Dry saline land: an investigation using ground-based geophysics, soil survey and spatial methods near Jamestown, South Australia

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Cover diagram

Whole-of-landscape 3-D process model for Cootes case study area showing:
(i) EM-38 map partly draped over the 3D-aerial photograph drape of study area with boundaries of landscape-soil units (LSU), (ii) photographs of representative soil profiles for each LSU, (iii) geology, (iv) cross-section of typical toposequence showing the main morphological, saline and sodic soil-regolith features/layers and (v) groundwater and fresh surface water flow paths. The EM-38 map designates high conductivity values in red (subsoil expressed dry saline land), medium values in yellow-turquoise and low values in dark blue.
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The National Action Plan for Salinity and Water quality is a joint initiative between the State and Commonwealth Governments.
TABLE OF CONTENTS

Important Disclaimer .............................................................................................................................. i
SUMMARY .............................................................................................................................................. 1

1. BACKGROUND AND REVIEW ..................................................................................................... 3
   1.1 Objectives ................................................................................................................................... 4
   1.2 Work strategies .......................................................................................................................... 4
   1.3 Dry saline land: a brief literature review ................................................................................... 5
       1.3.1 Dry saline land in root zones caused by slowly permeable subsoil layers ...................... 6
       1.3.2 Dry saline land with subsoil expression .......................................................................... 7
       1.3.3 Dry saline land with surface expression (magnesia patches) ......................................... 7
       1.3.4 Generalised best management practices for dry saline land ......................................... 8

2. METHODS ...................................................................................................................................... 9
   2.1 Selection of representative study areas with dry saline land .................................................... 9
   2.2 Site description of Cootes case study area ................................................................................. 9
   2.3 Site description of Munduney case study area .......................................................................... 15
   2.4 Electromagnetic induction principles ...................................................................................... 17
       2.4.1 EM-38 electromagnetic induction technique .................................................................... 17
       2.4.2 EM-31 electromagnetic induction technique .................................................................... 18
   2.5 Volume magnetic susceptibility technique ............................................................................... 18
   2.6 Ground-based surveys using EM-38, EM-31 and VMS geophysical techniques ..................... 20

3. RESULTS AND DISCUSSION ..................................................................................................... 21
   3.1 Soil and landscape data .......................................................................................................... 21
       3.1.1 Subsoil expressed dryland saline land: Cootes case study area ..................................... 21
       3.1.2 Surface expressed dryland saline land: Munduney case study area ............................. 23
   3.2 Geophysical data: EM-38, EM-31 and VMS .......................................................................... 24
       3.2.1 Subsoil expressed dry saline land: Cootes case study area ........................................... 25
       3.2.2 Surface expressed dryland saline land: Munduney case study area ............................. 27
   3.3 Integration of landscape-soil and geophysical data ................................................................. 27
       3.3.1 Whole-of-landscape 3-D process model for Cootes study area ...................................... 30
       3.3.1.1 Construction of soil-landscape process model ............................................................... 30
       3.3.1.2 Application of the soil-landscape process model .......................................................... 31

4. CONCLUSIONS AND FURTHER WORK ....................................................................................... 35

5. ACKNOWLEDGMENTS ................................................................................................................   37

6. REFERENCES .................................................................................................................................. 38

APPENDIX 1: Mineralogical data ....................................................................................................... 40
APPENDIX 2: EM 38, EM-31 and Volume magnetic susceptibility data ............................................. 41
LIST OF FIGURES

