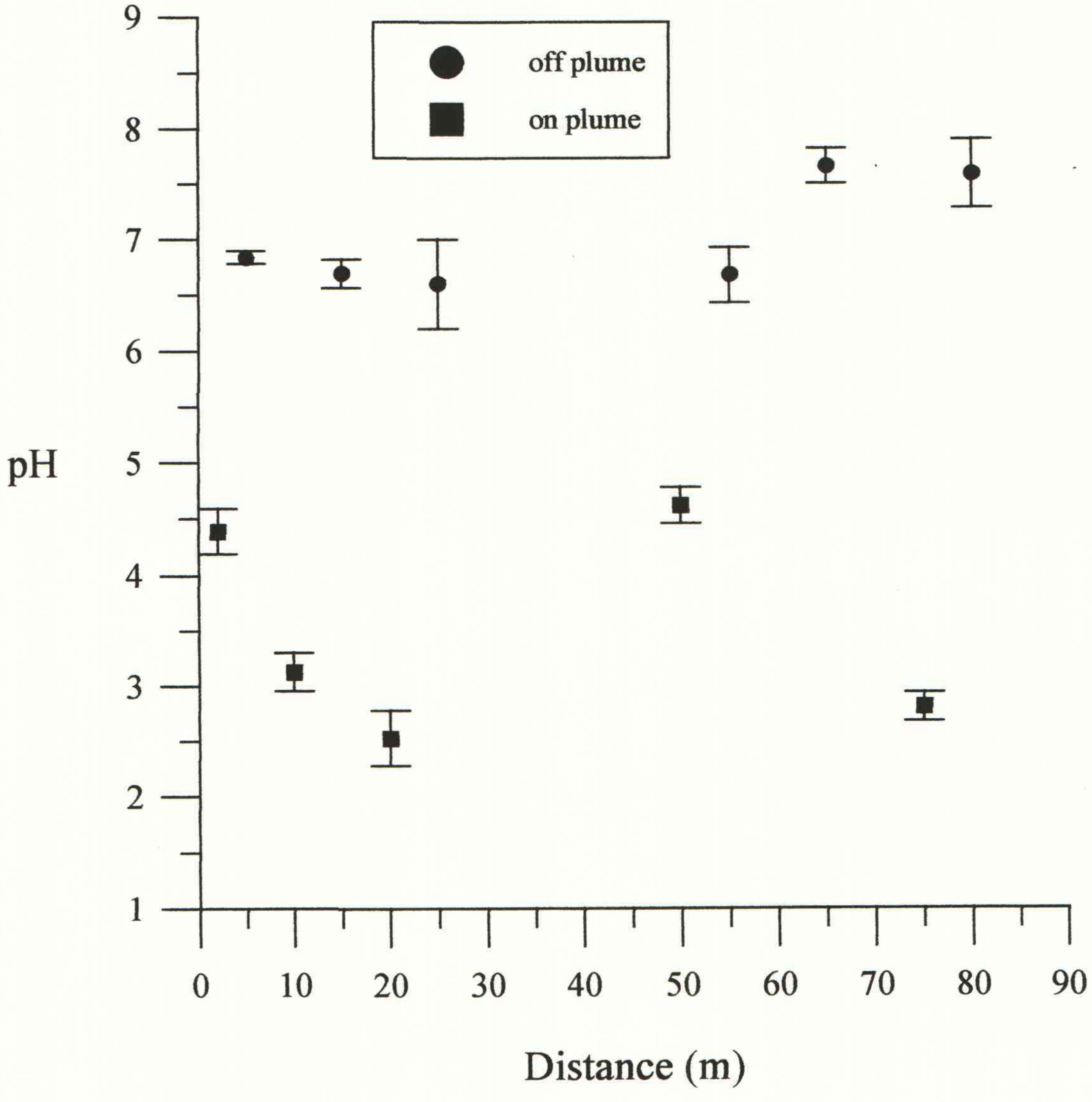

Figure 9. June 1994 surface (0-10 cm) pH (1:5) of a west/east transect originating 150 m from the primary discharge point along the western dam wall of Saraji tailings dam no. 3 (n=5). The transect was constructed to intersect plumes of coarse material radiating into the dryland from the primary discharge zone.

Salinity

Average surface EC in the dryland zone was 3.4 dS.m^{-1} (n=79) (Fig. 10). The primary and secondary discharge zones had an average surface EC of 2.8 dS m^{-1} (n=4) and 2.3 dS m^{-1} (n=3), respectively. Within each management zone EC decreased with depth to 100 cm in the profile (Fig. 11). Below 100 cm, EC remained relatively constant to the extent of the cores in all three management zones. The wetland contained less soluble salts than the other 2 management zones (Fig. 11).

For each management zone, pH and EC averages for the 0-30 cm mixed bulk sample (Table 4) were similar with those of the 0-10 cm samples (Fig. 10). Therefore, the 0-30 cm mixed bulk samples used for characterisation studies and potting trials were considered to be representative of the *in situ* tailings material.

Organic Carbon, Soluble Salts, Nutrient Status, CEC and Sodicity

The dryland and wetland zones were chemically similar and differed greatly from primary discharge zone (Table 4). Walkley-Black organic carbon was high (Harte 1982) in all zones at 5% (Table 4) and therefore not considered limiting to the revegetation of the substrate. Nitrate nitrogen content was low in all zones (Table 4) relative to that expected for low fertility Australian soils (Ladd and Russell 1983). Bicarbonate extractable phosphorus was considered deficient in the dryland (4 mg kg^{-1}) and wetland (9 mg kg^{-1}, Aitken *et al.* 1984). The high bicarbonate extractable phosphorus in the discharge zone may be due to the use of the bicarbonate method, which is not appropriate to use in low pH soils

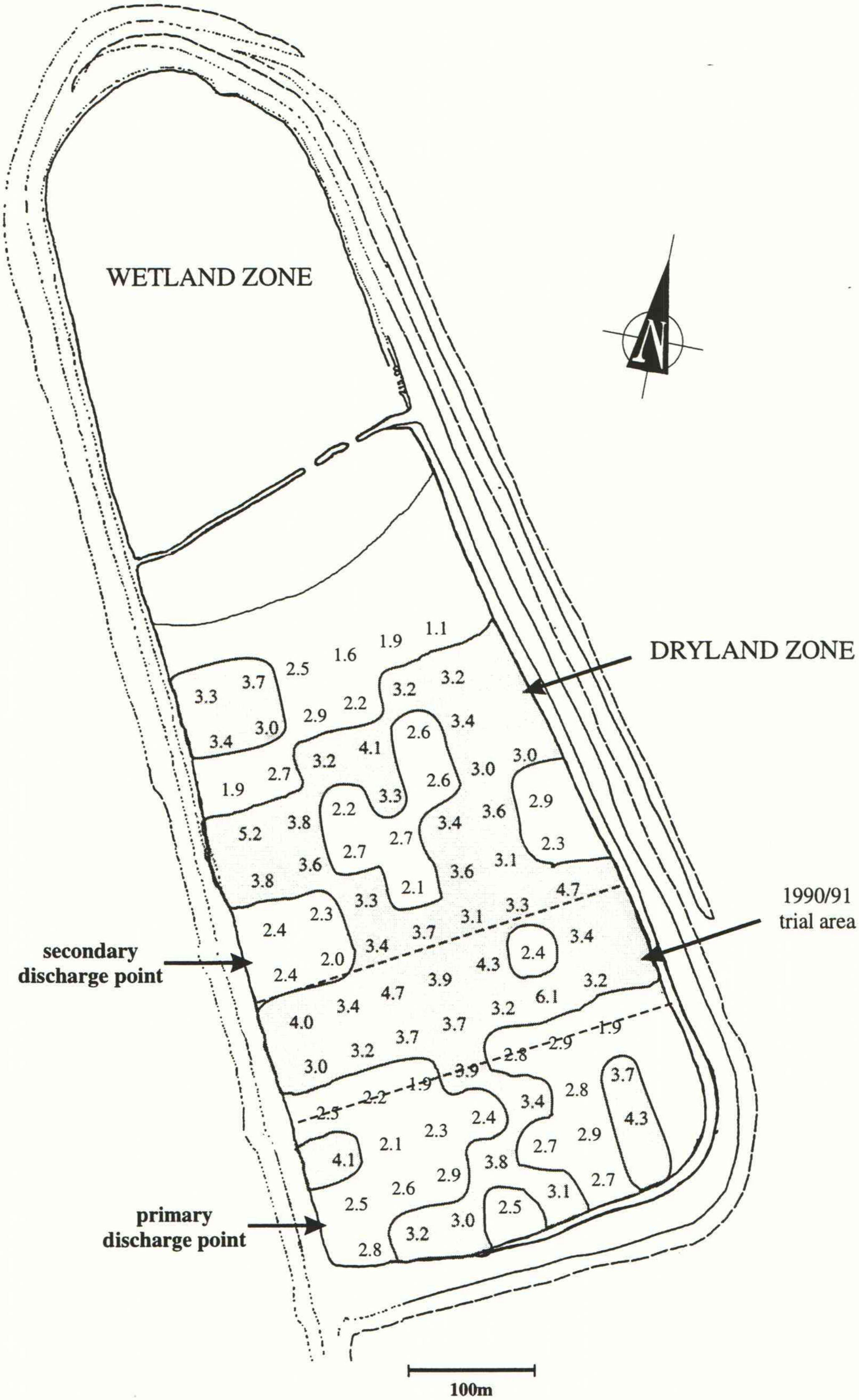

Figure 10. Saraji tailings dam no. 3 surface (0-10 cm) $EC_{1:5}$ survey at 50 m centres. Shading indicates $EC_{1:5} > 3.0$ dS m^{-1}.

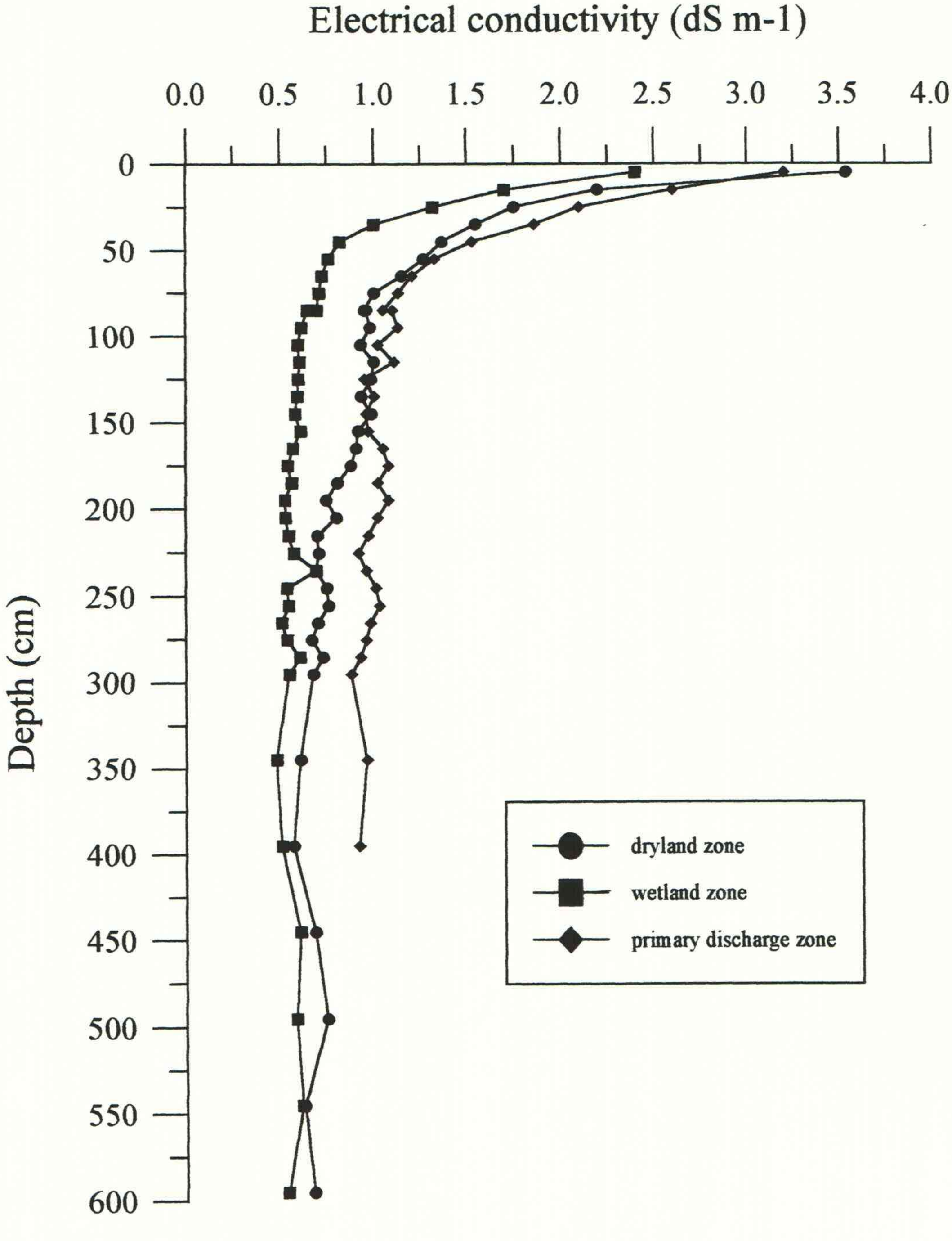

Figure 11. June 1994 electrical conductivity (1:5) profiles (10 cm segments) of the dryland, wetland and primary discharge zones of Saraji coal tailings dam no. 3 (lsd=0.32, n=3).

(Olsen and Sommers 1982). Potassium (K) and chloride appeared adequate to support plant growth in all zones except the primary discharge zone. Calcium, magnesium, sulphate sulphur, copper and zinc were not considered limiting to plant growth (Table 4). Aluminium, manganese, iron and boron concentrations were high in the primary discharge presumably solubilised as a result of the low pH. The major cations present were calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium and (Na^{+}), whilst the predominant anions were chloride (Cl^{-}), and sulphate (SO_4^{2-}) (Table 4).

CEC within the wetland zone (15 cmol(+) kg^{-1}) was lower than the dryland zone (26 cmol(+) kg^{-1}) and primary discharge zones (45 cmol(+) kg^{-1}) (Table 4), despite the higher clay particle size distribution in the wetland (Table 3). The CEC of the tailings was in the low to medium range and the use of slow release fertiliser or regular conventional fertiliser applications may be required for sustained plant growth.

The dryland and wetland zones were highly sodic with an ESP of 41 % and 29 % respectfully (Table 4). In contrast, the primary discharge zone was not sodic with an ESP of 0.02 % (Table 4) reflecting the high low sodium and high calcium levels detected in this zone.

Pyrite Content, Total Potential Acidity and Thiobacillus ferrooxidans Enumeration

Pyrite content was not correlated with pH or distance from the discharge points (Table 5). Pyrite content was higher in the primary discharge (0.58 %) and dryland zones, than the wetland zone (0.21 %), discharge zone 2 (0.19 %) and the plume material (0.18 %) (Table 5). The low pH and pyrite content of the discharge zone and plume material suggested that weathering of the tailings was well advanced. Total potential acidity was calculated from pyrite content (Table 5).

Table 5. Surface (0-10 cm) $pH_{1:5}$, pyrite content, potential acidity and *Thiobacillus ferrooxidans* density for Saraji coal tailings dam no. 3.

Sampling area	$pH_{1:5}$	Pyrite content (%)	Potential acidity (t $CaCO_3$ 1000 t material^{-1})	*Thiobacillus ferrooxidans* density (no. g dwt^{-1})
dryland zone	7.0	0.45 (0.03)	6.5	2800 (830)
wetland zone	7.0	0.21 (0.02)	3.1	3200 (770)
primary discharge zone	2.8	0.58 (0.16)	8.4	3600 (610)
secondary discharge zone	3.5	0.19 (0.01)	2.8	3000 (450)

Data are means with one standard error of three replicates given in parentheses (n=3).

T. ferrooxidans density did not differ between management zones (Table 5). *T. ferrooxidans* density was not correlated with pH, distance from the discharge points, or pyrite content (Table 5).

Liming Requirement

The equation pH = 1.66 + 0.10($CaCO_3$ 1000 t tailings^{-1})-0.0003($CaCO_3$ 1000 t tailings^{-1})^2 (R^2 = 0.97) explained the pH increase after lime addition and incubation for 68 days (Fig. 12). The liming rate to increase the pH of the primary discharge

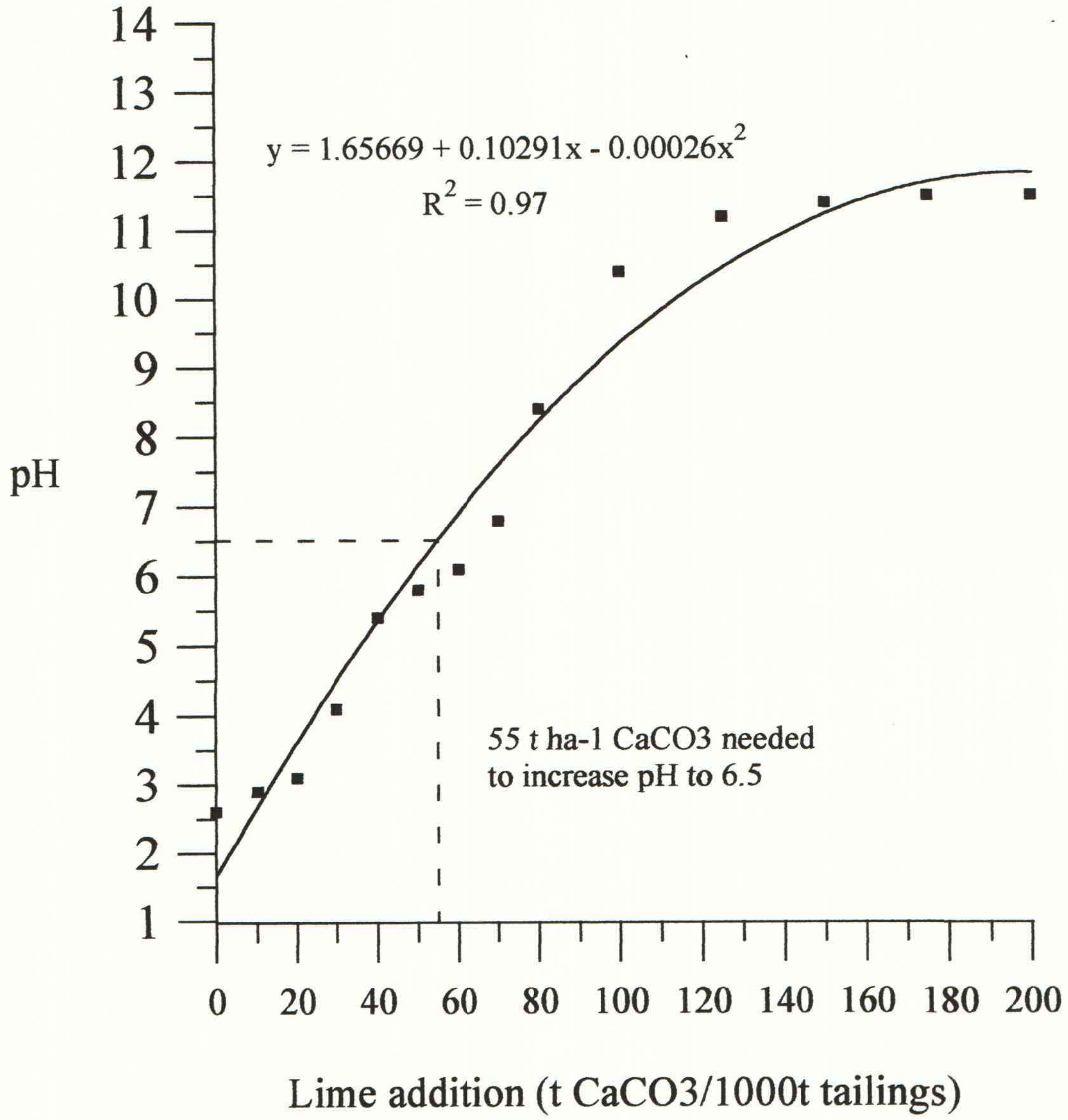

Figure 12. The effect of lime addition on the pH of primary discharge zone tailings (pH 2.6) after 68 d incubation with $Ca(OH)_2$ (Dunn 1943) at -0.1 bar (data are means of n=3).

material from 2.8 to 6.5 was therefore 55 t $CaCO_3$ 1000 t tailings^{-1} (Fig. 12). For a depth of 10 cm, and given an average bulk density of 1.15 t.m^{-3} (Table 3), 63 t ha^{-1} of pulverised limestone (90 % efficiency) would be required to increase the pH to 6.5.

4.2. GLASSHOUSE AND LABORATORY TRIALS

4.2.1. The Effect of Tailings Salt Extract on Tree and Saltbush Seed Germination

The only species to germinate in treatments containing tailings of the tree and saltbush germination and growth trial were *A. harpophylla* and *A. holosericea* (Fig. 13). Increasing the tailings salt extract EC from 0 to 20 dS m^{-1} had no effect on total germination at 28 days, or the time to 50 % germination for *A. holosericea*. For *A. harpophylla*, however, increasing the EC of the tailings salt extract from 0 to 20 dS m^{-1} significantly increased the time to 50 % germination (Fig. 13b).

4.2.2. Tree and Saltbush Germination and Growth Trial

Twenty eight days after sowing germination in all media was poorer than that in Petri plates (Fig. 13a). The only species to germinate in tailings was *A. harpophylla*. For both species tailings with topsoil increased germination above that of tailings alone with a seedbed of 5 cm topsoil increasing *A. harpophylla* germination to that of the topsoil control (Fig. 13a). Mulch had no beneficial effect on germination. These results indicated that tailings were not a good medium for germination, a result attributed to low macroporosity as the overall porosity (Table 3) was reasonable, and/or the sticky nature of the tailings material.

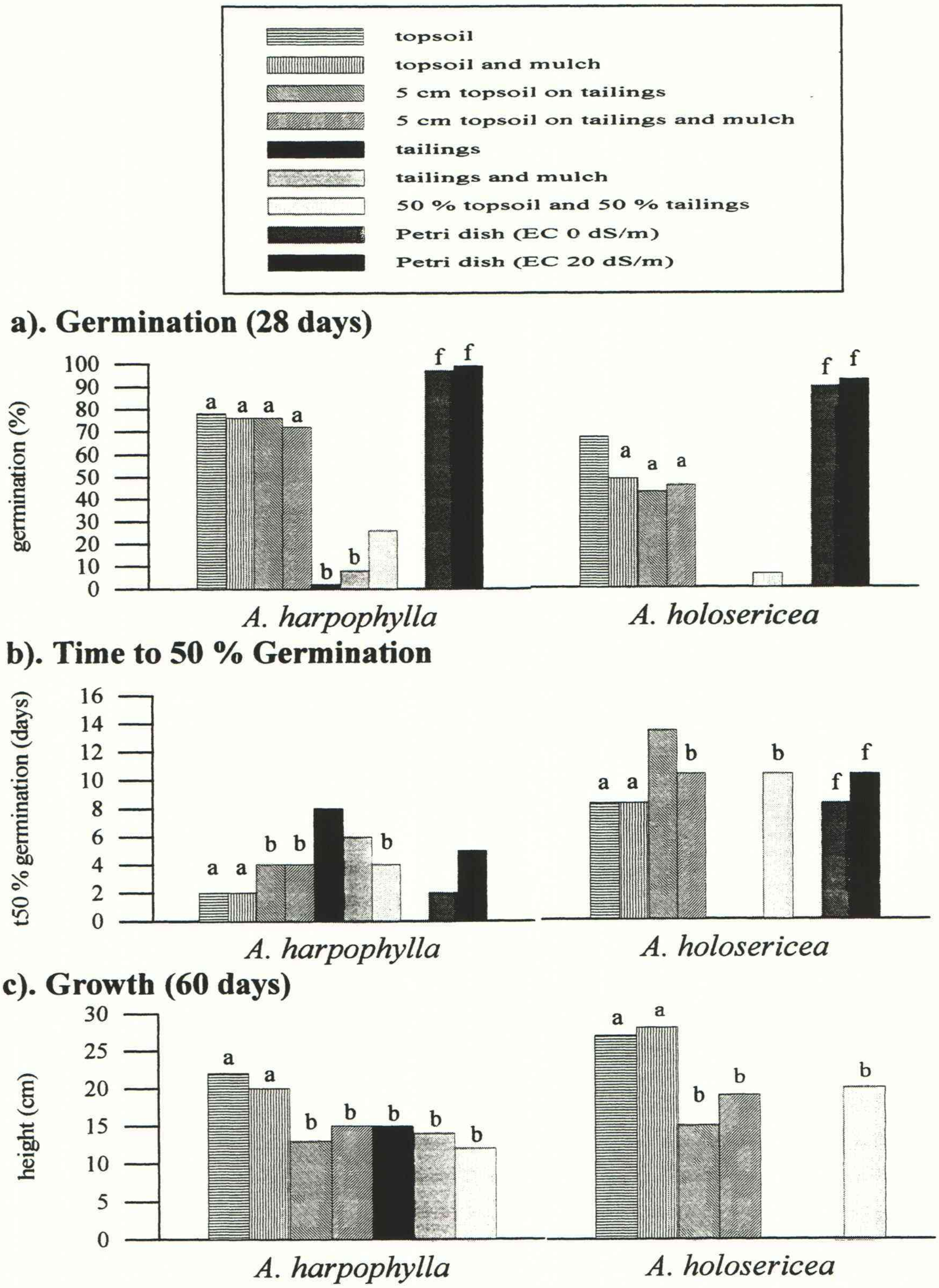

Figure 13. Germination characteristics of species in the tailings salt extract (Petri dishes, n=3, 30 seeds per dish), and germination and growth glasshouse pot trials (n=5, 25 seeds per pot, thinned to 3 seedlings per pot at 10 d). a) total germination in tailings salt extract and glasshouse trial media 28 d after sowing. b) time to 50 % germination under the above conditions. c) height 60 d after sowing on glasshouse trial media. Same letter indicates means are not significantly different ($P < 0.05$, intra-species comparisons only).

Germination time in the topsoil controls was similar to that in Petri dishes (Fig. 13b). For *A. harpophylla*, which was the only species to germinate in tailings, time to 50 % germination was significantly longer in tailings relative to the topsoil controls. Mulching tailings significantly reduced the time to 50 % germination for *A. harpophylla* (Fig. 13b). *A. holosericea* germination rate in unmulched topsoil over tailings was significantly slower than in 50 % topsoil and 50 % tailings. The tailings media alone was not as good a germination media as tailings with topsoil or mulch.

There was no significant growth difference between pots containing tailings, although growth was significantly less than in the topsoil controls (Fig. 13c). Mulching did not significantly affect the growth of either species. On harvesting the pots, roots were found to penetrate deeply into the tailings. The trend for tailings to be less conducive to growth and germination was attributed to the saline and/or the physically sticky (plasticine like) nature of the tailings material.

4.2.3. Nutrient Rate Trial

The dry matter yield of *C. gayana* (Rhodes grass) following 8 weeks growth in pots of tailings, was not significantly affected by the addition of K ($P = 0.699$, Appendix 2), although fertilisation with N and P produced a significant ($P = 0.000$ and 0.001 respectively) effect (Fig. 14). The addition of N and P in combination resulted in a marked increase in dry matter yield when compared with the effect due to one factor alone ($n = 10$, K not significant therefore data pooled and averaged over K treatment results) (Fig. 14). In the absence of P, increasing N fertilisation from 0 to 140 kg N ha^{-1} had a minimal effect on dry matter yield. With 35 and 70 kg P ha^{-1}, however, an

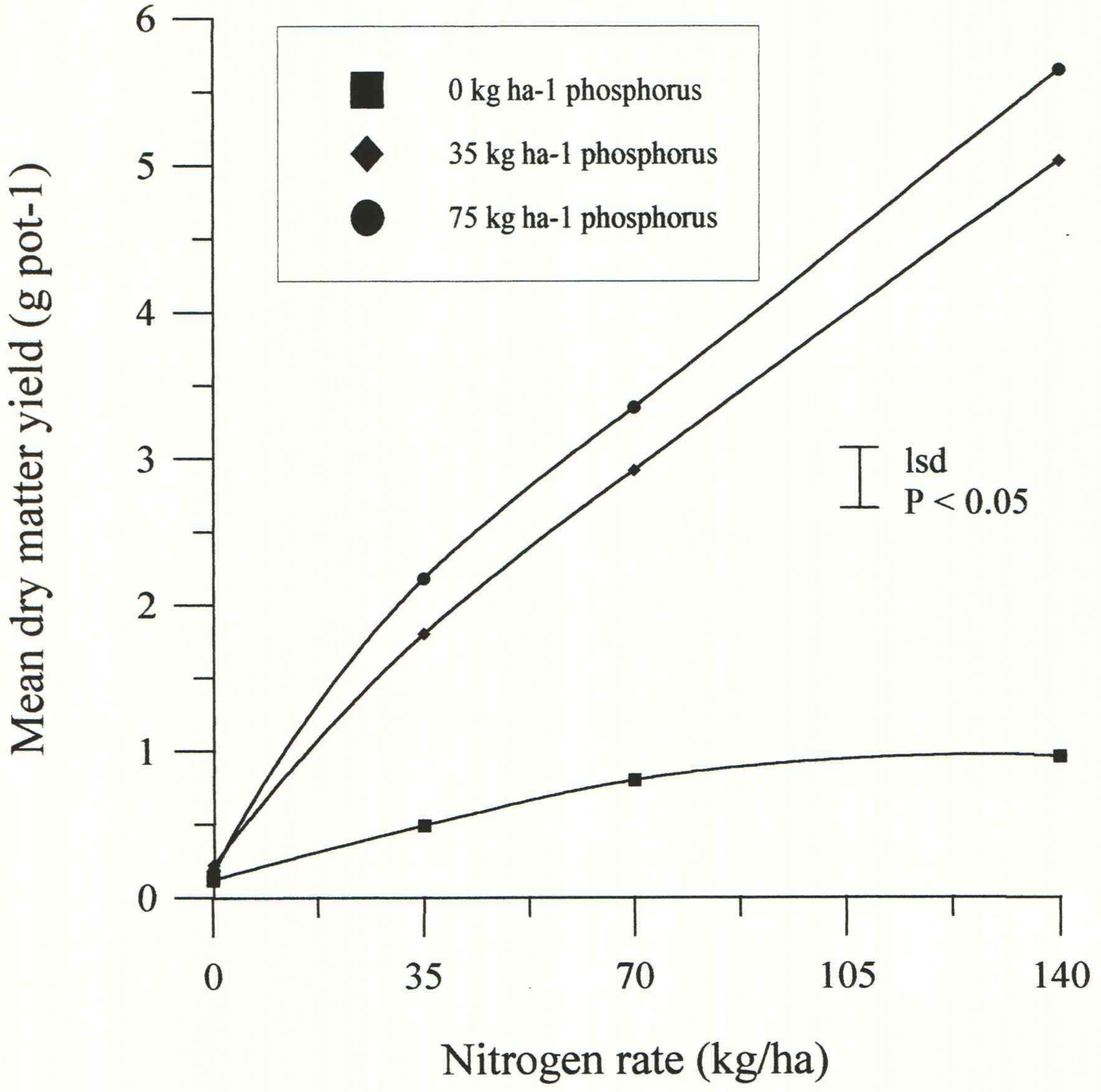

Figure 14. Rhodes grass dry matter yield after 8 weeks growth on Saraji coal tailings with nitrogen (0, 35, 70, 140 kgN ha-1) and phosphorus (0, 35, 70 kgP ha-1) fertilisation (n=10 with pooled K). X-Axis scale assumes fertiliser incorporation to a depth of 10 cm (1150 t tailings ha-1).

increase in N fertilisation rate resulted in a significant increase in dry matter yield (Fig. 14). An increase in P addition from 35 to 70 kg ha^{-1} had no significant effect on dry matter yield, except at the highest rate of N.

4.3. FIELD TRIALS

4.3.1. Wetland Species and Amelioration Techniques

Vetiveria zizanioides (vetiver grass) and *S. virginicus* (marine couch) were the only species surviving 12 months after planting in the wetland trial, with 55 % and 77 % survival, respectively. Kruskal-Wallis analyses indicated the survival of *V. zizanioides* and *S. virginicus* was not significantly affected by mulch or fertiliser.

The effects of fertiliser and mulch on *V. zizanioides* and *S. virginicus* growth were similar (Fig. 15). The factorial ANOVA on *V. zizanioides* dry weight indicated the main effects of fertiliser and mulch significantly increased growth ($P = 0.000$ and $P = 0.018$ respectively) and no significant interactions occurred between the treatments ($P = 0.247$). *S. virginicus* growth was also significantly ($P = 0.000$ and 0.042 respectively) increased by fertiliser and mulch (Fig. 15). For both species, the response to fertiliser or mulch did not plateau at the levels trialed (Fig. 15).

Without mulching, the GWC of the surface (0-10 cm) tailings declined rapidly from c. 40 % toward wilting point (10 %) as the wetland dried (Fig. 16) with plant available water being more abundant in the mulched treatments. The impact of 87 mm of rainfall in January 1995, 165 mm in February 1995 and 55 mm in August

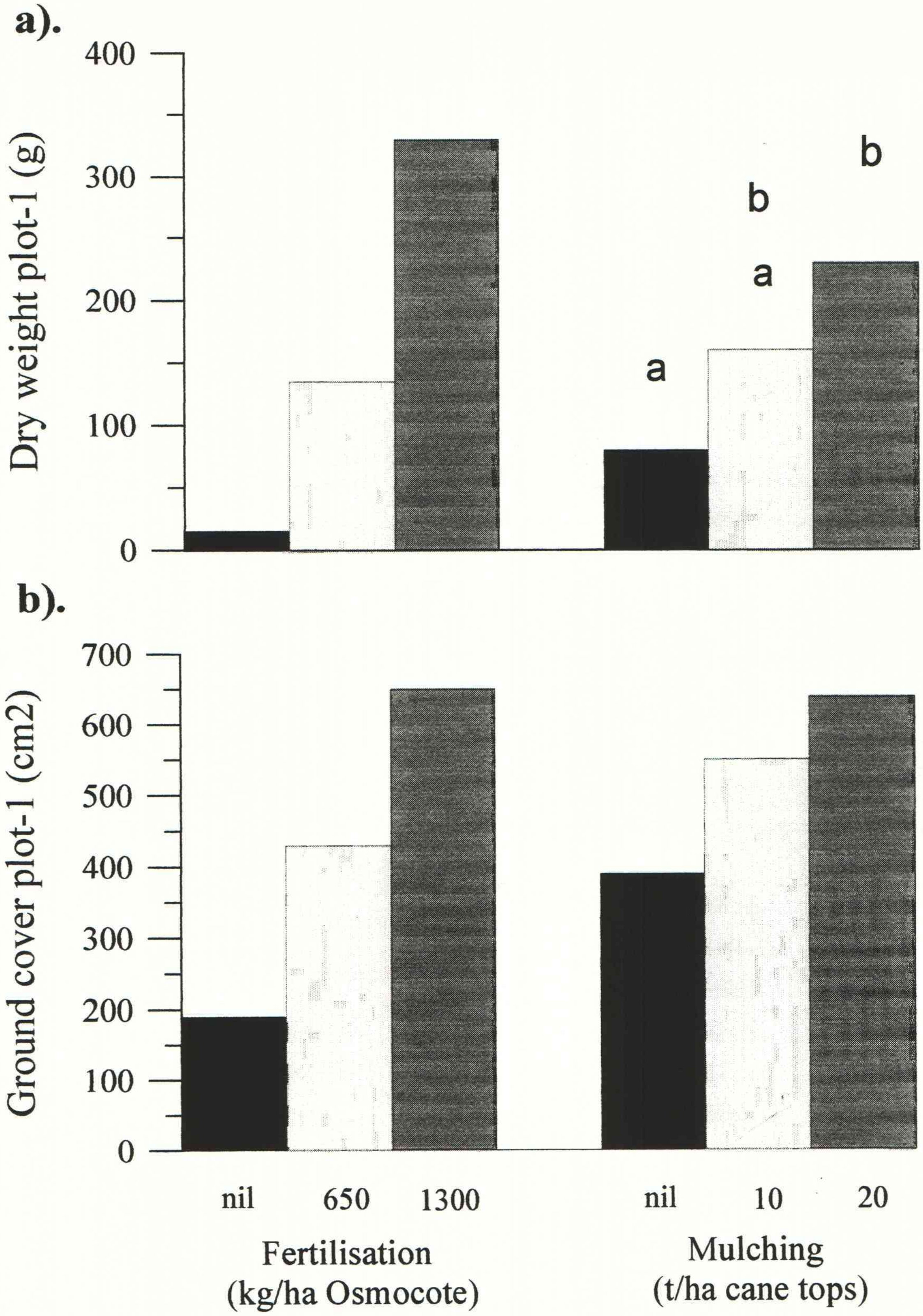

Figure 15. Effect of fertilisation and cane tops mulching on the growth of a) V. zizanioides and b) S. virginicus, 12 months after planting in the wetland zone of Saraji coal tailings dam no. 3 (n=15). Planting occurred in October 1994, 3 weeks after treatment establishment. Same letter indicates means not significantly different ($P < 0.05$).

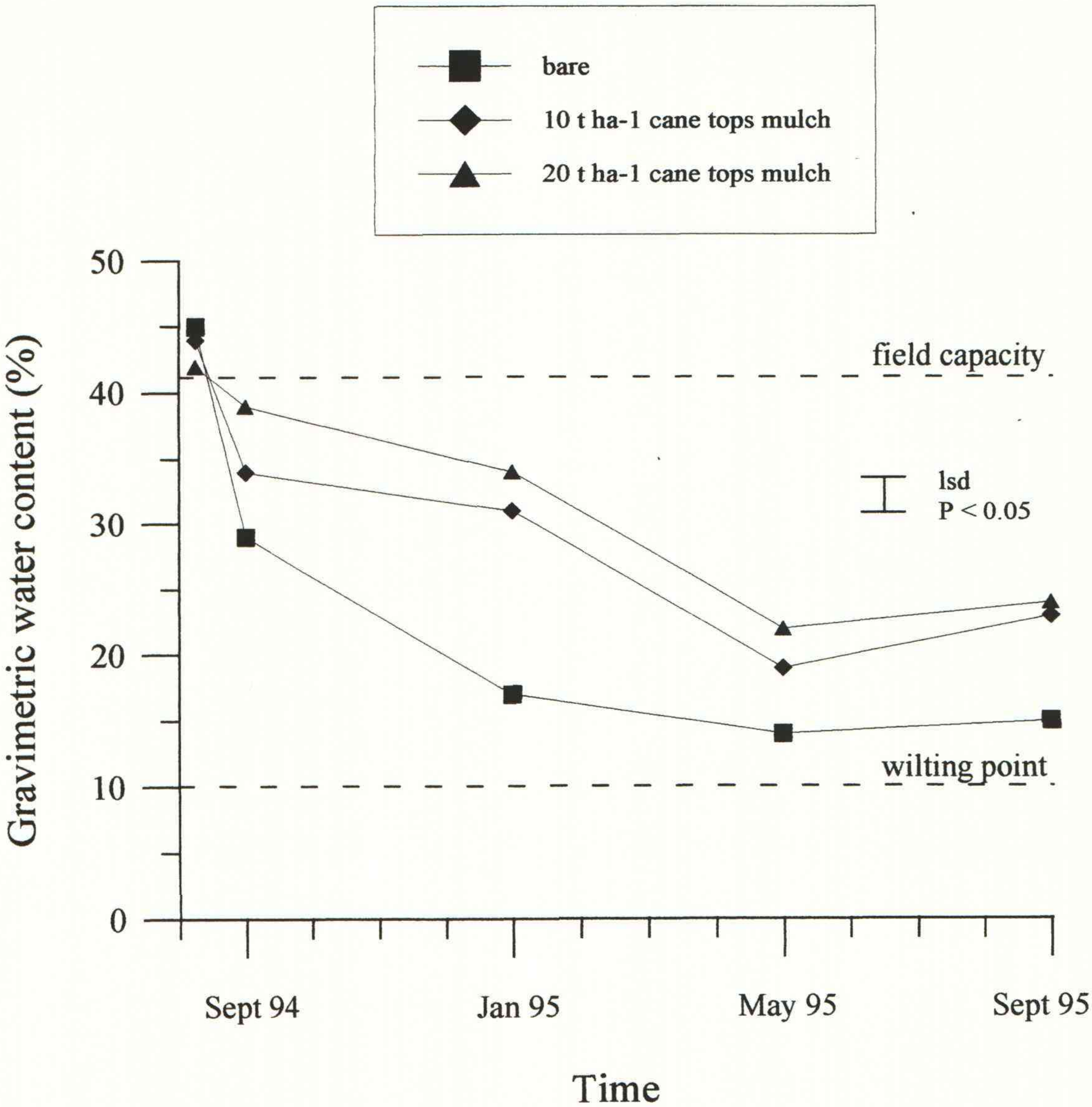

Figure 16. Gravimetric water content (0-10 cm) under cane tops mulching in the wetland plots established on Saraji coal tailings dam no. 3 (n=15). Treatments were imposed 3 weeks before planting in September 1994. Rainfall of 87 mm was received in January 1995, 165 mm in February 1995 and 55 mm in August 1995.

1995 on GWC were not substantial. The factorial ANOVA indicated an increase in mulching rate from 10 to 20 t ha^{-1} resulted in a significantly higher (P = 0.000) GWC, and thus plant water availability, throughout the trial.

Mulching also resulted in a significant (P = 0.000) reduction in surface (0-10 cm) EC relative to the unmulched controls (Fig. 17). Without mulch, the EC of the wetland surface (0-10 cm) increased for four months after planting, before equilibrating at 1.3 dS m^{-1}. Mulching at 10 t ha^{-1} decreased the rate at which EC rose, while mulching at 20 t ha^{-1} resulted in the initial EC being maintained (Fig. 17).