Figure 1. Locality of the Cootes and Munduney case study areas between Jamestown and Spalding, South Australia. .......................................................................................................................... 3
Figure 2. Dry saline land or transient salinity (not hydrologically connected to a saline watertable); primary salinity (caused by saline groundwater), salt bulges (below the root zone of former native vegetation) and secondary salinity (rising saline groundwater and salt accumulation due to evaporative water loss in saline seeps) (from Fitzpatrick et al., 2003). ................................................. 6
Figure 3. Soil-regolith model showing salt transport and erosion processes leading to formation of subsoil and surface dry saline land (not associated with the saline groundwater tables). NOTE: A sodic duplex soil is used here as an example. These processes also do however occur in gradational soils or in soils with thin A horizons directly overlying saprolite (from Fitzpatrick et al., 2003). .................................................................................................................. 8
Figure 4a and b. Cootes study area’s regional context (a) and landscape location with toposequence A-B marked (b). Inset, photo of study area looking from A to B, which is similar to photograph of transect (A'-A") shown Figure 5. ........................................................................................................ 12
Figure 4c. Photograph of Cootes case study area, looking north east along selected transect from A to B, which is similar to aerial photograph showing transect (A'-A") in Figure 5. .................................................. 13
Figures 4d, e and f showing the “Freshwater Creek” deep (12m) erosion gully containing highly saline soils (edge of gully EC$_{se}$ 360 dS/m; bottom of gully EC$_{se}$ 4-140dS/m) in the Cootes study area. .................................................................................................................. 13

Figure 5. Upper: soil map boundaries with Soil Map Units (SMU A to F) overlying a hill shaded aerial photo of the Cootes study area highlighted in yellow box with toposequence/transect described in Figure 14 highlighted with a red line. Lower: Enlargement of Cootes study area showing: (i) localities of geophysical survey points at 20 m intervals along survey lines with 50 m spacing (black dots), (ii) localities of soil profile sample points with morphological descriptions (green squares) and (iii) localities of soil profile sample points with morphological descriptions, chemical and physical soil data (red circles).............................................................................. 14
Figure 6. Photograph of (a) the Munduney study area north-west facing landscape with dry saline land and (b) geophysical survey lines. .......................................................................................... 15
Figure 7. Photograph of (a) surface expressed dry saline land in scalded area (i.e. magnesia patch typical of the area) and (b) exposed weathered shale coated with salt efflorescences and carbonate at the Munduney study area. ............................................................ 16
Figure 7. Photographs soil profiles with surface expressed dry saline land exposed in the drainage ditch in Munduney study area. ............................................................................................ 16
Figure 8. 3-D aerial photo drape of the Cootes study area with landscape soil unit boundaries, laboratory data and XRD sampling locations (a), (b) and (c) indicated. .......................................................... 22
Figure 9. Hill shaded regional context of Munduney and Cootes study areas showing (i) modelled drainage, (ii) land systems and soil landscape units (Soil and Land Information, 2002b) showing dry saline land magnesia patch mapping (red, 10-50% affected; pink, 2-10% affected; green, <2% affected), and (iii) hatched areas, showing pyritic and sulfidic geological units. ............................................................ 24
Figure 10. EM-38 (a) and EM-31 (b) and VMS (c) surveys over laid on a 3-D aerial photo drape of the study area and Landscape Soil Units (1-4). High response values are in red, medium values in yellow-turquoise, and low values in dark blue............................................................................. 26
Figure 11. EM-38, EM-31 and VMS data for transect lines 1 (above) and 2 (below). ................................. 28
Figure 12. EM-31, EM-38 and VMS data for transect lines 3 (above) and 4 (below). .............................. 29
Figure 13. Plot of EM-38 versus VMS data for line 4 (see figure 12) of the Munduney site. ..................... 30
Figure 14. Whole-of-landscape 3-D process model for Cootes case study area showing (i) 3D-aerial photograph drape of study area with boundaries of landscape-soil units (LSU), (ii) photographs of representative soil profiles for each LSU, (iii) geology, (iv) cross-section of typical toposequence showing the main morphological, saline and sodic soil-regolith features/layers and (v) groundwater and fresh surface water flow paths. ..................................................... 34
Figure 15. Whole-of-landscape 3-D process model for Cootes case study area showing (i) EM-38 map partly draped over the 3D-aerial photograph drape of study area with boundaries of landscape-soil units (LSU), (ii) photographs of representative soil profiles for each LSU, (iii) geology, (iv) cross-section of typical toposequence showing the main morphological, saline and sodic soil-regolith features/layers and (v) groundwater and fresh surface water flow paths. The EM-38 map designates high conductivity values in red (subsoil expressed dry saline land), medium values in yellow-turquoise and low values in dark blue. ................................................................. 35
LIST OF TABLES