Neither mulching nor fertilisation had a significant effect on surface pH throughout the trial period (P = 0.785 and 0.823 respectively, tested 12 months after planting).

4.3.2. Dryland Amelioration Techniques

Over the 14 month trial period *Casuarina glauca* survival varied from 45-100 %, depending on the imposed treatment (Fig. 18). The ANOVA performed on the embedded factorial consisting of the factors irrigation, cane tops mulching and cultivation indicated that irrigation and cane tops mulching resulted in a significant (P = 0.002 and 0.000 respectively) increase in *C. glauca* survival. Analysis of the embedded factorial consisting of irrigation, cane tops and plastic mulching, indicated a significant (P = 0.046) interaction between irrigation and mulching. LSD analyses indicated there was no significant difference between mulching types. The inclusion of a trough in the plastic treatments had no significant effect on survival.

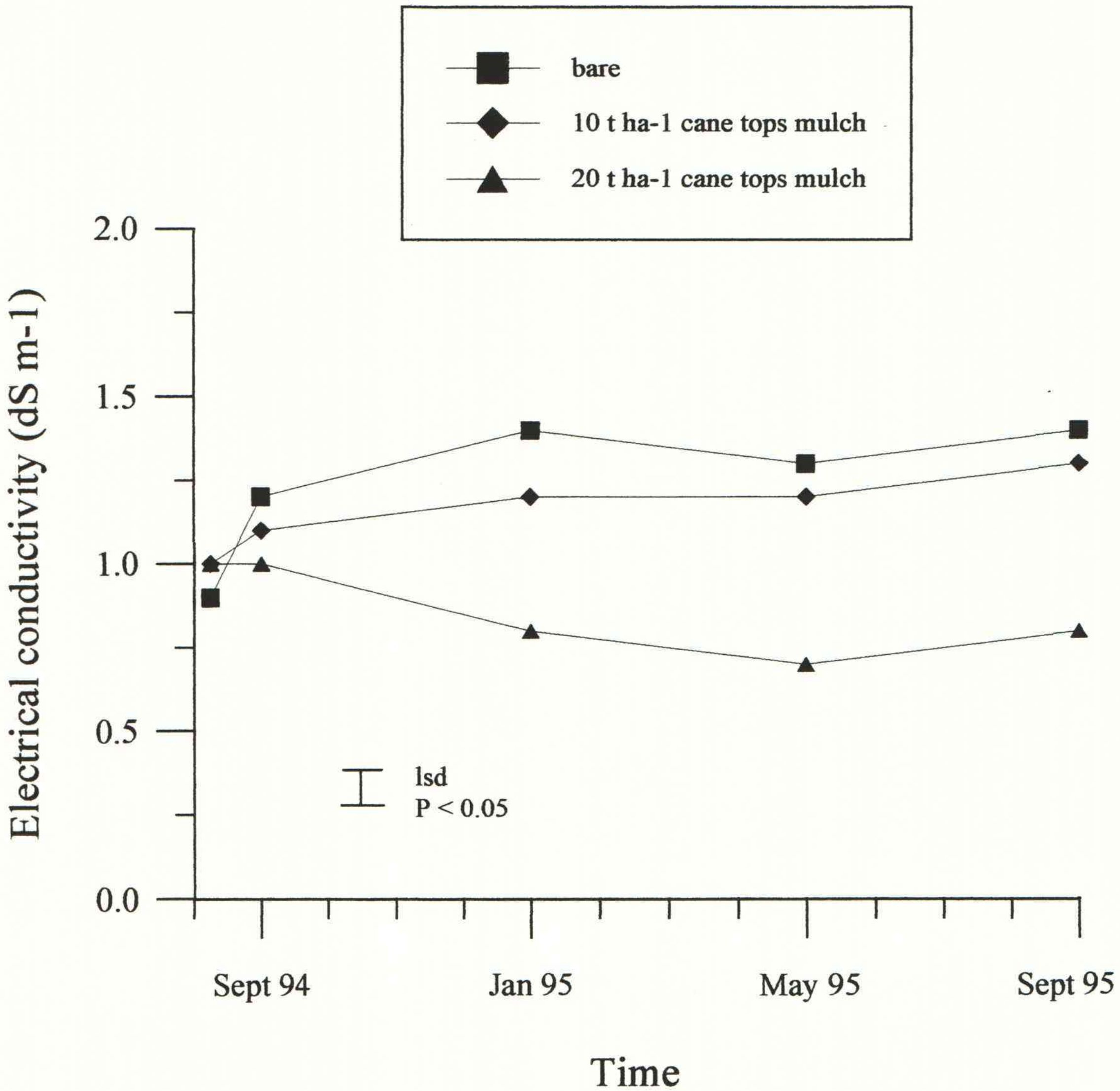

Figure 17. Surface (0-10 cm) electrical conductivity (1:5) under cane tops mulching in the wetland plots established on Saraji coal tailings dam no. 3 (n=15). Treatments were imposed 3 weeks before planting in September 1994. Rainfall of 87 mm was received in January 1995, 165 mm in February 1995 and 55 mm in August 1995.

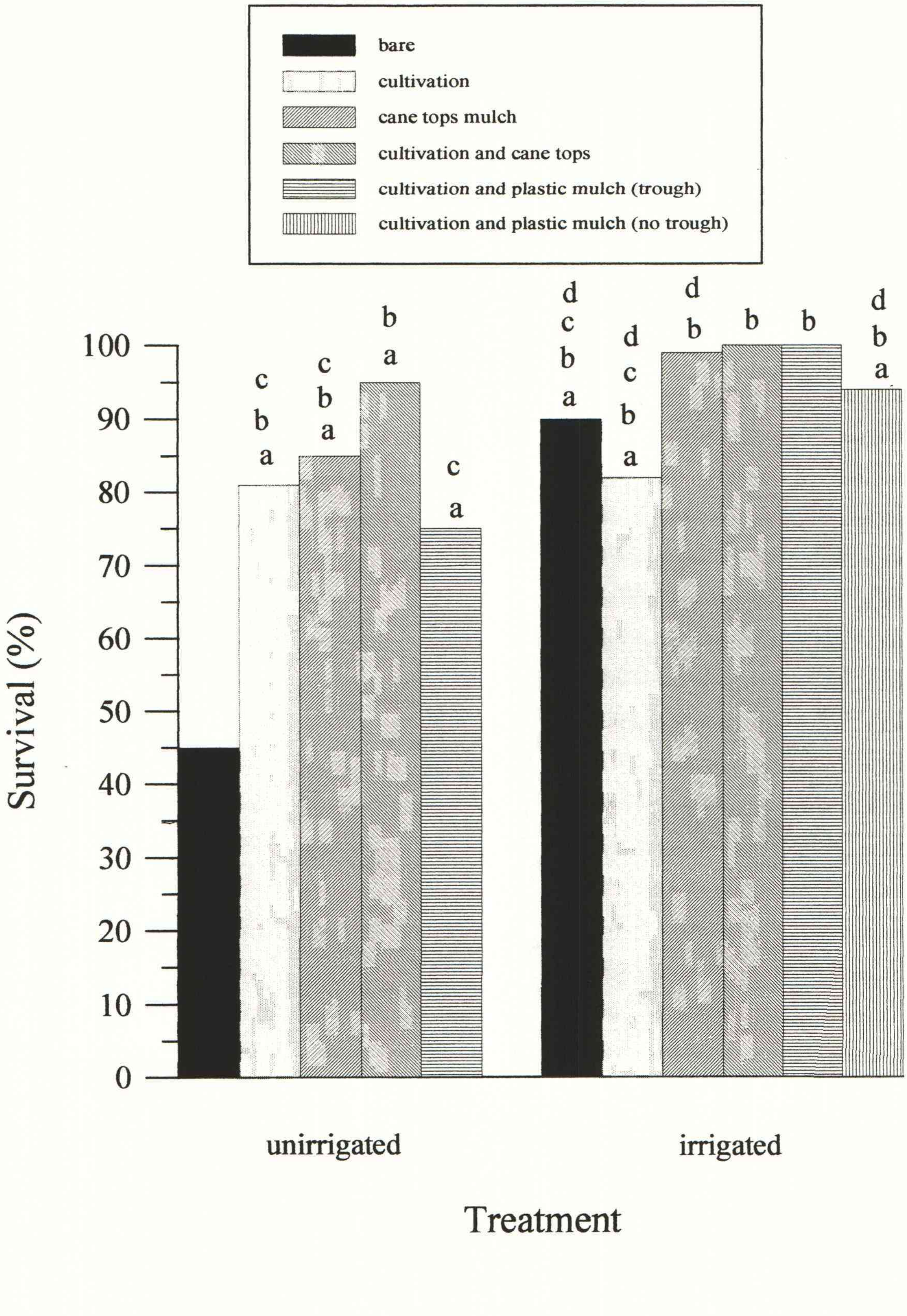

Figure 18. Survival of C. glauca tubestock 14 months after planting in dryland zone of Saraji coal tailings no. 3 (n=3). Planting occurred in January 1995, 3 weeks after treatment establishment. Same letter indicates means are not significantly different (P < 0.05).

Over the 14 month growing period *C. glauca* tubestock planted in bare tailings failed to increase in height (Fig. 19a) although tubestock planted in treatments with a combination of irrigation, mulching and cultivation however, attained heights of almost 2 m (Fig. 19b). Analysis of the embedded factorial including irrigation, cane tops mulching and cultivation indicated that after 14 months, all treatments significantly (P = 0.000) increased *C. glauca* growth. Similarly analysis of the embedded factorial including irrigation, cane tops and plastic mulching, indicated irrigation and mulching had a significant (P = 0.000) effect on *C glauca* growth. There was no significant difference between *C. glauca* growth in cane tops or plastic mulch. The absence of significant treatment interactions was reflected by the additive effect of each factor (Fig. 19). The inclusion of the central trough in the plastic treatments had no effect on growth.

A rainfall event of 70 mm was received over the three days before planting, resulted in a surface (0-10 cm) GWC much greater than wilting point in all but unwatered bare (control) and cultivated treatments (Fig. 20a). GWC subsequently declined in mulched and unirrigated treatments until a further 440 mm of rainfall was received between October 1995 and January 1996 (Fig. 20a). Before the 440 mm of rainfall, GWC under all unirrigated treatments had returned to that of the control. Without irrigation plastic mulching resulted in a higher GWC (Fig. 20a).

With irrigation, mulching significantly (P = 0.033) increased GWC compared to the unmulched treatments (Fig 20b). Irrigation in combination with mulching resulted in a GWC of 40-45 % throughout the period of watering (Fig. 20b). Although

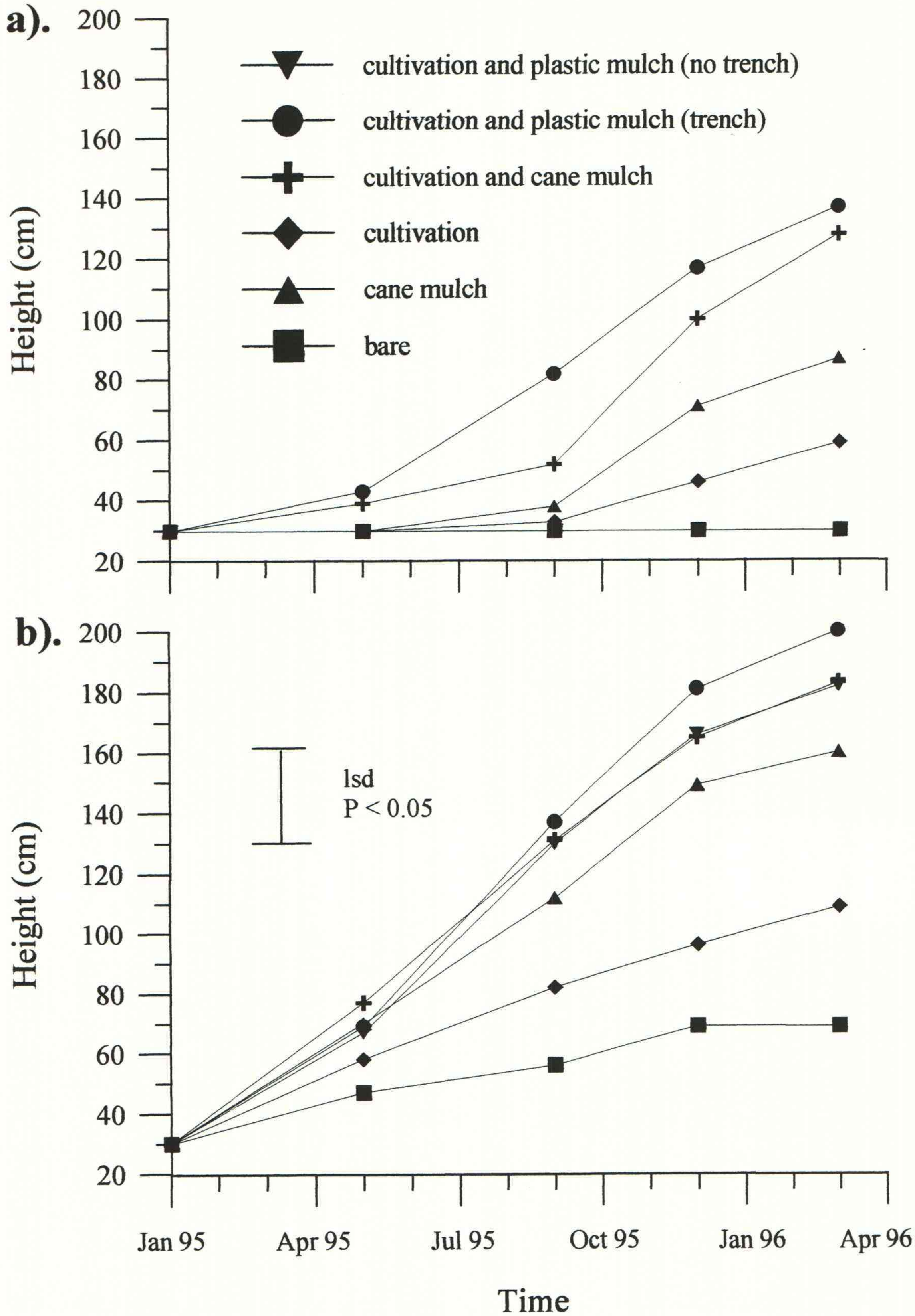

Figure 19. Average height (n=3) of <u>C. glauca</u> tubestock, grown in the dryland zone of Saraji coal tailings dam no. 3, under mulched (cane tops and plastic), cultivated, a) unirrigated and b) irrigated treatments. Planting occurred in January 1995, 3 weeks after treatments were imposed. Rainfall of 70 mm was received 3 days prior to planting, 165 mm in February 1995, and 440 mm between October 1995 and January 1996. Irrigation ceased 9 months after planting.

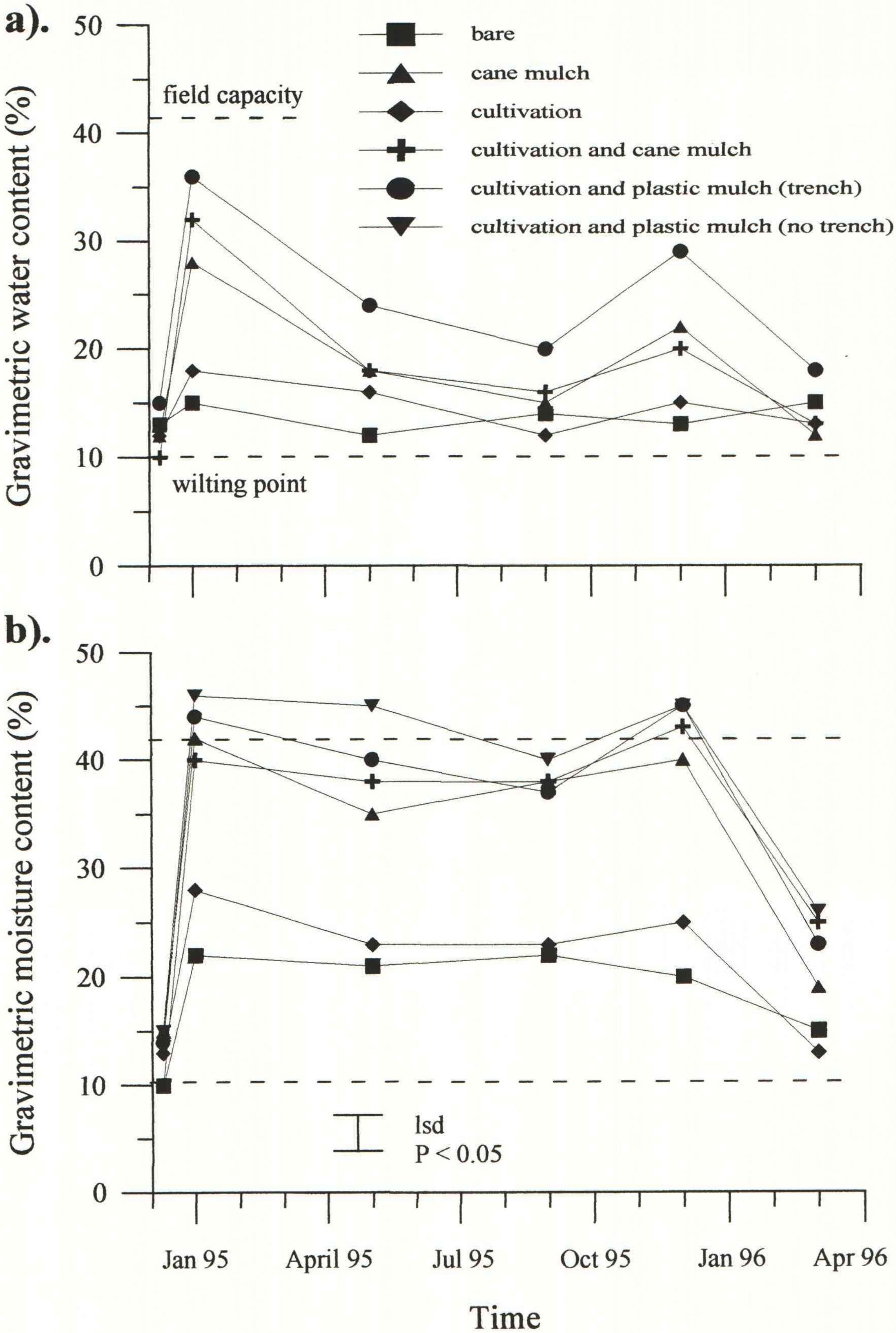

Figure 20. Gravimetric water content (0-10 cm) of the dryland plots established on Saraji coal dam no. 3 in mulched and cultivated treatments under a) unirrigated and b) irrigated conditions (n=3). Planting occurred in January 1995, 3 weeks after treatment establishment. Rainfall of 70 mm was received 3 days prior to planting in January 1995, 165 mm was received in February 1995, and 440 mm between October 1995 and January 1996. Irrigation ceased 9 months after planting (October 1995).

irrigation ceased nine months after planting (October 1995), GWC did not decrease until after January 1996, as 440 mm of rainfall was received between October 1995 and January 1996. Cultivation had no significant ($P = 0.150$) effect on GWC.

Mulching decreased the EC of the surface (0-10 cm) tailings material from about 3 to 2 dS m^{-1} over the 14 month trial period, whilst the EC of the unwatered and unmulched treatments remained at approximately 3 dS m^{-1} (Fig. 21a). Watering lead to an increase in surface EC when unmulched tailings were watered with saline (2-3 dS m^{-1}) irrigation water, while the EC of mulched tailings decreased from 3 to 2 dS m^{-1} (Fig. 21b). Significant two way interactions were observed with all factors. The interactions reflected the fact that watering resulted in an average increase in EC but mulching resulted in a large decrease in EC.

4.3.3. Dryland Direct Seeding Trial

Over the nine month period of the dryland direct seeding trial, *Chloris gayana* was the dominant species to establish, although *A. harpophylla*, *A. salicina*, *A. holosericea* and *A. lentiformis* also germinated and established. Germination occurred with a 54 mm rainfall event seven weeks after sowing. While no grass or shrub and tree species established on the bare tailings, establishment occurred where the tailings had been mulched (Fig. 22 and 23). Cover (assessed at three monthly intervals) increased consistently throughout the trial period in all treatments (data not shown).

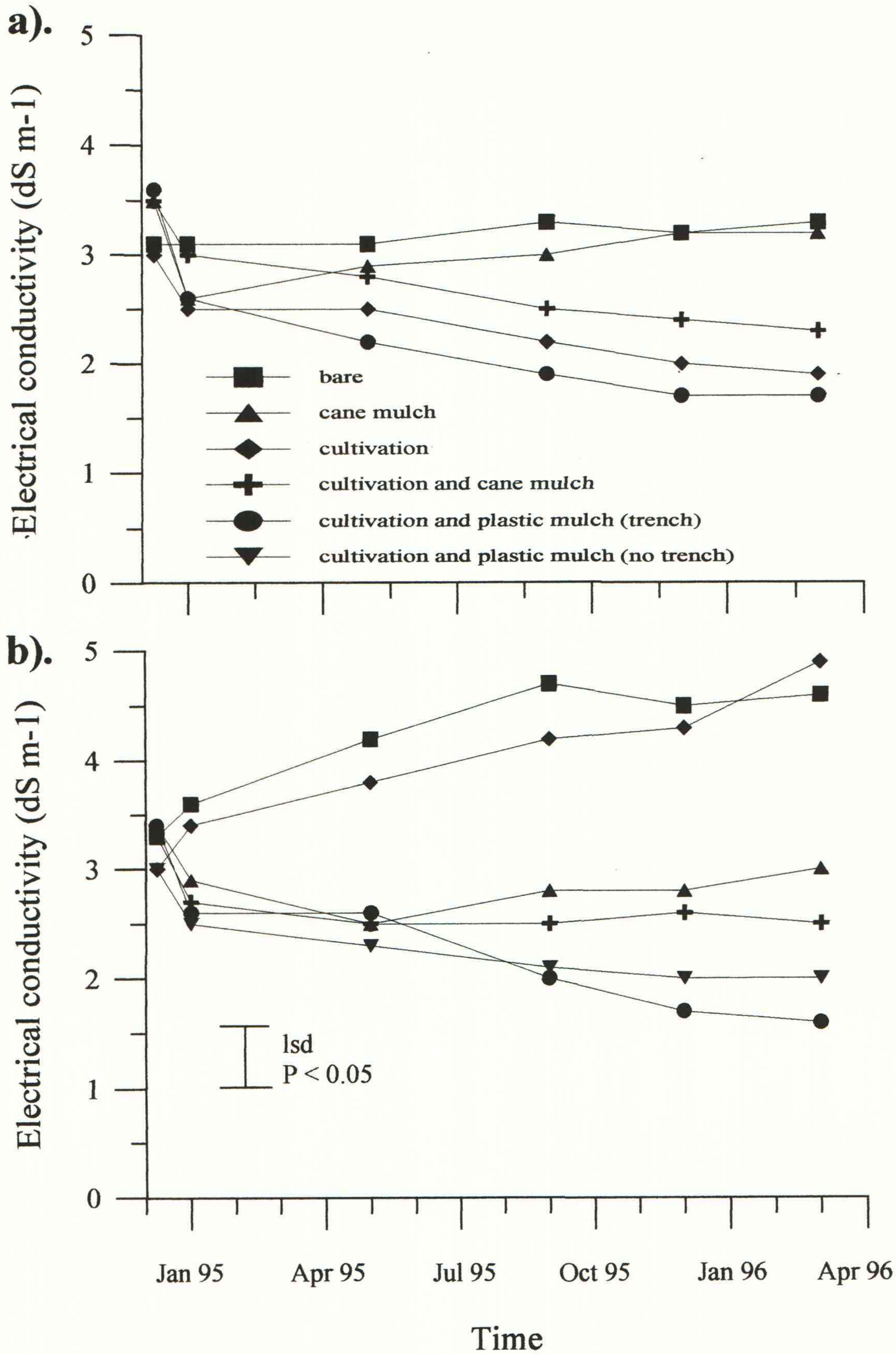

Figure 21. Surface (0-10 cm) electrical conductivity (1:5) of the dryland plots established on Saraji coal tailings dam no. 3, in mulched (cane tops and plastic) and cultivated treatments in a) unirrigated and b) irrigated conditions. Planting occurred in January 1995, 3 weeks after treatment establishment. Rainfall of 70 mm was received 3 days prior to planting, 165 mm in February 1995, and 440 mm between October 95 and January 1996. Irrigation ceased 9 months after planting (October 1995).

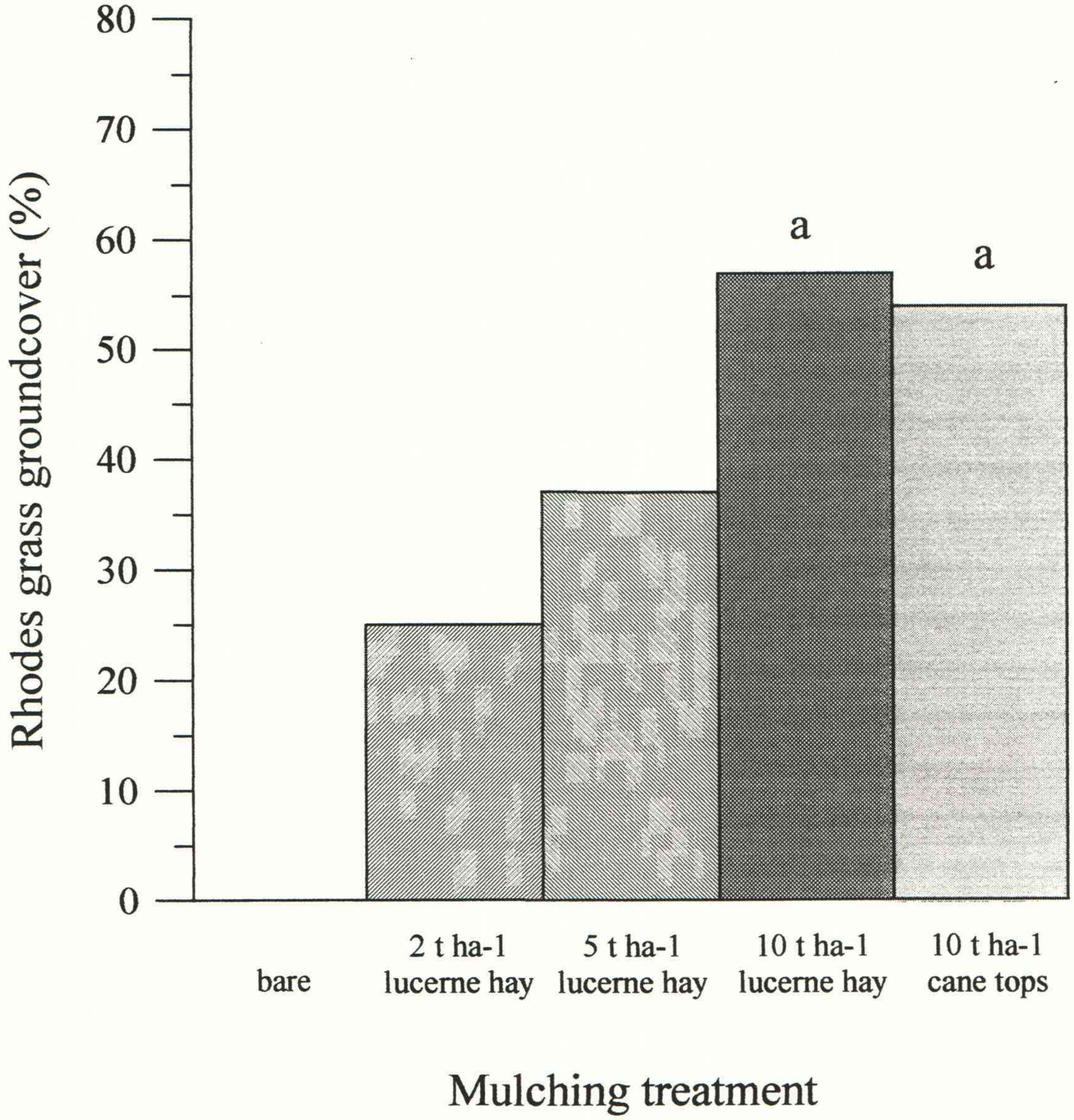

Figure 22. Average response of Rhodes grass to cane tops and lucerne hay mulching, 9 months after sowing (March 1996) in the dryland of Saraji coal tailings dam no. 3 (n=5). Bare tailings resulted in nil groundcover. The trial was established and seeded in June 1995. Same letter indicates means are not significantly different ($P < 0.05$).

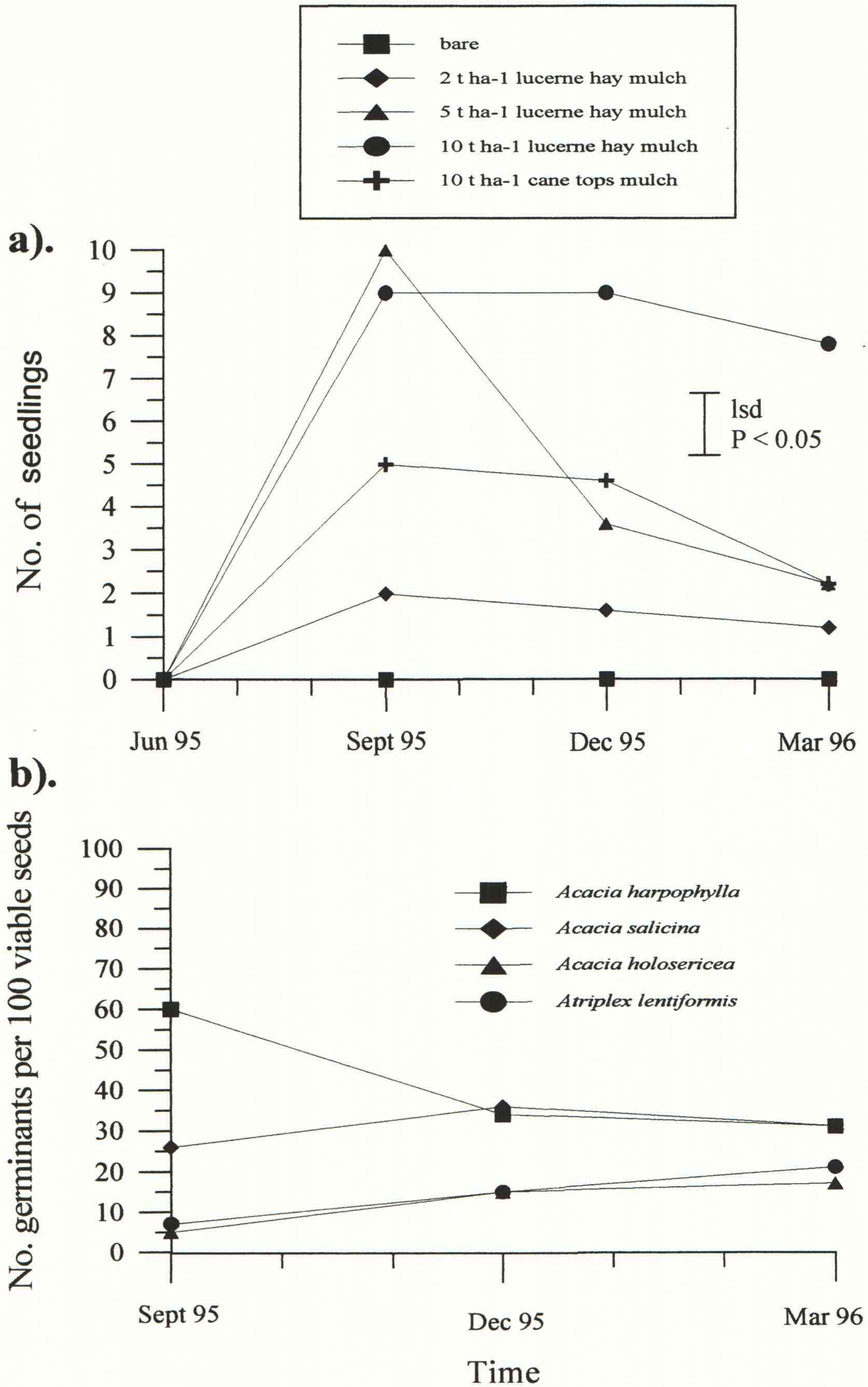

Figure 23. Average number of a) tree and saltbush seedlings and b) germinants per 100 viable seeds of tree and saltbush seedlings germinating under hay and cane tops mulch on the dryland of Saraji coal tailings dam no. 3 (n=5). The trial was established and seeded in June 1995. Rainfall of 440 mm was received between October 1995 and January 1996.

An increase in mulching rate resulted in a significant increase in the foliage projected cover of *C. gayana* nine months after sowing (Fig. 22). At this time, *C. gayana* cover reached 25, 35 and 54 % under 2, 5 and 10 t ha^{-1} lucerne hay mulch, respectively. Cane tops mulching at 10 t ha^{-1} resulted in the same *C. gayana* cover as recorded under 10 t ha^{-1} lucerne hay mulch (Fig. 22).

Four months after sowing (September 1995), seedling numbers were significantly (P = 0.001) higher under 5 and 10 t ha^{-1} lucerne hay mulch than other treatments (Fig. 23a). Subsequent mortality under 5 t ha^{-1} lucerne hay mulch resulted in a reduction in plant numbers to a level similar to that under 10 t ha^{-1} cane tops mulch. Mortality was low with 10 t ha^{-1} lucerne hay mulch resulting in a significantly higher number of plants in this treatment after nine months (March 1996) (Fig. 23a). The density of germinants at this time was 2 per square metre.

In the dryland seeding trial, *A. holosericea, A. salicina, A. holosericea and A. lentiformis* germinated. To allow establishment to be compared between species, the number of germinants per 100 sown viable sown seeds was calculate. On this basis *A. harpophylla* constituted 60 % of the total tree and saltbush plants that initially established (Fig. 23b). Mortality in the next four months resulted in a decreased in *A. harpophylla* relative abundance to that of *A. salicina* (31 % of the plants established). At this time *A. holosericea* and *A. lentiformis* constituted 17 and 21 % of the relative abundance, respectively (Fig. 23b). Although the tree and saltbush species did establish, the plants had not reached a height > 5 cm nine months after sowing.

There was no significant difference in surface GWC (0-10 cm) as a result of using either lucerne hay or cane tops mulch (Fig. 24). Mulching at 10 t ha^{-1}, however, resulted in an increase in surface (0-10 cm) GWC from 12 to 22 %, whilst under low mulching rates, GWC did not increase above that of unmulched tailings. Under all treatments, GWC decreased to the level of unmulched tailings by March 1996 (Fig. 24).

In contrast to the unmulched treatment, mulching at 10 t ha^{-1} resulted in a marked decrease in surface EC (from 3.3 to 1.2 dS m^{-1}, Fig. 25). Mulching with 5 t ha^{-1} lucerne hay mulch also decreased surface EC, whereas 2 t ha^{-1} lucerne hay mulch had no effect. The reduction in EC as a result of mulching at 10 t ha^{-1} was more than twice that obtained by mulching at 5 t ha^{-1} (Fig. 25).

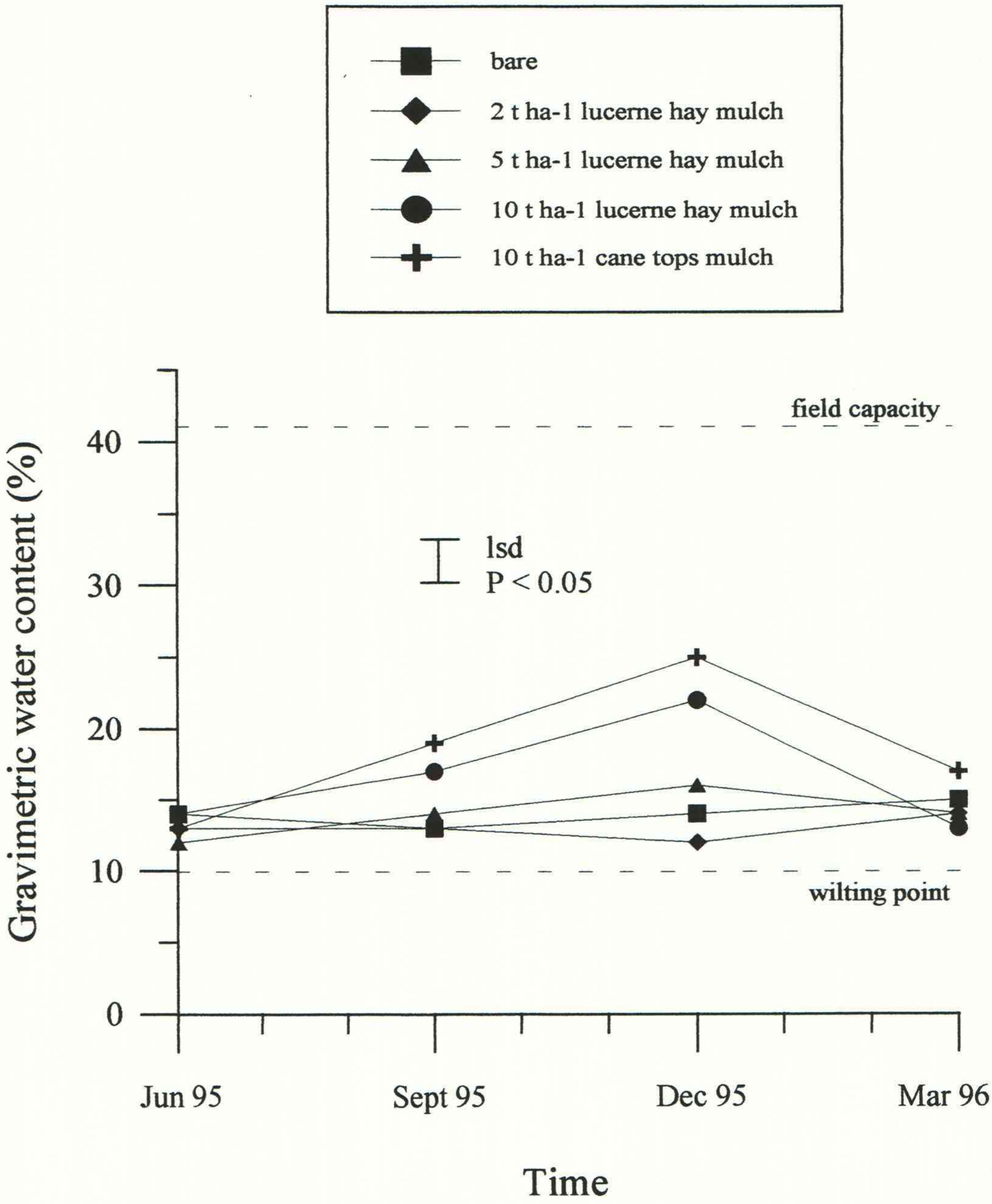

Figure 24. Gravimetric water content (0-10 cm) under lucerne hay and cane mulching on the dryland of Saraji coal tailings dam no. 3 (n=5). The trial was established and seeded in June 1995. Rainfall of 440 mm was received between October 1995 and January 1996.

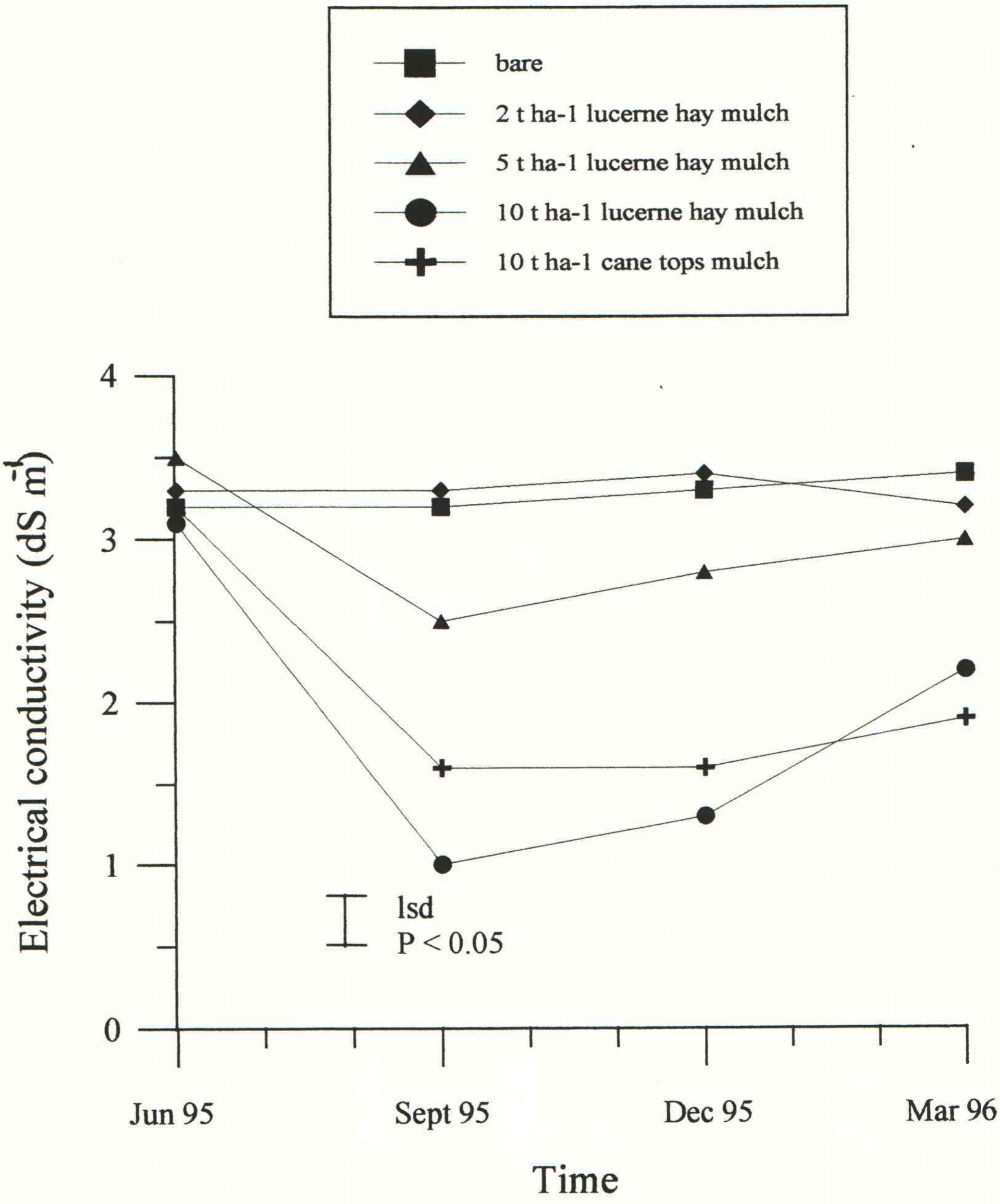

Figure 25. Surface (0-10 cm) electrical conductivity (1:5) under lucerne hay and cane tops mulching on the dryland of Saraji coal tailings dam no. 3 (n=5). The trial was established and seeded in June 1995. Rainfall of 440 mm was received between October 1995 and January 1996.