Table 1. Categories of dry saline land soils, as defined by hydrology, landscape features and soil chemistry (adapted from Fitzpatrick et al., 2003) .......................................................... 10
Table 2. Generalised best management practices (BMPs) after drainage or disturbance for different classes of dry saline land (from Fitzpatrick et al. 2003) .......................................................... 10
Table 3. The oxides, hydroxides and oxyhydroxides of iron (from Bigham et al. 2002) ...................... 19
Table 4. Particle size data and soil texture of shallow calcareous silty loam........................................ 23
Table 5. Electrical conductivity, pH, organic carbon, sulfur and carbonate carbon of shallow calcareous silty loam............................................................................................................. 23
Table 6. Exchangeable cations, cation exchange capacity and ESP of shallow calcareous silty loam. ........................................................................................................................................... 23
SUMMARY

The South Australian Salinity Mapping and Management Support Project commissioned this investigation to evaluate ground-based geophysical techniques such as electromagnetic induction (EM-38 and EM-31) and volume magnetic susceptibility (VMS) in the rapid detection and mapping of non-groundwater table related forms of soil salinity called dry saline land. This form of salinity is distinct from dryland salinity, which is induced by rising saline groundwater.

Firstly, we review the definition, landscape forming processes and best management practices of dry saline land. We conclude the existence of the following two “end member” forms of dry saline land, which adversely affect agricultural productivity: (i) “surface expressed”, featuring high concentrations of salts in soil surface layers - locally termed “magnesia patches” - and (ii) “subsoil expressed” exhibiting elevated concentrations of salts in the subsoil root zone.

Secondly, we present outcomes of field and laboratory studies to determine the value of EM-38, EM-31 and VMS in detecting and mapping forms of dry saline land in two study areas. The study areas chosen are located in dryland farming areas between Jamestown and Spalding in South Australia’s Northern Agricultural District where dry saline land covers approximately 60% of the area. The area is also characterised by a complex mosaic of soils associated with dryland salinity (saline groundwater related), sodicity and waterlogging that is detrimental to agricultural production. Ground-based geophysical interpretations were made in conjunction with exiting soil survey, terrain (digital elevation model - DEM) and land use information. Several key findings emerged from the study:

- EM-38 performs well in being able to detect shallow subsoil (>1.5m) and surface expressed dry saline land. This is because both these forms of dry saline land reside at or near the surface (i.e. within the optimum operating depth range of the instrument). This field instrument proved cost-effective and easy to use.
- EM-31 shows where salts are located deep (i.e. ~5m) in the landscape. As such, it is not strictly useful in mapping shallow accumulations of salts, although it reveals soil-landscape processes associated with deeper salt storage and mobilisation.
- VMS revealed a strong correlation ($r^2 = 0.77$) with EM-38 in some landscape situations. This correlation is explained largely by soil-landscape processes linked to the presence of iron oxides in soils, which in turn is associated with redox conditions and water movement. Consequently, interpretation of VMS data is anticipated to be highly site specific. As such, with further investigation, VMS may prove an easy-to-use surrogate for mapping dry saline land.
- Combined EM-38, EM-31, VMS, soil survey patterns and topographic (DEM) information form the basis for developing and constructing improved whole-of-landscape process models with three-dimensional architecture and water flow systems (not readily apparent from previous two-dimensional toposquence models).
• These models provide a powerful tool for communicating salt storage and salt mobilisation knowledge for these complex landscapes affected by dry saline land and dryland salinity, and a framework for determining optimal patterns of regional land use and land management.
1. BACKGROUND AND REVIEW

This investigation was commissioned by the South Australian Salt Mapping and Management Support Project (SASMMSP) (Munday et al., 2003) as part of the National Action Plan (NAP). The work described here was conducted in the “Jamestown” SASMMSP region. This region is located in South Australia’s Northern Agricultural District (NAD) and surrounds the town of Jamestown. This is a rich dryland farming area affected by a form of soil salinity called “dry saline land”. The locations of the study areas - “Cootes” and “Munduney” - are shown in Figure 1. Dry saline land is alternatively referred to as “magnesia patches” (Soil and Land Information, 2002a), “magnesia country” (Kennewell, 1999), or more recently, “transient salinity” (e.g. Rengasamy, 2002). It is a form of soil salinity often associated with sodicity in subsoils that are not influenced by current saline groundwater tables (Fitzpatrick et al., 2003). Dry saline land salinity in various forms covers approximately 67% of South Australia’s NAD, and presents a threat to crop production in this important agricultural area (Rengasamy 2002). The area is also characterised by a complex mosaic of soils with the associated issues of “dryland salinity” (i.e. saline groundwater related soil salinity), sodicity and waterlogging; individually or combined, these soil issues also hamper crop production in varying degrees.