5. DISCUSSION

5.1. SITE CHARACTERISTICS

The physical characteristics of the Saraji dam no. 3 tailings (Table 3) were comparable to those of other Australian tailings from the Bowen Basin, Hunter Valley (Williams and Morris 1990), Western Sydney Basin (Dwyer 1981) and Indiana/Illinois American (Nawrot *et al.* 1981, Nawrot and Yaich 1982, Thompson 1988, Warburton *et al.* 1988). Particle size, specific gravity and bulk density decreased with distance from the discharge point (Table 3) indicating that the hydraulic sorting of tailings particles occurred once released from the discharge pipe. Tailings gravimetric water content, porosity and pore saturation reflected the change in particle size, specific gravity and bulk density (Table 3). Given that hydraulic sorting occurred and tailings characteristics differed markedly between the discharge, dryland and wetland zones, the division of the tailings surface into management zones was justified.

The strong zonation of Saraji tailings dam no. 3 in relation to strongly acid tailings near the discharge point but circum-neutral tailings near the wetland zones was as found in Indiana and Illinois (Nawrot *et al.* 1981, Nawrot and Yaich 1982, Thompson 1988, Warburton *et al.* 1988). In the acid zone of the primary discharge zone of the Saraji tailings, similar acid producing potentials and phytotoxic metal iron concentrations to those found in weathered American tailings were apparent (Nawrot and Yaich 1984, Thompson 1988). Low levels of plant available nitrogen and phosphorus were common to all dams studied. The similar characteristics between tailings from sites of very different geographical locations and climatic influences are most likely a reflection of similar parent materials and technologies used in the coal preparation and tailings discharge.

5.1.1 Tailings Physical Characteristics: A substrate for plant growth?

The physical nature of Saraji tailings dam no. 3 tailings *per se* are not expected to limit plant growth apart from the low hydraulic conductivity and poor structure which will result in poor aeration (waterlogging), infiltration and drainage. Seedling germination however, may be reduced by the sticky nature of the material physically coating the epicotyl and retarding germination.

The effect of low hydraulic conductivity, poor structure, the material's black colour and the high evaporation rate environment (Lloyd 1984) generate a hot (Fig. 4), dry (Fig. 6) environment for plant growth except within where free standing water is present within the ephemeral wetland. Plant growth would therefore be limited by low plant water availability in the dryland, and without the selection of appropriate species, cycles of flooding and drying in the wetland. A tailings rehabilitation strategy based on wetland habitat creation is clearly unacceptable for central Queensland tailings dams where active management, such as maintaining a water cover, is not desired.

Tailings plastic limit (26 %) was lower than field capacity (41 %, Table 3.1.1) indicating that the ability of the tailings to support machinery at moisture contents conducive to plant growth was poor. Given the relationship between plastic limit and field capacity, trafficing should be undertaken when substrate moisture contents were near wilting point. Consequently, at the time of planting substrate moisture levels would be lower than necessary for plant growth. Therefore, to maximise the survival of planted tubestock, an irrigation system need be installed to provide water to the plants directly after planting. With the high moisture content and the shallow surface crust in the wetland, vane-sheer analyses should be undertaken to determine bearing capacity before trafficing.

5.1.2 Tailings Chemical Characteristics: A substrate for plant growth?

The chemical characteristics primarily limiting plant growth on the Saraji tailings were high salinity, low plant available nitrogen and phosphorus and the $pH_{1:5}$ of the discharge zone (Table 4).

The high salinity of the tailings substrate (Table 4) was a major consideration in developing a protocol for vegetation establishment on Saraji tailings. Due to the high level of salinity the growth of non-salinity tolerant plant species would be greatly compromised (Aitken *et al.* 1984, Badawy 1992) through decreased plant water availability and specific iron effects (Bell 1999). Consequently, salinity tolerant species were selected. Although the tailings were saline, higher salinity sites have been rehabilitated through the selection of appropriate species (Marcar *et al.* 1995, Marcar 1992, Truong and Roberts 1992) and substrate amelioration techniques (Nawrot *et al.* 1991, Hoy *et al.* 1994).

Across the discharge and dryland zones, surface salinity was randomly distributed (Fig. 10). Tailings salinity profiles (Fig. 11) indicated surface salinity developed from the concentration of salts, presumably originating from the washery feed water, by capillary rise and evaporation, a process analogous to the salination of discharge areas following tree clearing (George 1990, Schofield 1991). A saline discharge area with similar characteristics has been rehabilitated in central Queensland (Hoy *et al.* 1994). Hoy *et al.* 1994 found that by reducing evaporation and allowing rainfall to leach salts down the profile, mulching and cultivation reduced surface soil salinity from an $EC_{1:5}$ of about 8 down to 3 dS m^{-1}. Therefore, mulching, cultivation and irrigation were trialed as amelioration techniques for establishing vegetation on tailings dam no. 3 at Saraji Mine.

The neutral dryland and wetland tailings were severely deficient in plant available nitrogen and phosphorus with potassium availability adequate for plant growth (Table 4). Nitrate nitrogen, phosphorus and potassium levels were generally in the range of those for circum-neutral American tailings (Nawrot and Yaich 1992, Warberton *et. al.* 1988). Nitrogen may have been low as the sample was not immediately analysed or stored below 4 °C prior to analysis (Rayment and Higginson 1992). The findings of the nutrient addition trial (Fig. 14) supported the low plant available nitrogen result obtained by chemical analysis however, the media was from the stored 0-30 cm bulk sample and therefore available nitrate levels may have been reduced from those in the field.

To achieve suitable levels of available phosphorus for plant establishment, fertiliser requirement was calculated by subtracting the critical value (30 mg kg^{-1}, Aitken *et al.* 1984) from the dryland tailings analytical result, and calculating the fertiliser requirement for the surface 10 cm (bulk density of 1.15 g cm^{-3}; 1150 t tailings $10cm^{-1}$ ha^{-1}). The rate of phosphorus fertiliser required for the dryland tailings was 35 kg P ha^{-1}. As the levels of plant available nitrogen could not be accurately determined and the critical levels given were for crop species (Aitken *et al.* 1984), fertilisation trials examining *C. gayana* growth in tailings with nitrogen, phosphorus and potassium were undertaken. These trials were focussed on levels of nutrients for plant establishment which would be greater than those required for the maintenance of vegetation over the longer term.

To better understand the fertiliser requirements for revegetating Saraji tailings, it is recommended that nitrate-nitrogen be measured on samples stored immediately at 4 °C and nitrogen requirement calculated. Following the calculation of nitrogen and phosphorus requirement, a glasshouse nutrient omission trial could be undertaken to establish whether the rate of fertiliser addition is suitable for both grass and pioneering tree species. Care needs to be taken with nitrogen fixing pioneer species such as acacias and casuarinas, as nodulation and thus nitrogen fixation may be inhibited with high rates of nitrogen fertiliser even though nodulated prior to planting.

Cation exchange capacity did not increase from dryland to wetland (Table 4) with increasing clay composition (Table 3). As cation exchange capacity was estimated by summing the total exchangeable basic cations and as the material was highly saline, cation exchange capacity would have been overestimated due high soil salinity (Rayment and Higginson 1992). Therefore, the actual cation exchange capacity would be lower than the medium range for soils (Bell 1993b) as indicated by the tailings result. It is not known how tailings organic matter contributed to actual cation exchange capacity.

The tailings were highly sodic as indicated by the high exchangeable sodium percentage (ESP) (Table 4). However, as no pre-treatment for soluble salts was performed, exchangeable sodium and cation exchange capacity were overestimated and ESP was only an approximation. To determine ESP accurately, exchangeable sodium and cation exchange capacity should be determined after pre-treatment for soluble salts (Rayment and Higginson 1992). If sodicity remained high, a trial evaluating gypsum amelioration on crust strength, seedling emergence and plant growth could be undertaken. Without gypsum amelioration, sodic tailings may crust, decreasing infiltration and seedling emergence (Shaw 1988).

With the approximations of cation exchange capacity and ESP, a target ESP of 5 %, and a bulk density of 1.15 $g.cm^{-3}$ gypsum requirement (GR) for the dryland was calculated. The value was derived by subtracting initial ESP from the target ESP, multiplying by CEC and dividing by 100 to obtain GR in cmol(+) kg^{-1}. Since 1 cmol(+) kg^{-1} material was equivalent to 860 mg kg^{-1} of gypsum and the weight of tailings in 1 ha to 30 cm depth was 3450 t, GR was 28 t $CaSO_4.2H_20$ ha^{-1}.

The discharge zones and associated surface plumes were highly acidic ($pH_{1:5}$ 2.5, Fig. 7, 8, 9). Extremely acid substrates are difficult to rehabilitate as high levels of hydrogen ions *per se*, metal toxicity and nutrient imbalances impair plant growth (Russell 1973). However there are a number of acidic native soils and species from these sites could prove valuable in revegetation efforts. From a direct vegetation viewpoint, however, filling tailings dams from a single point should be avoided and the discharge pipe moved around the dam wall as in America (Thompson 1988). Moving the discharge during filling would also have the affect of increasing particle size across the dam thus improving substrate aeration and geotechnical performance.

Direct revegetation into the primary discharge zones of the Saraji tailings dam no. 3 is recommended as a relatively low lime requirement of 55 t ha^{-1} was required to establish a pH of 6.5 (Fig. 12) and the total potential acidity was in the range of 2.6-8.4 t $CaCO_3$ 1000 t^{-1} tailings (Table 5). Consequently the incorporation of 75 t ha^{-1} of lime to a depth of 10 cm would increase the pH and remove any threat of re-acidification. An economic threshold of 100 t $CaCO_3$ 1000 ha^{-1} which is well above that recommended for Saraji tailings has been reported by Bell (1993) and Warberton *et al.* (1988). The application depth of 10 cm should allow the establishment of a grass cover for dust suppression. Alternatively, lime could be incorporated to 30 cm in depth if the establishment of deeper rooted vegetation is required. Further work on the direct revegetation of the discharge zones should be pursued as due to these zones representing only 10 % of the dam's surface area their revegetation was not further pursued.

In the surface material examined, pyrite content *and T. ferrooxidans* density could not be correlated with pH (Table 5). The relatively low pyrite content and pH indicated that substantial pyrite oxidation could have had already occurred and *T. ferrooxidans* activity had decreased to a low level.

5.2 THE PERFORMANCE OF SELECTED SPECIES AND SUBSTRATE AMELIORATION TECHNIQUES

5.2.1 Species for the Wetland

Vetiveria zizanioides and *Sporobolus virginicus* survived and grew, in contrast to the other species planted that were not observed during the 12 month trial period. Due to the high salinity and acidity tolerance of *V. zizanioides* it has proven particularly useful for the stabilisation of hostile substrates (Truong and Roberts 1992). The Monto cultivar is particularly attractive for revegetation as a result of its tolerance of acid and saline substrates as indicated by high growth rates in adverse substrates (Truong and Roberts 1992). With sterile seeds and a clumping habit, the cultivar has a low weed potential and was released in 1994 by the Queensland Department of Environment (Truong pers. comm.).

After 12 months growth in the field under 1300 $kg.ha^{-1}$ Osmocote fertiliser and 10 t ha^{-1} cane tops mulch, *V. zizanioides* survival was 65 % (unpublished data) and the plants had grown to 1.5 m in height and 1 m in width. On this basis *V. zizanioides* is recommended for establishment in the wetland zone. With the ephemeral nature of the wetland, the deep rooted characteristic of the species (Truong and Roberts 1992) should prove advantageous in surviving dry periods, whereas, the ability to tolerate waterlogged soils (Truong and Roberts 1992) will be advantageous in the wet.

The performance of *S. virginicus* reflected its ecological niche. The species occurs naturally in intertidal estuarine salt marshes along the central Queensland coast and was used successfully to colonise a saline waterlogged discharge site near Rockhampton (Hoy *et al.* 1994). The species is therefore suited to the saline nature of the wetland, however, it may struggle if submerged for long periods as its natural niche does not require this adaptation. The relatively slow growth rate of *S. virginicus* would require improving if the species were to be used to rehabilitate 7 ha of tailings as after 12 months growth, *S. virginicus* groundcover had only increased from 0.01 to 0.1 m^2 per plot. At that growth rate 700 000 clumps of *S. virginicus* would need be planted to cover the wetland. The establishment of *S. virginicus* in the wetland will be a slow process best pursued by establishing a colony of the grass around the bounds of the wetland and facilitating growth by fertiliser addition.

In addition to the opportunities for establishing a vegetation cover of *V. zizanioides* and *S. virginicus* there is potential to increase the cover of stands of *T. domingensis* volunteering on the wetland tailings surface. These reeds have volunteered and established in tailings with it's the inherent constraints on plant growth and as such to increase their cover across the wetland area may be relatively simple. Given the stoloniferous root structure and leafy nature of this species and the low plant available nitrogen and phosphorus within the wetland tailings, it is likely *T. domingensis* cover could be significantly increased with the addition of nitrogen and phosphorus fertiliser and the maintenance of wetland water levels. After *T. domingensis* was well established the wetland could be dried and the organic mater used as a mulch to suppress wind blown dust without substantially detracting from the ability to recover the tailings resource. Due to the potential and low cost of this option, it is recommended that a study focused on establishing *T. domingensis* in this manner is undertaken.

5.2.2. Species for the Dryland

Nine months after seeding, a *C. gayana* cover of 55 % was attained in the dryland (Fig. 22). Given that, with this level of cover, 45 % of the tailings would be exposed and wind velocities near the tailings surface substantially reduced, this level of cover would be sufficient to substantially reduce wind erosion. The species is also salt tolerant, having been reported to grow at levels of 3 dS m^{-1} (Hoy *et al.* 1994) and has been shown to be useful in Central Queensland mine rehabilitation (Silcock 1991). Consequently, *C. gayana* is recommended for broad acre establishment by direct seeding in the dryland zone.

Of the tree and saltbush species sown on dryland tailings *Acacia harpophylla*, *A. holosericea*, *A. salicina* and *Atriplex lentiformis* established (Fig. 13, Fig. 23). The success of the *Acacia* species may be attributed to their large seed size as large seeds give rise to large radicals which may exert sufficient force to germinate from the wet plastic tailings material or penetrate the dry crust beneath.

Although the *Acacia* and *Atriplex* species germinated and persisted for nine months in the field (Fig. 23), they failed to grow to a height of more than 5 cm. In the glasshouse however, *A. harpophylla* and *A. holosericea* grew to about 30 cm after 60 days (Fig. 13). In the field, competition with *C. gayana* for water and nutrients may have suppressed the growth of the less aggressive tree and saltbush species. To reduce competition with *C. gayana* and increase species diversity, areas could be seeded with *A. harpophylla*, *A. holosericea*, *A. salicina* and *Atriplex lentiformis* alone.

Casuarina glauca did not germinate in tailings. However when planted as tubestock, the species has been recommended as a pioneer tree species for rehabilitating highly saline lands in the central Queensland region (Hoy *et al.* 1994) and has a form conducive to the formation of windbreaks. When planted in ameliorated plots *C. glauca* tubestock performed well with 100 % survival (Fig. 18) and approximately 2 m in height being attained after 14 months growth (Fig. 19). Therefore the establishment of *C. glauca* in windrows may prove effective for dust suppression. Each tree grew to a crown width of approximately 1 m in watered and mulched treatments and therefore planting at 2-3 m intervals should allow for efficient windrow establishment.

The ecological niche of *C. glauca* is highly saline as the species occurs in the moist estuarine salt marshes of coastal southern and central Queensland and northern New South Wales (Hoy *et al.* 1994) which experiences periodic waterlogging. Given that the long term survival of *C. glauca* on dry coal tailings has not been determined and the species is outside its normal range and not tolerant of fire, the planting and long term (2-5 years) monitoring of salinity tolerant species from drier ecotones (eg. *A. harpophylla*, *A. holosericea*, *A. salicina* and *E. camaldulensis*) has merit. Conversely, *C. glauca* may perform well in the higher wetland zone where periods of prolonged inundation would not be uncommon.

Water use by the *C. glauca* trees established was not studied as part of this study and it is recommended that stem flow or porometer measurements of the trees be undertaken in order to determine their water use and thus their effect on tailings consolidation. The measurement of gravimetric water content beneath tree stands on a periodic basis would also be of benefit in this regard.

5.2.3. Substrate Amelioration Techniques

Successful amelioration techniques increased plant available water by increasing surface gravimetric water content and decreasing salinity.

Mulching

In the field, mulching increased germination (Fig. 22, 23a), improved *C. glauca* survival in unirrigated dryland treatments (Fig. 18) and increased growth in all trials (Fig. 15, 19, 21). The increase in germination, survival and growth was attributed to greater plant water availability, as evidenced by increased surface gravimetric water content (Fig. 16, 20, 24) and decreased EC (Fig. 17, 21, 25). The beneficial effects of mulching saline soils to increase plant available water by increasing infiltration, reducing evaporation and leaching salts from the root zone, have been well established (see Chapter 2).

At 10 t ha^{-1}, lucerne hay had the same effect on *C. gayana* cover (Fig. 21), gravimetric water content (Fig. 24) and EC (Fig. 25) as cane tops mulch, although lucerne hay resulted in higher germination (Fig. 23a). The deeper cane tops mulch layer suppressed germination by preventing the emergence of seedlings, but did not further reduce evaporation and improve surface gravimetric water content or EC. Similarly, in the wetland, increasing the mulching rate from 10 to 20 t ha^{-1} had no effect on the growth of *V. zizanioides* (Fig. 15a) or gravimetric water content (Fig. 16) and only a minor effect on EC (Fig. 17). Therefore, lucerne hay mulching at 10 t ha^{-1} was considered suitable for broad acre application in the dryland and wetland.

For *C. glauca* tubestock establishment, mulching treatments resulted in greater survival (Fig. 18), growth (Fig. 19b), GWC (Fig. 20b) and lower EC (Fig. 21b). A site inspection in September 1996 indicated that plants growing in plastic mulch treatments appeared healthy and had outgrown those in cane tops. Hoy *et al.* (1994) noted a similar effect in saline ground and reported a rise in salinity under sugar cane mulch treatments as the mulch decomposed. As the performance of plastic was better than that of cane tops, and the cost of plastic less (c. \$0.90 m^{-2} for plastic and \$1.50 m^{-2} for cane tops), the establishment of tubestock in plastic mulched rows is recommended for the dryland zone.

Irrigation

Irrigation with saline (c. 3 dS m^{-1}) water increased *C. glauca* survival (Fig. 18) and growth (Fig. 19). With irrigation, gravimetric water content increased (Fig. 20) and EC decreased where irrigation was used with mulch (Fig. 21). As with mulching, the increase in *C. glauca* survival and growth was attributed to an increase in plant available water in the surface material.

Where irrigation was used without mulch, evaporation concentrated salts at the surface resulting in an increase in EC (Fig. 21b) and a significant interaction between irrigation and mulching resulted. The critical aspect in achieving an increase in plant available water was to minimise evaporation and maximise infiltration, thus increasing surface gravimetric water content and leaching salts from the root zone. Therefore, mulching was used in conjunction with minimal irrigation. To encourage leaching and deep root penetration, irrigation was applied at three day intervals in the early evening. Thus when applying saline irrigation water, a similar watering and mulching regime is recommended for tubestock establishment in the dryland. Alternatively, irrigation with non-saline water may result in higher plant available water and thus higher growth rates. Therefore, irrigation with non saline water and mulching would be preferred. Irrigation should also prove beneficial for *V. zizanioides* establishment. The area could be planted when dry and irrigation used to facilitate establishment until rain is received.

Cultivation

Cultivation increased *C. glauca* survival and growth but not to the same extent as mulching or irrigation (Fig. 18, 19). As cultivation had no effect on surface EC and gravimetric water content, the increases in survival and growth may be attributable to a decrease in penetration resistance and a resultant increase in root development. The limited advantage in cultivating may have been due to the sodic nature of the material producing a surface seal, and the failure of cultivation to decrease surface EC at planting by mixing surface and subsurface soils. Cultivation is therefore not recommended except for the installation of plastic mulch.