Figure 1. Locality of the Cootes and Munduney case study areas between Jamestown and Spalding, South Australia.
The airborne electromagnetics (AEM) commissioned by the SASMMSP detects regolith (i.e. >5m) conductivities linked to salt accumulation and transport systems with a nominal ground resolution of 80m. With dry saline land salinity a problem associated with the soil surface and subsoil (i.e. <1.5m) and occurring in discrete spatial patterns, AEM is therefore unlikely to be of much value in detecting this form of salinity. In addition, the costs for targeted, key area AEM acquisitions are almost always likely to be prohibitive for project-based dryland farming applications. However, ground-based electromagnetic (EM) methods such as EM-38 and EM-31 may be useful in this respect, relatively easy to interpret, and cost-effective to contract. Considerable research effort has been devoted into the use of ground-based EM methods to detect and manage dryland salinity (associated with rising groundwater tables), yet little has been done to detect dry saline land using the same techniques. Here we address this shortcoming.

The terminology and definitions surrounding the concept and various forms of dry saline land is confused. This has important implications for research, farmer, conservation and policy communication. Consequently, the scope of this project was to provide a brief literature review on the terminology of dry saline land. Further, we use field information on the application of ground-based EM-38 and EM-31 techniques for rapid detection of the various forms of dry saline land from studies conducted in dry saline land-affected landscapes. Finally, we describe the use of a low cost, lightweight, ground-based geophysical technique called volume magnetic susceptibility (VMS) - used simultaneously with the EM instruments - to characterise soil-landscape attributes in the two study areas.

1.1 Objectives

The objectives of this investigation were to: (i) briefly review and define the forms of “dry saline land”, (ii) report on the field application of ground-based geophysical techniques such as electromagnetic induction (EM-38 and EM-31) and volume magnetic susceptibility (VMS) techniques for rapid detection and mapping of dry saline land, and (iii) interpret EM-38, EM-31 and VMS data, together with topographic (DEM), soil survey and geological information to construct 3-D soil-landscape process models to help explain salt storage and salt mobilisation in complex landscapes affected by dry saline land.

1.2 Work strategies

Strategies adopted in this work were:

- Compilation of a brief review of dry saline land.
- Selection of two case study areas that illustrate the typical range of dry saline land between Jamestown and Spalding (in consultation with Ms Mary–Anne Young, Rural Solutions SA, Jamestown).
- Conduct EM-38, EM-31 and VMS surveys using high sampling intensities throughout the case study areas.
• Assessment of existing and newly sampled soil data, with emphasis on the following soil attributes from laboratory analyses:
  o pH,
  o particle size analysis,
  o electrical conductivity (EC),
  o exchangeable cations and cation exchange capacity (CEC),
  o organic carbon, and carbonate,
  o mineralogy (powder X-ray diffraction analysis).
• Construct 3-D soil-landscape process models by integrating topographic, soil and ground-based geophysics data to explain salt storage and salt mobilisation in complex landscapes affected by dry saline land.
• Provide advice on the concept of dry saline land and applicability of ground-based EM and VMS devices for mapping dry saline land.

1.3 Dry saline land: a brief literature review

Dry saline land or transient salinity (subsurface and surface expressed) occurs in upper parts of landscapes not influenced by saline groundwater (Fitzpatrick et al. 2003). Accumulation of salts in the soil surface range from EC_{se} 4-60 dS/m (surface form) and EC_{se} 2-8 dS/m in the subsoil (i.e. 0.3-1.0 m) (subsoil form) can be detrimental to crops, especially with increasing salt concentrations (Rengasamy 2002). This phenomenon of salt accumulation within root zones of sodic soils is different from the "secondary" or "seepage" salinity (i.e. dryland salinity) found typically in low parts of landscapes with shallow, rising watertables (Figure 2). Dry saline land is not hydrologically connected to a saline watertable and is extensive in many sodic soil landscapes in Australia, especially in low rainfall areas where evapotranspiration is high during summer, and winter leaching of salts is minimal. While 16% of the dryland cropping area is likely to be affected by salinity induced by shallow watertables (dryland salinity), 67% of the area has a potential for induced dry saline land salinity, not associated with groundwater and other subsoil constraints. These forms of soil degradation cost the Australian farming economy in the vicinity of A$1330 million per year (Rengasamy 2002). Where the upper layers of soil are sodic, water infiltration is very slow because dispersed clay clogs soils pores. If the subsoils are also sodic, the downward movement of water is restricted, thus causing temporary waterlogging in the subsoil, and the development of "perched watertables". Salts accumulate above perched watertables during the wet winter and accumulate in the sodic subsoils following drying by water uptake by plant roots and evaporation. Not all dry saline land is associated with the presence of perched watertables, or soils with sodic B horizons; in some landscapes clay layers or poorly permeable, near-surface regolith with are sufficient to impede the downward leaching of salts with the wetting front, resulting in the local accumulation of subsoil salts in the perched watertables. The rate of salt accumulation is not large, but over time can be detrimental to crops. This so-called ‘subsoil transient salinity’ fluctuates with depth and also changes with season as the balance between downward and upward fluxes change.
1.3.1 **Dry saline land in root zones caused by slowly permeable subsoil layers**

In upper parts of agricultural landscapes, where saline groundwater tables are generally deep (i.e. greater than 20-30 m depth), salt accumulation is usually below 5m depth and thus does not affect crops (Figures 2 and 3). Prior to agricultural development the upper soil layers (i.e. <1m) in these virgin soils were weakly saline (Figure 3a). However, leaching and saturation within the rooting zone causes a number of chemical, biological and physical changes, including: (i) acidity, (ii) sodicity, (iii) sodicity and salinity, and (iv) sodicity and alkalinity.

Rate and amount of downward percolation of salts are primarily controlled by soil texture and subsoil layer permeability. In coarse textured horizons faster rates of water flow occur since the average pore diameter is larger than in fine textured soils. Also, less water storage is directly related to greater pore diameters. As a result, deep percolation of water and salts is more likely to occur in coarse textured soils.

![Figure 2](image)

Figure 2. Dry saline land or transient salinity (not hydrologically connected to a saline watertable); primary salinity (caused by saline groundwater), salt bulges (below the root zone of former native vegetation) and secondary salinity (rising saline groundwater and salt accumulation due to evaporative water loss in saline seeps) (from Fitzpatrick et al., 2003).

In some localities in Australia relatively coarse textured soils overlie slowly permeable sodic clay horizons (Figure 3a). Under these circumstances, percolation leads to lateral flow of water and solutes along the surface of the impermeable layer. If the contact between the two different layers approaches the soil surface along a hill slope, as often happens, the laterally moving water (with solutes) will create a wet spot (i.e. "perched watertable"), becoming saline as the accumulated water evaporates (Figures 2 and 3b).
1.3.2 Dry saline land with subsoil expression

Subsoil expressed dry saline land has been estimated to occur on about 30% of the land in the wheat growing regions of the mid-north of South Australia (Soil and Land Information, 2000a). Subsoil layers between 0.3 and 0.6m deep have accumulated salt with an electrical conductivity of the soil saturation extract (EC$_{sat}$) ranging between 2-16 dS/m and the surface soil layers ranging between EC$_{sat}$ 2-8 dS/m. This high salt concentration may cause osmotic effects, which prevents plants from absorbing water from soil. As the soil layers dry out after winter, salt concentrations increase, plants show grey symptoms (from lack of photosynthetic activity) and lose leaf area with some senescence. Generally, the accumulated salts in the cropping regions of southern Australia are dominated by sodium chloride. However, significant sodium carbonate and bicarbonate may also exist in alkaline soils with a soil pH >9.0 (i.e. alkaline-sodic saline soils).