Fertilisation

Low tailings nutrient status limited plant growth, as evidenced by the marked effect of fertilisation on the growth (dry matter yield) of *C. gayana* in the glasshouse (Fig. 14) and *V. zizanioides* and *S. virginicus* in the field (Fig. 15).

The increase in *C. gayana* growth with nitrogen and phosphorus fertiliser (Fig. 14), reflected the highly deficiency status of these elements in the tailings as detected in characterisation studies. The interaction between nitrogen and phosphorus indicated that growth was greater when the nutrients were added in combination than alone. Growth responses where all nutrients are available are greater than where any single nutrient is limiting (Bell 1985), and thus the interaction with combined nitrogen and phosphorus addition was expected. Potassium had no effect on *C. gayana* growth indicating that potassium availability was adequate. Although the response of *C. gayana* to nitrogen and phosphorus did not plateau, a large increase in fertilisation rate is not recommended as *C. gayana* may further out compete seeded tree and saltbush species and nitrogen fixation in *Acacia* and *Casuarina* species may reduce.

Field trials were fertilised with 1300 kg.ha^{-1} Osmocote (195 kg N ha^{-1}, 45 kg P ha^{-1}, 130 kg K ha^{-1}) which resulted in reasonable plant growth. As nitrogen and phosphorus levels in the tailings were low and the fertiliser would be effective for approximately 12 months under field conditions, however, 12 monthly maintenance applications of approximately 140 kg N ha^{-1} and 70 kg P ha^{-1} through inorganic fertiliser applications are recommended to maintain grass and wetland species cover. Although these levels may not maximise *C. gayana*, *V. zizanioides* and *S. virginicus* growth rates, they will favour the establishment of the less vigorous tree and saltbush species and may, therefore, lead to an increase in species diversity. Establishment of the acacias and other leguminous species such as casuarinas should be encouraged to increase diversity and nitrogen fixation in the longer term. It is recommended that a further study to identify the optimum fertiliser requirement for plant establishment and species diversity be pursued.

5.3. RECOMMENDATIONS FOR VEGETATION ESTABLISHMENT

5.3.1 Time of Treatment Establishment and Planting Techniques

Plant water availability in the surface tailings was found to limit plant survival. It is, therefore, recommended that broad acre treatments be established in spring and planting undertaken in early summer to coincide with summer rain (60 % of annual total, Fig. 4). The establishment of treatments in late spring after the dry winter period will maximise trafficability and facilitate cultivation. A freshly mulched and cultivated surface at the onset of summer rain would prove advantageous in maximising infiltration and minimising evaporation, increasing surface moisture and lowering salinity.

In plastic mulch treatments, the plastic should be punctured directly after installation where tubestock will be planted, allowing infiltration with subsequent rains. Seeding in late spring and planting hardened tubestock with summer rain should maximise growth rates leading to a rapid vegetation cover, and maximise the opportunity for plant roots to reach sub-surface moisture before the drier winter period. In the wetland treatment, establishment in late spring when the wetland is reduced in area would facilitate access.

5.3.2. Species and Amelioration Techniques

Wetland Zone

The rapid establishment *V. zizanioides* indicated that the species would not suffer from planting in a 2 m mulched and fertilised windrow. To suppress the impact of the predominate south-easterly and north-easterly winds, plantings should be of north-south orientation (Fig. 26). Both species may be planted in 10 t ha^{-1} lucerne hay mulch after fertilisation with 140 kg N ha^{-1} and 70 kg P ha^{-1}.

Conventional farming machinery will not be able to access the wetland due to low bearing capacities. It is, therefore, recommended that the area be fertilised and mulched using a mulch blower with an extended hose in the short term, or a mulch blower and fertiliser spreader with low bearing capacity drawn behind a swamp dozer once the methodology is more rigorously trialled. It is estimated that about 40 % of the area could be seeded and mulched from the dam wall and bund if the machinery had a reach of 40 m. With vegetation established on all sides, dust generation from the unvegetated central region of the dam would be minimal if the wetland dried.

Given that *V. zizanioides* survival was 65 % and growth 1-1.5 m in height and 1m in width after 12 months growth, 1000 slips ha^{-1} planted at 2 m spacing in rows 10 m apart is recommended to form a windbreak within 12 months. To provide a ground cover between the rows, *S. virginicus* should be planted as 1000 clumps 10 cm by 10 cm clumps ha^{-1}. *V. zizanioides* slips and *S. virginicus* clumps would need be planted. This could be achieved through the employment of a Greencorp. Team and treated as a public relations exercise.

It is also recommended that a study to determine mechanisms of facilitating the growth of existing volunteer stands of *T. domingensis* be pursued as a effective but low cost dust control strategy.

Dryland Zone

For dust suppression and dewatering of the dryland tailings, it is recommended that a combination of *C. glauca* trees and *C. gayana* grasses be established (Fig. 26). Plastic mulch is recommended for the establishment of trees to minimise the potential of saline surface conditions re-occurring and channel collected rainwater to the planted trees. The rows should be spaced 10 m apart and planted at 2-3 m intervals with hardened six month old *C. glauca* tube stock. As a surface cover *C. gayana* may be established between the rows under 10 t ha^{-1} lucerne hay mulch (Fig. 26).

Plastic mulch rows for *C. glauca* establishment should be rotary hoed to 15 cm, fertilised (140 kg N ha^{-1} and 70 kg P ha^{-1}) and contain two lines of T-Tape for irrigation controlled by a timer and solenoid or flowmeter for automatic application. Although 35 and 70 kg P ha^{-1} produced no significant difference in relation to plant growth, the higher level of P fertilisation was selected so as to reduce the chance of P becoming limiting under the plastic mulch. Irrigation water of EC 3-6 dS m^{-1} (Ramp 4 dam water) or less should be applied at 1 L m^{-2} d^{-1} at three day intervals, commencing immediately after treatment establishment to increase surface moisture and decrease salinity before planting tubestock. Irrigation would be necessary for a period of approximately 9-12 months after planting. To overcome difficulties with meeting future fertilisation requirements, the incorporation of a fertigator (fertiliser dosing unit attached to watering system) in the irrigation system is suggested. If a fertigator were employed, the irrigation system would need to remain in place.

Lucerne hay mulching for the establishment of *C. gayana* should be undertaken with a mulch blower. Before mulching, fertilisation with 140 kg N ha^{-1} and 70 kg P ha^{-1} and seeding with 6 kg ha^{-1} *C. gayana* is recommended. The lucerne hay mulched area can be planted with additional tubestock of *C. glauca* or used as an area for further tree, shrub and saltbush selection trials to increase diversity. Species trialed

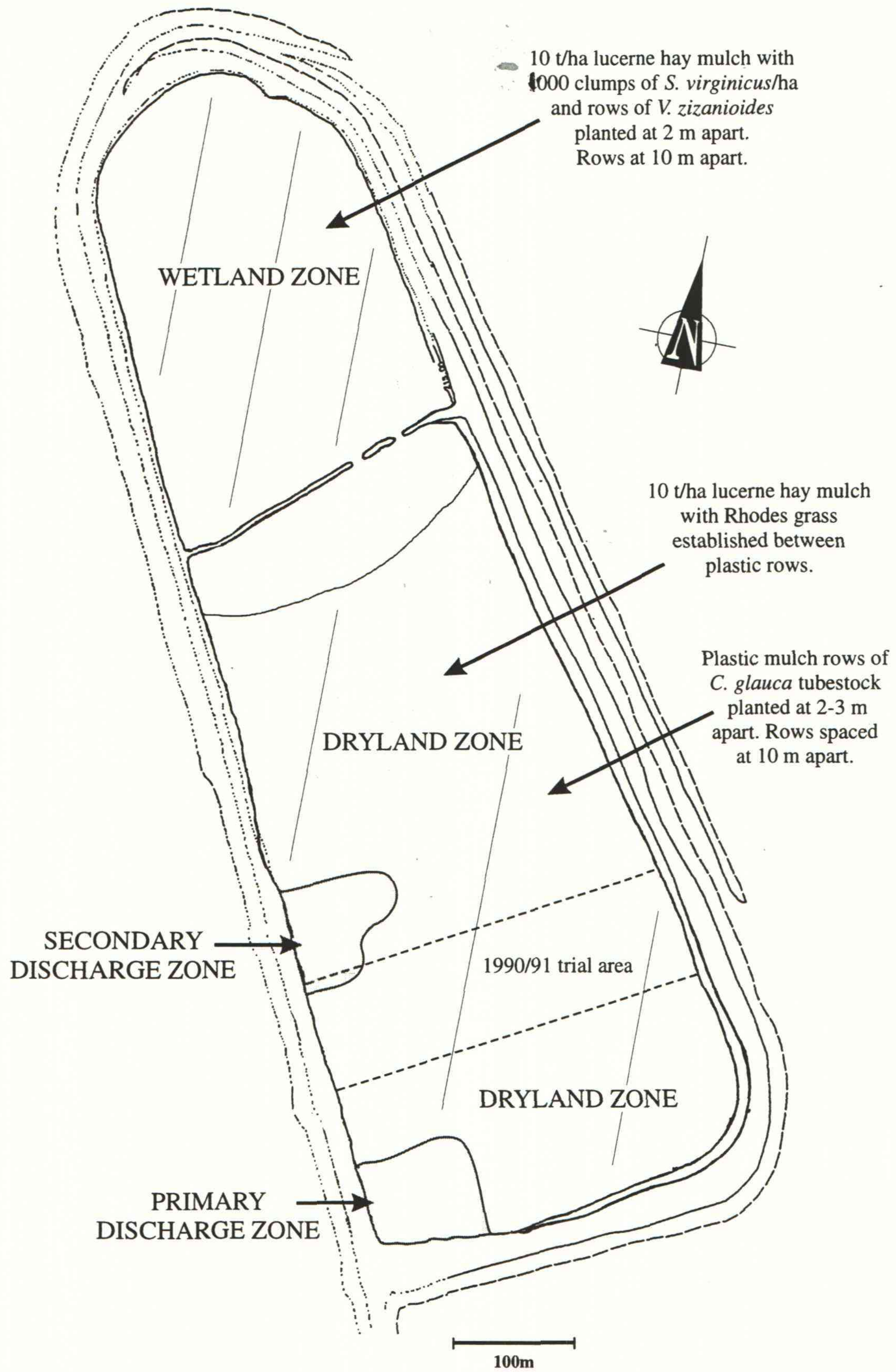

Figure 26. Layout of treatments and planting strategies for vegetation establishment on Saraji coal tailings dam no. 3.

should include those identified as tolerant to the climatic and edaphic conditions of the site.

The most efficient and effective method of establishing the plastic rows and lucerne hay mulching treatments is to fertilise and seed the entire dryland zone with a hydroseeder, install the plastic rows, then seed with *C. gayana* and hay mulch between the rows. Following this protocol would ensure that the lucerne hay mulch was not damaged by machinery when installing the plastic rows.

Maintenance

As this study has not focused on ongoing maintenance requirements firm recommendations can not be presented. Given the low substrate nitrogen and phosphorus levels, however, it is suggested that the trials are re-fertilised with the initial rates twice per year in the first 12 months and foliar nutrient analyses be undertaken to investigate ongoing nutrition status. If a drought occurred in the year after irrigation ceased, further irrigation of the *C. glauca* tubestock may be necessary. For subsequent fertilisation and irrigation it is suggested the irrigation system remain in place.

5.4 TRIAL PROGRESS

The 1999 study by others on the progress of the field trials reported that the dryland amelioration and direct seeding trials had improved (Appendix 1). In the dryland, which constituted approximately 60% of the dam surface area, biomass and groundcover continued to increase, whereas in the wetland biomass and groundcover decreased. Groundcover species were reported in the mulch treatment within the dryland amelioration trial. Electrical conductivity under high densities of vegetation had continued to decrease indicating that vegetation establishment was a viable option for reducing dust and maintaining access to the resource in the central Queensland coal fields.

A high tree density attributed to late germination dominated by *Eucalyptus camaldulensis* was reported colonising the dryland direct species area. This observation was more likely to be of a selection of tubestock planted at the completion of experimental work for this thesis and not from sown seed. This tree growth could form a valuable resource as a species selection trial for coal tailings.

6. CONCLUSION

Due to the different geological nature of coal deposits, different coal washing requirements and different coal washing infrastructure, coal tailings may vary markedly from mine to mine. Variations in tailings characteristics in combination with differing climatic, endemic species and legislative requirements dictate that each attempt to revegetate tailings directly needs to be planned after the required outcomes are understood.

This thesis demonstrated that vegetation can be established directly on the tailings of Saraji Mine tailings dam no. 3. Methods to facilitate vegetation establishment included the division of the dam into discharge, dryland and wetland management zones on the basis of revegetation niches, the selection of plant species tolerant to the adverse conditions and the use of appropriate substrate amelioration techniques. Factors found limiting to vegetation establishment were substrate acidity, salinity, low plant available nitrogen and phosphorus, low plant available water.

Further studies are required to determine species and amelioration trials for the dryland zone, appropriate nutrient requirements, improving the growth of volunteering wetland species, monitoring the progress of the trials over time, increasing the diversity of the plant communities and understanding the potential for tailings to be dewatered by trees.

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APPENDIX 1

REVEGETATION OF COAL TAILINGS AT SARAJI MINE, CENTRAL QUEENSLAND

Re-assessment of vegetation trials on Tailings Dam 3, December 1999

Report prepared for Saraji mine, BHP Coal Pty Limited

April 2000

Centre for Mined Land Rehabilitation
The University of Queensland

CENTRE FOR MINED LAND REHABILITATION

THE UNIVERSITY OF QUEENSLAND

Revegetation of Coal Tailings at Saraji Mine, Central Queensland

Re-assessment of vegetation trials on Tailings Dam 3, December 1999

A.H. Grigg and D.R. Mulligan

Centre for Mined Land Rehabilitation
The University of Queensland

April 2000

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Cover photo: Block 3 of the dryland amelioration trial using tubestock *Casuarina glauca*, December 1999.

INTRODUCTION

In 1994, field trials were established on Tailings Dam 3 at Saraji coal mine to investigate strategies for revegetation without the use of a capping layer (Radloff, 1996). A minimal capping strategy was needed to reduce the dust hazard from dried tailings, yet allow the possibility of mining the tailings sometime in the future. The tailings had aged for 10 years, were moderately saline ($EC_{1:5}$ 2.5 dS/m) and, in discharge areas, were highly acid (pH 2 - 4). Acidity was related to the presence of pyritic material of higher specific gravity than that of the coal tailings, and was restricted to within approximately 100 m of the primary and secondary discharge points. Tailings were also deficient in nitrogen and phosphorus.

Three field experiments were established, involving directly seeded native species, tubestock plantings and transplants of wetland vegetation. In each experiment, a range of surface ameliorants were imposed on the tailings in an effort to make the material more amenable to the establishment and growth of vegetation. They involved the use of mulch materials, fertiliser and for the tubestock plantings, irrigation, to reduce the effects of salinity and optimise nutritional and moisture supply in the surface of the tailings.

Measurements of plant growth, survival and tailings pH and EC were taken between 1994 and 1996 and reported by Radloff (1996).

The Centre for Mined Land Rehabilitation was engaged to reassess the three trials in December 1999, to evaluate the longer-term performance of the vegetation. The 1999 data are the subject of this report.

METHODS

The work was conducted within the three trial areas on Tailings Dam No. 3 at the Saraji mine in central Queensland (Figure 1). Coal tailings had been disposed in the dam through two discharge points up until 1985. This method of discharge resulted in marked segregation of coarse and finer tailings components, with the coarse fraction deposited in proximity to the discharge points. There were distinct dryland and wetland areas formed as a result of the discharge method. Tailings aged under seasonal wetting and drying conditions for ten years prior to the commencement of the experimental program. From April-May 1999, the ponded water at the northern end of the dam was decanted for geotechnical stability and has been kept relatively drained since that time.

Full details of trial establishment are contained in Radloff (1996). Trial design, treatments and measurements taken in the current assessment are briefly described below:

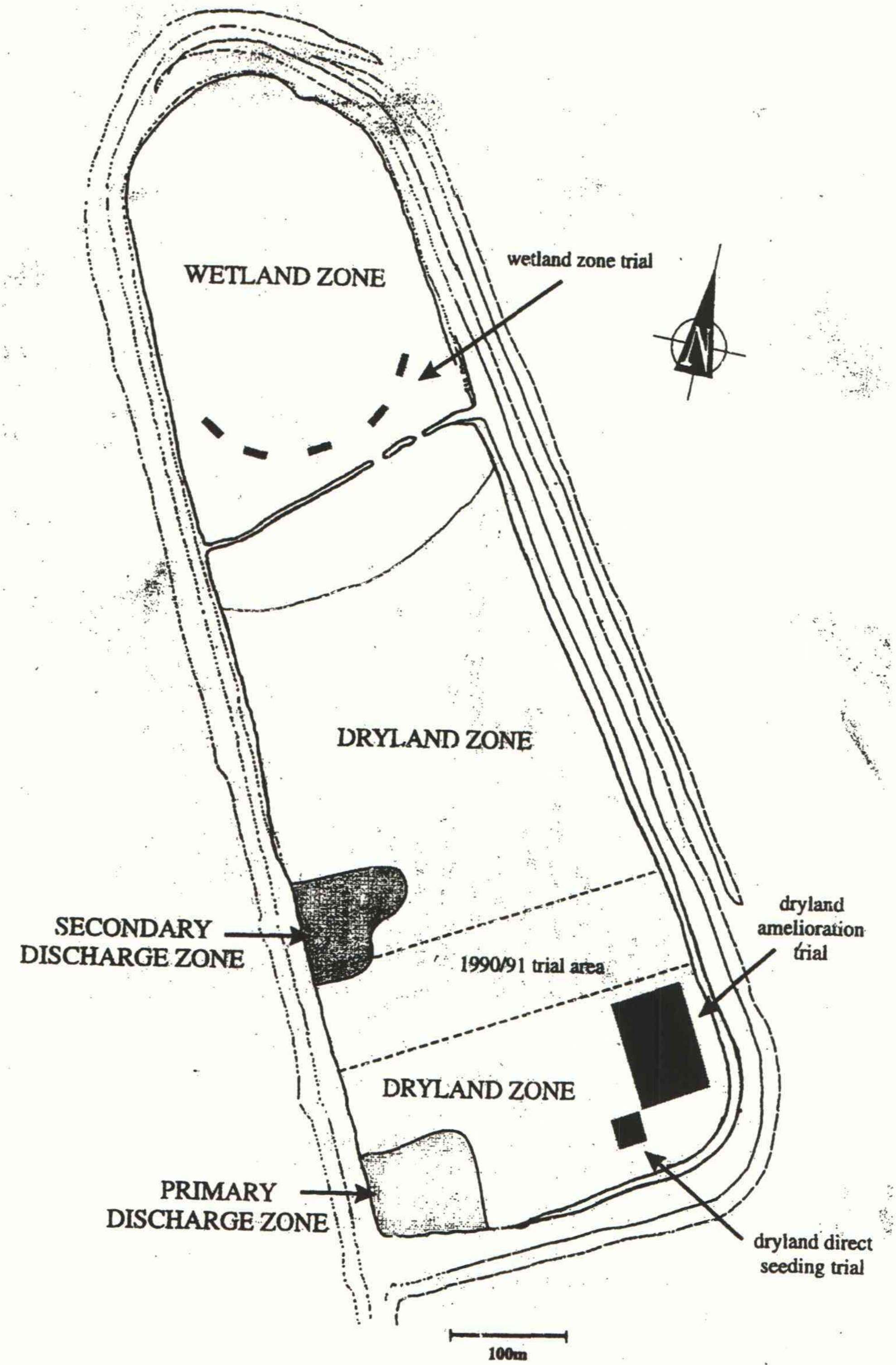

Figure 1. Location of the three trial areas within Tailings Dam No. 3 at Saraji coal mine (from Radloff, 1996).

Direct seeding on dryland tailings

Five mulching treatments (0, 2, 5, 10 t/ha lucerne straw, and 10 t/ha cane mulch) were applied to the surface of the tailings to assess the effects of mulching on establishment and growth of vegetation. There were five replicate plots in a randomised block design. For each 5 x 5 m plot, a range of native tree species and exotic grasses were sown, as follows: 100 viable seeds of *Acacia harpophylla*, *A. salicina* and *A. holosericea*, 2500 viable seeds of *Casuarina glauca*, 800 viable seeds of *Atriplex lentiformis*, 4000 seeds of *Melaleuca bracteata*, 3000 seeds of *Eucalyptus camaldulensis*, and 6 kg/ha each of Pioneer Rhodes grass (*Chloris gayana*) and couch grass (*Cynodon dactylon)*. Plots were fertilised with 1300 kg Osmocote/ha. The trial was established in June 1995.

In the December 1999 assessment, tree density and height, tree canopy cover and ground cover were recorded within an internal 4 m x 4 m measurement plot. Canopy and ground cover was assessed as projective cover at 49 points on a 0.5 m grid. Cumulative height for each treatment was calculated as the sum of the individual heights multiplied by plant number. At the centre of each plot, a single core to a depth of 1 m was collected using a jackhammer, and the profile divided into intervals of 5 cm up to 20 cm depth, then at 10 cm intervals thereafter. Samples were air dried and analysed for pH and EC on 1:5 soil:deionised water extracts.

Amelioration of dryland tailings

A factorial array of mulch (sugar cane tops or silver horticultural plastic), cultivation (0 and 15 cm depth) and irrigation (0 and $1L/m^2$ per 3 days) treatments was imposed. However, plastic mulch was not used without cultivation. There were three replicate plots or rows of each treatment. *Casuarina glauca* was the test species planted as tubestock. Irrigation occurred between January and October 1995 using alkaline, saline water (pH 8, EC 3-6 dS/m) from the coal preparation feed water supply. Osmocote was applied at a rate of 1300 kg/ha along the tree rows. The trial was established in December 1994.

Tubestock were assessed for survival and height. Sucker growth was commonly encountered, but analysis was restricted to the original planted individuals. Between 6-13 surface samples (0-10 cm) were collected from each plot at approximately 2 m intervals, and analysed for pH and EC as above.

Amelioration of wetland tailings

A factorial array comprising three levels of cane mulch (0, 10 and 20 t/ha) and three levels of Osmocote^R (0, 650 and 1300 kg/ha) were imposed. The nine treatments were replicated within each of five blocks, giving a total of 45 plots. Fertilisation at 1300 kg/ha provided 195 kg N/ha, 45 kg P/ha and 130 kg K/ha. Five species (*Vetiveria zizanioides*, *Sporobolus virginicus*, *Phragmites australis*, *Typha domingensis* and *Sarcocornia quinqueflora*) were used in each of these treatments in small plots (2 x 2 m with an internal 1 m x 1 m measurement plot). Vegetative material (slips and associated roots) of each species was planted 1 metre from the water's edge in August 1994.

Vegetation was assessed for height, and where appropriate, for basal area. A single surface (0-10 cm) sample of tailings was collected from each plot, and analysed for pH and EC as above.

RESULTS

Rainfall

Annual rainfall at the site during the experimental period was well below the long-term average of 723 mm for the area (Table 1). The exception was 1998, in which above-average rainfall was recorded owing to a particularly wet Spring period.

Table 1. Monthly rainfall (mm) at the Saraji mine during the experimental period, and long-term average rainfall (1956-89) at Dysart.

Month	1994	1995	1996	1997	1998	1999	Long-term
Jan	22	68	30	104	176	113	121
Feb	125	146	135	3	27	84	89
Mar	217	23	4	226	48	26	87
Apr	24	19	4	74	27	6	53
May	4	48	57	16	19	5	65
Jun	3	48	11	33	70	3	28
Jul	4	4	16	19	57	21	34
Aug	2	0	8	2	3	14	16
Sep	0	52	16	17	246	7	13
Oct	30	9	4	12	72	0	35
Nov	18	115	40	11	146	69	68
Dec	45	54	38	26	123	68	114
ANNUAL	**494**	**586**	**363**	**543**	**1014**	**416**	**723**

Dryland direct seeding trial

Species recorded within the plots are listed in Table 2. All species except an unidentified *Grevillea* (possibly *G. striata* or *G. parallela*) were sown as part of the original seed mix. The eucalypt was most probably *E. camaldulensis*, and the saltbush *Atriplex lentiformis*, since these species were sown at establishment, but identification could not be confirmed. The eucalypt, *C. glauca*, *Grevillea* sp. and *M. bracteata*, were not recorded at the last assessment in March 1996.

Cumulative height of all trees increased markedly with increasing mulch rate (Table 2). Maximum cumulative height was recorded for cane mulch at 10 t/ha. However, there were considerable differences in response between species. The eucalypt grew as well on the bare tailings as with the mulches. The *Casuarina*, the three *Acacia* species and the *Grevillea* also grew well but generally responded up to the highest rate of mulch. The remaining species did not grow particularly well and plant numbers were low.

Table 2. Effect of hay mulch rate and type (lucerne or sugar cane tops) on the mean height (cm) and cumulative height (m) of eight tree and shrub species directly sown on the Saraji tailings dam. The trial was established in June 1995 and measurements were made in December 1999.

Species	Mulching rate (t/ha)				
	0	2	5	10	10 (cane)
Eucalyptus sp.	248	160	123	111	239
Casuarina glauca	68	173	250	292	305
Acacia holosericea	68	229	227	190	303
Acacia salicina	70	150	206	177	88
Grevillea sp.	140	297	245	244	302
Atriplex sp.	51	46	64	80	67
Acacia harpophylla	31	29	50	91	87
Melaleuca bracteata	39	43	0	50	69
Cumulative height (m)	38.3	79.6	109.4	148.4	200.6

Total tree and shrub density consistently increased with increasing rates of mulch (Table 3), with similar responses for most individual species. The eucalypt was the most abundant species across treatments, notably on bare tailings.

Table 3. Effect of hay mulch rate and type (lucerne or sugar cane tops) on the mean density (stems/ha) of eight tree and shrub species directly sown on the Saraji tailings dam. The trial was established in June 1995 and measurements were made in December 1999.

Species	Mulching rate (t/ha)					
	0	2	5	10	10 (cane)	Mean
Eucalyptus sp.	1250	1875	2250	1625	2750	1950
Casuarina glauca	250	625	1375	1000	1750	1000
Acacia holosericea	500	375	1125	1125	875	800
Acacia salicina	125	625	250	3500	1250	1150
Grevillea sp.	500	1250	1500	2000	2375	1525
Atriplex sp.	500	500	875	125	1000	600
Acacia harpophylla	125	250	375	500	1500	550
Melaleuca bracteata	250	125	0	125	375	175
Mean total density	3500	5625	7750	10000	11875	

A visual record of vegetation characteristics under each treatment is contained in Appendix I.

Consistent with the positive effect of mulch on the height and density of the trees, there was a trend for increasing grass cover and litter, and a decrease in exposed tailings with increasing mulch rates (Table 4). However, only bare tailings gave significantly lower ground cover. None of the mulch treatments were significantly ($P < 0.05$) different. The amount of ground cover (litter and grass) was closely related to the density of trees, but the relationship was not linear (Figure 2). Ground cover increased rapidly with increasing tree density but levelled off at densities greater than approximately 5000 stems/ha.

Table 4. Effect of hay mulch rate and type (lucerne or sugar cane tops) on projective ground cover (%) on the Saraji tailings dam. The trial was established in June 1995 and measurements were made in December 1999. Values in parentheses are standard errors of the mean.

Cover (%)	Mulching Rate (t/ha)				
	0	2	5	10	10 (cane)
Bare tails	68 (9)	31 (6)	16 (5)	13 (1)	15 (7)
Litter	28 (8)	51 (7)	55 (6)	51 (4)	59 (7)
Rhodes grass	3 (0.7)	16 (2)	23 (5)	29 (3)	21 (9)
Canopy species	2	2	6	6	5

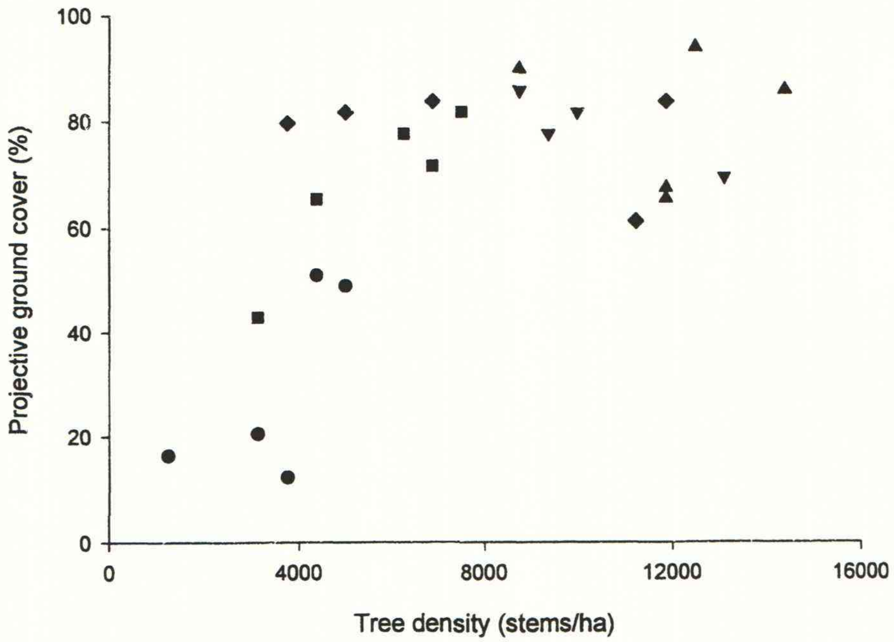

Figure 2. Relationship between tree and shrub density and ground cover (litter and live grass) for direct seeded plots on Tailings Dam 3 in December 1999. Data are for (●) control, (■) 2 t/ha mulch, (◆) 5 t/ha mulch, (▲) 10 t/ha mulch and (▼) 10 t/ha cane tops treatments.

Electrical conductivity in the surface 10 cm generally decreased as the rate of mulch application increased (Table 5). There was a decline in surface EC with time for all treatments, although more so in the highest mulch rate treatments. Surface conductivities were variable between plots, and while the mean value for bare tailings appeared low, surface EC up to 2.8 dS/m were observed (Appendix II). Decreasing surface salinity might be expected to follow accumulating surface litter, but there was no significant relationship between measured salinity and ground cover (either litter only, or total ground cover including live grass). However, there was a strong relationship ($P < 0.01$) between surface salinity and tree density (Figure 3).

Table 5. Effect of hay mulch rate and type (lucerne or sugar cane tops) on the electrical conductivity (dS/m) in the surface 10 cm the Saraji tailings dam. Data for 1995 and 1996 are from Radloff (1996). Values in parentheses indicate standard errors (n=5) for the current measure.

Year	Mulching Rate (t/ha)				
	0	2	5	10	10 (cane)
1995	3.2	3.3	3.5	3.1	3.2
1996	3.4	3.3	2.9	2.2	1.8
1999	1.8 (0.3)	2.2 (0.4)	2.5 (0.5)	1.2 (0.2)	1.2 (0.2)

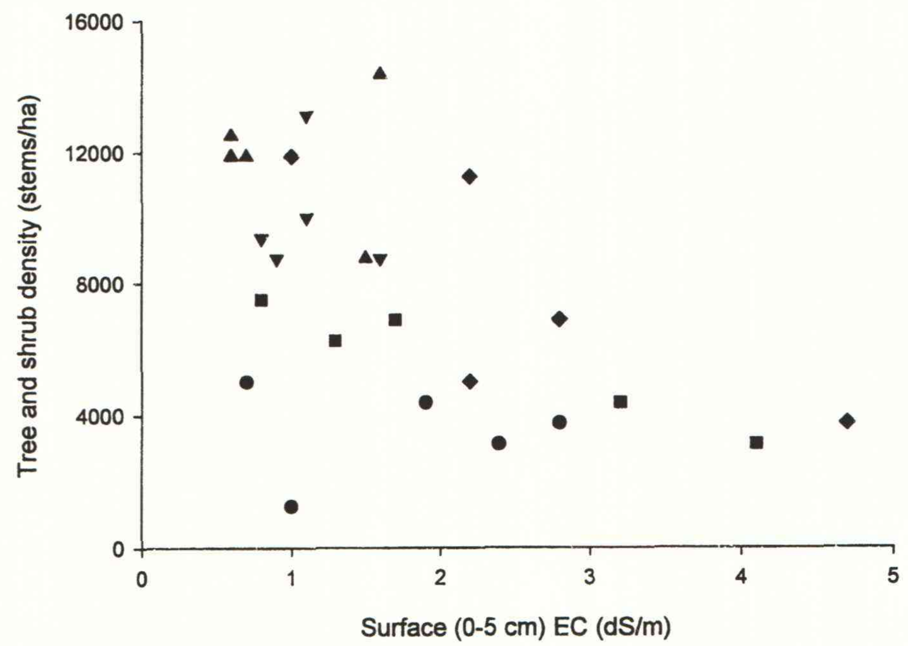

Figure 3. Effect of tree density on surface salinity within direct seeded dryland plots on Tailings Dam 3. Data are for (●) control, (■) 2 t/ha mulch, (◆) 5 t/ha mulch, (▲) 10 t/ha mulch and (▼) 10 t/ha cane tops treatments. The relationship is described by the equation $y = 11000 - 1844\,x$ (n = 25, $r^2 = 0.27$).

Surface amelioration of dryland tailings

There were beneficial effects of irrigation, cultivation and mulch on the survival and height of *Casuarina glauca* plants in 1996 and again in 1999 (Tables 6 and 7). Plant survival decreased with time, but the effect was more pronounced on the bare tailings than on the mulched tailings. Both survival and plant height were lowest on the bare tailings and highest on the plastic mulch treatments (Plate 1). Analysis of the 1999

Plate 1. Surface amelioration of drylands trial. Cultivation only in the foreground. The larger trees both to the left and behind were treated with plastic mulch (with and without irrigation, respectively).

Table 6. Effect of irrigation, cultivation and mulch on survival (%) of *Casuarina glauca* in February 1996 (Radloff, 1996) and December 1999. Tubestock were sown in December 1994.

	Unirrigated		Irrigated		
1996	**No cult**	**Cult**	**No cult**	**Cult**	**Mean**
Bare soil	45	81	90	81	74
Cane	85	95	99	100	95
Plastic		75*		94 100*	82*
1999					
Bare soil	30	47	60	79	54
Cane	76	86	95	97	89
Plastic		73*		84 91*	82*

*Gully mounded

Table 7. Effect of irrigation, cultivation and mulch on height (cm) of *Casuarina glauca* in April 1996 (Radloff 1996) and December 1999. Tubestock were sown in December 1994.

	Unirrigated		Irrigated		
1996	**No cult**	**Cult**	**No cult**	**Cult**	**Mean**
Bare soil	30	60	70	108	67
Cane	85	127	160	180	138
Plastic		138*		180 200*	169*
1999					
Bare soil	131	151	195	325	201
Cane	289	336	328	401	339
Plastic		440*		439 508*	474*

*Gully mounded

data for the factors of irrigation, cane tops mulch and cultivation indicated significant ($P < 0.01$) increases in tree height for each factor. There were no interactions between the factors. Analysis of irrigation, cane tops and plastic mulching indicated that irrigation improved height growth in the absence of mulching or with cane tops mulch, but there was no effect with the plastic mulch. The inclusion of the central trough in the plastic treatments had no effect on height.

In 1996 without irrigation, all forms of mulch significantly decreased the EC in the surface 10 cm of tailings compared with no mulching (bare tailings or cultivation alone), which changed little (3 dS/m) since the commencement of the trial in January 1995 (Table 8). Irrigation (with saline water) increased EC markedly in the no mulch treatments but had little effect under the mulch treatments.

In 1999, cane mulch decreased the EC of the surface 10 cm of the tailings irrespective of the irrigation treatment (Table 8), except where cultivation was also applied. This interaction was highly significant ($P < 0.01$). Plastic mulch was associated with significantly ($P < 0.01$) lower surface EC than cane mulch. In the bare tailings treatment, irrigation (during the first 9 months of the experiment only) increased EC from 4.4 to 6.6 dS/m. There was a marked increase in EC between 1996 and 1999. Unmulched treatments indicated extremely saline surface conditions, greatly exceeding the surface salinities recorded in the dryland directly seeded trial.

Table 8. Effect of irrigation, cultivation and mulch on the EC (dS/m) in the surface 10 cm of coal tailings in April 1996 (Radloff, 1996) and December 1999. Tubestock of *Casuarina glauca* were sown in December 1994. * indicates gully mounding.

	Unirrigated		Irrigated		
1996	**No cult**	**Cult**	**No cult**	**Cult**	**Mean**
Bare soil	3.4	3.3	4.6	5.0	4.1
Cane	2.0	2.4	3.0	2.5	2.5
Plastic		1.7*		2.0 1.6*	1.7*
1999					
Bare soil	4.4	7.5	6.6	5.0	5.9
Cane	3.7	4.2	3.6	4.9	4.1
Plastic		2.9*		4.5 3.0*	3.0*

Surface pH was affected in a similar manner to EC, though there appeared to be a small, positive effect of previous irrigation and cultivation (Table 9). Mean plot surface EC and pH data are contained in Appendix III.

Table 9. Effect of irrigation, cultivation and mulch on pH in the surface 10 cm of coal tailings in December 1999. Tubestock of *Casuarina glauca* were sown in December 1994. * indicates gully mounding.

	Unirrigated		Irrigated		
	No cult	**Cult**	**No cult**	**Cult**	**Mean**
Bare soil	6.8	7.2	7.8	7.4	7.3
Cane	6.5	6.7	6.9	7.0	6.8
Plastic		6.1*		6.7 6.8*	6.5*

Amelioration of wetland tailings

Marine couch (*Sporobolus virginicus*) was the most abundant species within the trial plots. Also present in the plots were an unidentified sedge (Cyperaceae), and limited numbers of *Phragmites australis* and *Typha* prob. *orientalis*. Elsewhere on the wetlands zone, *Phragmites* and *Typha* appeared to be successfully colonising (Plates 2 and 3; Appendix I). Species composition had altered dramatically from the previous measure in 1996, in which the couch grass and vetiver grass (*Vetiveria zizanoides*) were the only surviving species. *Typha* and *Phragmites* were both absent at that time (Radloff, 1996).

The plant height data for the wetland species trial were extremely variable (Table 10), and showed no effect of mulch and fertiliser rate.

Table 10. Effect of mulch and fertiliser rate on the height (cm) of marine couch (*Sporobolus virginicus)* and a local sedge species in the coal tailings wetlands in December 1999. Cuttings were planted in August 1994.

Fertiliser rate	**Mulch application rate (t/ha)**			
Couch	**0**	**10**	**20**	**Mean**
0	52	57	110	73
100	79	69	49	66
200	58	30	75	54
Mean	63	52	78	
Sedge				
0	73	96	96	88
100	97	66	94	86
200	95	86	74	85
Mean	88	83	88	

As for vegetation, there was no effect of mulch and fertiliser rate on the EC in the surface 10 cm of wetland tailings (mean EC for each mulch treatment varied from 2.3 to 2.9 dS/m). These values were approximately 1-2 dS/m higher than when measurements were taken in September 1995.

Plate 2. View of Block 1 on the western side of the tailings dam showing poor survival of the planted trial vegetation, but colonisation of other areas by *Typha* sp. and *Phragmites australis*.

Plate 3. Growth of *Typha* sp. and *Phragmites australis* in Block 2 of the wetlands trial.

DISCUSSION

Dryland tailings

There can be no doubt that irrigation, fertilisation and mulching have benefited both initial establishment and subsequent growth of trees and shrubs on the Saraji tailings. Radloff (1996) attributed improved establishment and early growth to a combination of increased moisture availability and reduced salinity at the surface of the tailings. Irrigation provided a supply of moisture, while mulching reduced the evaporative demand and associated capillary rise of salts. Although irrigation only took place between January and October 1995, and the physical presence of the original organic mulches will almost certainly have disappeared prior to the current assessment in 1999, there were ongoing benefits in terms of growth and survival of trees and the amount of ground cover.

Of the mulches tested in the surface amelioration trial, the plastic mulch had the most beneficial effect on performance, both initially and over the five year period. This is likely to be due to the relative impermeability of the material, and its persistence since the plastic was still present at the current measure. In contrast, the organic mulches originally applied will have been depleted through decomposition and/or physical removal. The impermeable nature of the plastic maximises effective plant-available moisture (Radloff, 1996) by inhibiting evaporative losses which reduce water content and drive capillary rise of salts. Similarly, Hoy *et al.* (1994) found that on saline, waterlogged soil in central Queensland, mulch greatly improved survival and growth of *Casuarina glauca*, and reduced EC in the surface soil during the first two years. Furthermore, they found that plastic mulches were more effective than sugar cane mulch.

For the more successful dryland treatments where initial establishment was good, live ground cover and accumulated litter was high, in the vicinity of 80 % in the direct seeding trial (Table 4), and frequently substantial under the *C. glauca* trees (Appendix I). This self-mulching mechanism could be expected to improve surface growth conditions similar to the effect of the originally applied mulch treatments in increasing water retention, leaching and reducing temperature extremes. An initial analysis of the relationship between salinity and ground cover for the direct seeding plots appears not to support this, however, tree density provides the link (Figure 4). The fact that tree density was closely related to both ground cover and surface salinity (Figures 2 and 3, respectively) in itself suggests that ground cover must be playing a role in reducing surface salinity. This becomes clearer in Figure 4. Ground cover stabilises at around 70-80 % for tree densities above approximately 6000 stems/ha. Below this density, ground cover drops markedly, and at the same time, salinity rises rapidly. This has the effect that at low levels of cover, there is a wide range of observed salinities which masks the relationship between the two variables. In practical terms, Figure 4 indicates that to improve and maintain surface salinities at levels that enhance the potential for germination and early seedling survival, there is a minimum canopy density that needs to be achieved. It would be of interest to relate the currently existing amounts of ground cover (which includes litter) to the rates of mulch applied at establishment. Information on stocking densities in the adjacent surface amelioration trial are not available, but on an estimated row spacing of 2.5-3 m, tree densities would be in the order of 3000-3,600 stems/ha. This is well below the threshold suggested by the direct seeding trial, and may provide an explanation for rising surface salinities on this trial. EC levels rose from 3 dS/m in 1994, to a range of 2 - 4.6 dS/m in 1996, and to a range of 2.9 - 7.5 dS/m in 1999. Large bare areas are clearly evident between and even within the rows (Plate 1 and Appendix I), supporting the argument that a minimum canopy density is required to achieve an effective surface mulch. There may, however, be differences between species, for example in rooting depths or rates of litter production, that are also important factors.

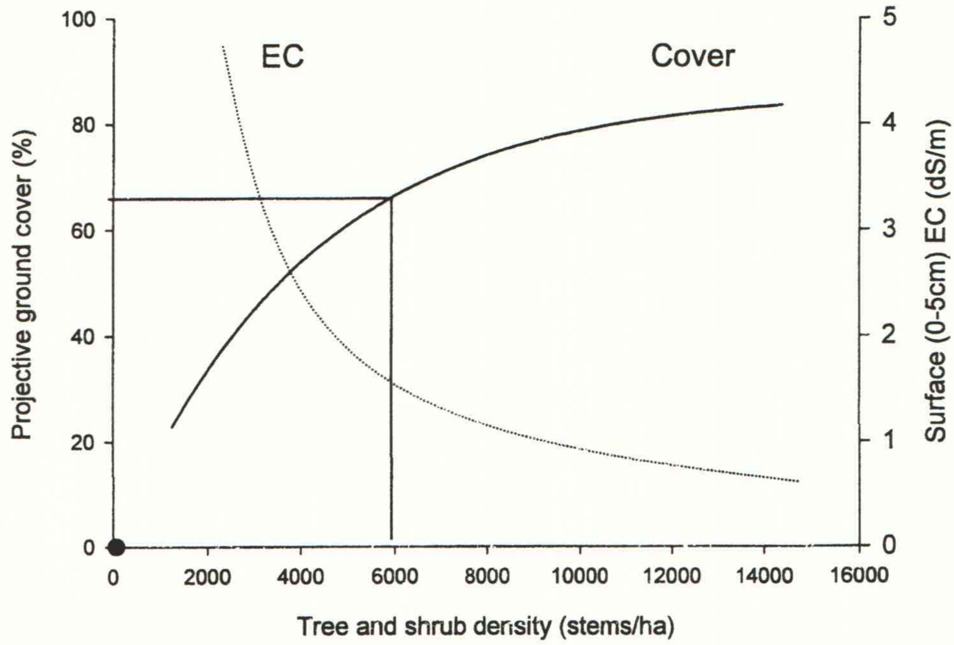

Figure 4. Effect of tree and shrub density on ground cover and surface salinity within the dryland direct seeding trial. Curves are fitted by eye.

In the long-term, high evaporative and evapotranspiration demands (Walsh *et al.*, 1995) in the central Queensland environment will eventually exhaust sub-surface moisture supplies, which must play a crucial role in maintaining the current growth of deeper rooted species. At this time, vegetation will rely solely on incident rainfall for moisture and will most likely suffer extreme moisture and osmotic stresses in the intervening periods. Therefore, direct revegetation of these saline tailings may not be a long-term option, emphasizing direct revegetation approaches as suitable only where future alternative uses of the tailings are proposed.

All species used in the two dryland trials were originally selected for their ability to colonise saline sites (Radloff, 1996), and most of these have been successful in establishing and growing on the tailings. Hoy *et al.* (1994) found that *C. glauca* and *E. camaldulensis* both performed well at a saline, waterlogged site near Rockhampton. However, the most tolerant of the species tested, *C. glauca*, succumbed steadily to rising salinity above 2-3 dS/m, with 100% mortality at 9 dS/m. This reinforces the concern over increasing surface EC with time, and future survival of vegetation. *E. camaldulensis* was not recorded in the original assessments, but has subsequently become the most abundant canopy species in the direct seeding plots (Table 3), and is present within the surface amelioration trial (see cover photo). The eucalypt is a relatively longer lived species and can be regarded as a species with long-term potential for colonising coal tailings of the quality encountered at Saraji. The good performance of *Acacia holosericea* and *A. salicina* is expected, with both these species tolerating saline spoils at Saraji (e.g Grigg and Catchpoole, 1999) and elsewhere, but these species are relatively shorter lived and are best regarded as useful colonisers. The unidentified *Grevillea* sp. was apparently not sown in the original seed mixture, and was either a contaminant in the mix, or incorrectly supplied. In any case, it appears to be quite successful and may be worth considering on other rehabilitated areas. *Melaleuca bracteata*, *Atriplex* spp. and *Acacia harpophylla* were less prominent, even with high levels of mulch. For *M. bracteata* (black teatree) this finding was surprising because in its natural state is often found in alkaline and saline soils along watercourses (Anderson 1993). The Melaleuca group including *M. leucadendra*, *M. nervosa* and *M. viridiflora* should be evaluated for growth in the wetland tailings area.

Wetland tailings

Experimental plantings on the wetland area were generally unsuccessful over the trial period, reflecting fluctuating periods of inundation and drying. Significantly, the water at the northern end of the dam was decanted for geotechnical stability reasons in April-May 1999 and has been kept relatively drained since. Conditions will therefore have become considerably drier in that time, although it is unknown what effect this may have had on the trial plantings. Although there was a strong linear response in terms of biomass and groundcover to fertiliser and cane mulch in 1996, these effects had disappeared by 1999. The previously successful Vetiver grass and marine couch have not persisted, possibly due to the altered conditions or seasonal fluctuations. In contrast, the area appears to be being naturally colonised by the wetland species *Phragmites*, *Typha* and the local sedge. The former two species are common in wetland areas on numerous minesites, and given their apparent tolerance of the local conditions, may be the more appropriate for rehabilitation purposes.

Fertility

A superficial assessment of the tailings fertility status shows deficiencies of nitrogen and phosphorus. There is also the possibility of a calcium/magnesium imbalance, as well as the over-riding influence of sodium. The present suite of trials has confirmed nitrogen and phosphorus deficiency for establishment of vegetation but provides little information on the residual effects. Responses to Osmocote fertiliser were related to the low levels of nitrogen and phosphorus in the tailings, and, whilst the responses were still obvious in 1999, it is not known whether the supply of those elements was ample for longer-term growth and survival. Given the initial application of 195 kg N/ha and 45 kg P/ha as Osmocote in the high fertiliser treatment, it would be surprising if there was a significant fertiliser residue after 5 years. Soil testing combined with long-term fertilisation trials would shed light on this matter.

RECOMMENDATIONS

The current re-assessment of the revegetation trials on Tailings Dam 3 approximately five years after establishment has suggested a number of revisions to the earlier recommendations of Radloff (1996), which were necessarily limited to the establishment and early growth phases.

Dryland areas

For the dryland sections of the Saraji tailings dam, rehabilitation options involving the use of plastic mulch remain an effective method of reducing salinity, and possibly maintaining favourable moisture availability conditions, over time. This is attributable to the persistence of the plastic membrane. However, the recommendation to use this mulch for rehabilitation was based on employing strip plantings of tubestock *C. glauca* for dust suppression and dewatering. Results from the dryland trial have indicated that satisfactory tree densities can be achieved by direct seeding methods, utilising a surface mulch of lucerne hay at 10 t/ha, the same rate recommended for cover establishment bewteen the rows of tubestock (Radloff, 1996). Furthermore, the current measure has demonstrated an ongoing benefit of the original organic mulch through the generation of litter *in situ*, and the promotion of grass growth, as the vegetation has developed (Figure 2). Provided trees establish at a minimum threshold density of approximately 6000 stems/ha, the resultant ground layer appears to have a lasting effect similar to that of the plastic sheeting.

A direct seeding approach with a mix of salt tolerant grass and woody species is therefore a viable alternative. Direct seeding is, of course, subject to greater risk of failure at establishment, being dependent on rainfall patterns for an adequate supply of moisture initially. However, rainfall conditions within the first 12 months of the direct seeding trial were below average (Table 1), suggesting the approach is feasible. Given the costs of tubestock planting combined with irrigation, direct seeding may be the more cost effective approach.

C. glauca remains as a suitable and recommended species, but other species including *E. camaldulensis* and the *Grevillea* species also appear to be adapted to the saline conditions and should be considered as part of a direct seeding mix. Apart from *A. salicina*, the acacia species that were most successful initially have not performed as well over the five year period.

An effective canopy and associated ground mulch layer is essential in combating capillary rise and surface salinisation over time. While the separate effects of a ground layer and the woody species on reducing surface salinity can not be ascertained, the tree and shrub component is likely to be important in maintaining the system through access to subsurface moisture. However, sub-surface moisture supply may diminish in the longer-term as dewatering progresses, placing severe stresses on the deeper-rooted vegetation. While more work with water balances is required, direct revegetation may best be regarded as a relatively temporary cover.

Wetland areas

For the wetland areas, *Phragmites*, *Typha* and the local sedge are the most suitable species. Vetiver grass and marine couch appear not to be adapted to the wetland tailings dam situation after five years, in contrast to earlier recommendations, although draining of the wetland area may well have substantially altered the growth conditions. The sedge should be identified and its spread actively encouraged by the use of fertiliser throughout the wetland areas.

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APPENDIX I

VISUAL RECORD OF TRIALS, DECEMBER 1999

Dryland Direct Seeding Trial - Plot 1 / 1, No Mulch

Dryland Direct Seeding Trial - Plot 4 / 5, 2 t/ha Straw

Dryland Direct Seeding Trial - Plot 5 / 1, 5 t/ha Straw

Dryland Direct Seeding Trial - Plot 3 / 1, 10 t/ha Straw

Dryland Direct Seeding Trial - Plot 4 / 1, 10 t/ha Cane Tops

Dryland Amelioration Trial - Foreground Block 2, Plot 9, Treatment 7. Background Block 2, Plot 10, Treatment 10

Dryland Amelioration Trial - Block 2, Plot 5, Treatment 5.

Dryland Amelioration Trial - (left to right) Block 1, Plots 8, 9, 10, 11. Treatments (left to right) 7, 8, 4, 6.

Dryland Amelioration Trial - (left to right) Block 3, Plots 3, 33, 6. Treatments (left to right) 10, 3, 7.

Wetlands Trial - Blocks 5, 4 & 3 (view east)

Wetlands Trial - Block 4 (view west)

Wetlands Trial - Block 2 (view east)

APPENDIX II

PROFILE pH AND ELECTRICAL CONDUCTIVITY DETERMINATIONS
IN THE DRYLAND DIRECT SEEDING TRIAL, DECEMBER 1999

EC (dS/m)

Block No.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Plot No.	1	4	1	4	5	4	5	3	1	2	2	1	2	3	4	5	3	4	5	1	3	2	5	2	3
Treat.	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
Depth (cm)																									
0-5	2.38	1.92	2.77	0.70	1.00	0.62	1.62	1.51	0.65	0.69	3.21	1.72	0.82	1.26	4.06	2.23	1.02	4.71	2.21	2.81	1.60	0.87	1.13	1.06	0.81
5- 10	1.32	2.18	2.57	1.39	1.07	1.00	1.63	1.77	0.97	1.40	3.14	2.77	2.31	1.19	1.77	2.17	1.40	4.20	2.21	2.02	1.88	0.73	1.69	1.10	0.97
10-15	0.93	1.51	2.16	1.05	0.73	1.40	2.15	1.51	1.53	1.33	1.99	2.79	2.30	1.61	1.18	0.80	1.43	1.28	2.29	1.89	1.93	1.53	1.28	1.05	1.10
15-20	0.81	1.45	1.58	1.20	0.95	2.25	1.74	1.70	1.21	1.88	2.15	2.01	2.13	1.43	1.34	1.28	1.29	2.85	1.83	1.66	1.70	1.89	1.58	0.96	1.10
20-30	0.97	1.98	1.51	1.38	1.09	1.79	2.00	1.39	1.37	0.70	2.24	2.06	1.57	1.77	1.34	1.41	1.45	2.67	1.77	1.55	2.00	1.55	1.97	0.94	1.37
30-40	1.47	1.84	1.66	1.17	0.79	2.07	2.39	1.43	1.90	1.21	2.18	2.28	2.06	2.23	1.11	2.01	1.40	2.54	1.92	2.12	1.96	0.81	1.76	1.17	1.55
40-50	0.96	1.18	1.69	0.75	0.67	2.65	1.86	1.90	2.15	1.62	1.70	2.17	2.24	1.93	1.08	1.25	1.21	1.69	2.04	2.02	1.50	0.97	1.66	1.47	1.65
50-60	0.82	0.97	1.17	0.94	1.10	1.46	1.76	0.91	1.07	1.69	1.47	1.27	1.10	1.94	1.15	1.10	0.99	1.22	1.81	1.20	1.01	1.17	1.91	1.33	1.99
60-70	1.06	1.01	1.92	1.01	0.97	1.67	2.48	1.49	0.80	1.58	1.88	1.56	2.12	1.20	1.05	1.31	1.34	2.02	1.82	2.30	2.09	1.10	1.89	1.57	2.05
70-80	0.85	0.76	1.27	0.81	0.58	2.16	2.40	1.98	2.01	2.79	1.20	2.00	2.26	1.09	0.98	0.69	0.99	1.53	1.81	1.71	1.53	0.98	1.67	1.51	1.50
80-90	0.57	0.96	0.85	0.44	0.72	2.71	1.87	1.47	2.20	2.79	1.04	1.22	1.74	0.99	0.94	0.88	0.74	1.17	2.02	1.40	1.40	0.83	1.17	1.48	1.21
90-100	0.68	0.78	0.84	0.56	0.71	2.96	1.76	1.48	2.70	2.08	0.91	1.47	1.31	1.08	0.95	0.74	0.69	1.26	2.03	1.41	1.87	1.00	1.67	1.07	1.48

pH

Block No.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Plot No.	1	4	1	4	5	4	5	3	1	2	2	1	2	3	4	5	3	4	5	1	3	2	5	2	3
Treat.	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
Depth (cm)																									
0-5	6.36	6.18	5.23	6.12	6.49	3.90	3.91	5.57	6.54	4.73	6.45	6.83	5.89	4.98	6.33	7.54	6.99	6.99	6.57	7.23	5.81	6.77	5.96	6.06	5.98
5- 10	6.58	6.75	6.45	6.61	6.27	3.80	4.20	6.39	6.54	5.45	6.75	6.60	6.29	4.98	7.11	7.52	7.35	6.98	6.94	7.42	6.89	7.50	7.29	6.06	6.62
10-15	7.27	6.93	7.08	6.59	6.02	4.14	5.09	6.84	6.65	5.90	7.10	6.58	6.76	4.95	7.01	7.53	7.62	7.09	7.01	7.34	7.50	7.82	7.67	6.35	7.11
15-20	7.36	6.83	6.75	6.53	5.70	4.80	5.99	7.16	7.18	7.20	7.26	6.70	6.86	5.01	6.79	7.20	7.74	6.85	6.99	7.28	7.56	7.81	8.02	6.34	7.03
20-30	6.98	6.79	5.29	6.14	6.14	5.98	5.96	7.10	7.08	7.45	7.38	6.49	6.67	5.05	5.43	7.17	7.57	5.84	7.01	7.09	7.60	7.65	6.06	6.09	6.86
30-40	5.24	6.88	5.26	6.25	7.28	5.81	6.05	6.91	6.95	7.15	7.17	4.86	6.26	5.01	5.89	6.98	7.36	5.81	6.42	6.64	7.43	6.80	5.61	5.78	6.33
40-50	6.46	7.11	6.75	6.60	7.46	5.74	6.01	6.88	6.87	6.96	7.48	5.17	6.36	5.01	7.05	7.20	7.44	6.91	6.45	6.82	7.58	6.87	6.49	5.75	5.83
50-60	6.80	7.15	7.18	6.81	7.15	6.46	6.32	7.37	7.59	7.02	7.54	6.43	6.78	5.00	7.42	7.51	7.42	7.04	6.67	7.22	7.85	7.36	7.53	6.44	6.64
60-70	6.64	7.30	7.60	6.64	5.20	6.60	6.43	7.50	7.76	7.13	7.97	6.74	6.74	4.95	7.37	7.45	7.39	7.11	6.73	7.09	8.06	7.31	7.68	6.62	6.76
70-80	6.71	7.34	6.75	6.34	5.30	6.81	6.75	7.35	7.67	7.36	5.13	6.10	6.91	5.02	7.06	7.50	7.49	7.13	6.82	4.79	7.83	5.43	7.60	6.84	4.31
80-90	6.89	7.50	5.95	6.53	7.04	6.62	6.72	7.34	6.80	7.28	5.96	5.09	6.92	5.03	7.10	7.30	7.58	7.16	6.80	4.95	7.79	5.40	7.52	6.87	4.26
90-100	6.85	7.61	6.60	7.22	7.24	6.47	6.81	7.25	4.23	7.49	6.47	5.73	6.81	4.99	7.16	7.48	7.45	7.03	6.79	5.42	7.70	6.09	7.27	6.61	4.49

Treatment: 1 = Bare, 2 = 10t/ha Cane Tops, 3 = 2t/ha Straw, 4 = 5t/ha Straw, 5 = 10t/ha Straw.

APPENDIX III

MEAN SURFACE (0-10cm) pH AND ELECTRICAL CONDUCTIVITY DETERMINATIONS IN THE DRYLAND SURFACE AMELIORATION TRIAL DECEMBER 1999

Block	Plot	Treatment *	No. of Samples	EC mean	SE	pH mean	SE
1	6	1	11	3.98	0.61	6.45	0.34
2	8	1	6	6.98	1.71	6.75	0.11
3	9	1	6	2.62	0.68	7.65	0.17
1	1	2	13	3.15	0.43	6.11	0.23
3	4	2	11	2.39	0.38	6.90	0.11
2	11	2	6	7.30	0.56	6.65	0.23
1	5	3	11	5.94	0.57	7.01	0.21
2	7	3	11	11.97	1.17	7.35	0.07
3	2	3	5	2.13	0.19	7.94	0.09
2	3	4	11	4.35	0.29	6.75	0.33
3	7	4	11	2.59	0.19	6.43	0.12
1	10	4	6	6.88	0.71	7.23	0.15
2	3	5	11	1.75	0.11	5.28	0.21
3	5	5	11	3.76	0.77	7.25	0.17
2	5	5	11	3.16	0.41	5.77	0.33
2	6	6	11	6.51	0.67	7.80	0.09
3	11	6	6	2.50	0.51	8.08	0.09
1	11	6	6	11.00	1.23	7.33	0.14
3	3	7	11	2.35	0.38	7.27	0.08
1	8	7	10	7.48	0.96	7.30	0.09
2	9	7	6	5.77	1.31	7.60	0.15
2	2	8	11	5.05	0.73	7.21	0.18
3	8	8	11	1.82	0.27	6.70	0.11
1	9	8	6	4.32	0.81	6.90	0.30
2	4	9	12	5.13	0.51	7.37	0.18
3	6	9	11	2.57	0.19	6.86	0.18
1	7	9	9	7.40	0.76	6.84	0.15
3	1	10	11	2.05	0.42	7.45	0.16
1	4	10	11	2.78	0.43	6.34	0.24
2	10	10	6	5.15	2.22	6.67	0.32
2	1	11	11	6.37	0.78	7.12	0.19
1	3	11	11	2.41	0.30	6.10	0.16
3	10	11	6	4.88	0.45	7.28	0.31

***Treatment**

1 = No Mulch
2 = 10 t/ha Cane Tops Mulch
3 = Cultivation
4 = Cultivation + Cane Tops Mulch
5 = Cultivation + Plastic Mulch
6 = Irrigation + No Mulch
7 = Irrigation + Cultivation
8 = Irrigation + Cane Tops Mulch
9 = Irrigation + Cultivation + Cane Tops Mulch
10 = Irrigation + Cultivation + Plastic Mulch + Mound in Row
11 = Irrigation + Cultivation + Plastic Mulch + No Mound in Row

APPENDIX 2

WED 2/10/96 4:54:02 PM

SYSTAT VERSION 5.0
COPYRIGI 1990-1992
SYSTAT INC.

Welcome to SYSTAT!
WORKSPACE CLEAR FOR CREATING NEW DATASET

WED 2/10/96 5:26:39 PM C:\BRAD\THESIS\NUT.SYS
LEVELS ENCOUNTERED DURING PROCESSING ARE:

BLOCK
1.000 2.000 3.000 4.000

NIT
0.000 1.000 2.000 3.000

POS
0.000 1.000 2.000

POT
0.000 1.000

MODEL CONTAINS NO CONSTANT.

DEP VAR: DWT N: 96 MULTIPLE R: 0.669 SQUARED MULTIPLE R: 0.448

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
BLOCK	0.382	3	0.127	0.023	0.995
NIT	169.688	3	56.563	10.054	0.000
POS	94.296	2	47.148	8.380	0.001
POT	0.848	1	0.848	0.151	0.699
NIT*POS*POT	0.428	6	0.071	0.013	1.000
NIT*POS	52.504	6	8.751	1.555	0.173
POS*POT	1.079	2	0.540	0.096	0.909
NIT*POT	0.556	3	0.185	0.033	0.992
ERROR	393.819	70	5.626		

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