When dry saline land with subsoil expression is drained and leached by rainfall, secondary sodic soils are developed (Figure 3c). The development of sodic layers with low hydraulic conductivity and high bulk density further restrict downward movement of water, leading to waterlogging, tunnel erosion and enhanced lateral movement of water and colloids to streams. Eventually a saline scald is formed (Figure 3c).

1.3.3 Dry saline land with surface expression (magnesia patches)

The most extreme case of salt accumulation is where EC$_{sat}$ values are very high at the surface (EC$_{sat}$ >16 up to 60.0 dS/m) and often has salt efflorescences. These high levels of salt prevent crops - and even halophytes - from growing and can cause the soil to be susceptible to scalding and erosion. The cause of this salinity is the localised mobilisation of salts above slowly permeable sodic B horizons by throughflow to topographic depressions (Figure 3b) and salt accumulation by evaporation. This dry saline land with surface expression (i.e. surface soil transient salinity) can occur in a variety of soil types and at all positions within undulating landscapes, and was first reported in South Australia by Herriot (1942). Approximately 45,000 ha of marginal cropping land in South Australia are affected by this problem (Kennewell, 1999). This form of dry saline land salinity is commonly referred to as "magnesia patches" because of the apparent dominance of Mg when first documented. Subsequently, however, Na has been shown to generally dominate as a natural part of the salt evaporation sequence.

When dry saline land with surface expression (magnesia patches) is drained, soils are leached and salt efflorescences on the soil surface are dissolved (Figure 3c). Salt crystals develop at depth in sodic soils where salt is leached through the subsoil clay layers on edges of gullies or drains. This causes stream banks to erode by salt weathering (Figure 3c). If these processes are expressed on the surface of the soil, bare eroded saline scalds are evident (Figure 3c).
1.3.4 Generalised best management practices for dry saline land

The capacity to reverse established salinisation in dry saline land will depend strongly on the specific class of saline soil that exists (Table 1). Different management techniques are necessary for soils with different soil textures, salt compositions and water regimes. These management techniques can include draining, application of gypsum, ripping, mulching and efforts to revegetate (Table 2).

Figure 3. Soil-regolith model showing salt transport and erosion processes leading to formation of subsoil and surface dry saline land (not associated with the saline groundwater tables). NOTE: A sodic duplex soil is used here as an example. These processes also do however occur in gradational soils or in soils with thin A horizons directly overlying saprolite (from Fitzpatrick et al., 2003).
2. METHODS

2.1 Selection of representative study areas with dry saline land

Based on the literature review of the definition, landscape forming processes and best management practices of dry saline land, we concluded the existence of two "end member" forms of dry saline land that adversely affect agricultural productivity: (i) "surface expressed", featuring high concentrations of salts in the soil surface layer - locally termed "magnesia patches" - and (ii) "subsoil expressed", exhibiting elevated concentrations of salts in the subsoil root zone.

Two representative study areas showing symptoms of each of the above forms of dry saline land were selected from the Jamestown area. Site selection benefited considerably from local knowledge and experience of Ms Mary-Anne Young, Rural Solutions SA senior extension officer based in Jamestown. Both sites were located in the “Belalie Plains” area (Figures 1 and 4a), a broad valley system oriented north-to-south and running between Jamestown (north) and Spalding (south). A "subsoil expressed" dry saline land example study site was selected at the farming property of the Cootes and Ashby families - known as the “Cootes study area”, and a “surface expressed” example was located at the “Munduney” property, operated by the University of Adelaide (Figures 6 and 7). These study sites were located 25 and 20 km south of Jamestown respectively.

2.2 Site description of Cootes case study area

The Cootes study area (121 ha) was selected as an example of the subsoil form of dry saline land, demonstrating typical landscape/environmental conditions for the Jamestown area from the perspective of geology, soils, land use, climate, and soil-water movement. To the north is Jamestown (25 km), and to the south Spalding (20 km) and Adelaide (180 km) (Figures 1 and 4a,b). The study area is on the east-facing slope of a broad north-south valley system, which is drained southwards by the "Freshwater Creek" (Figures 4c, d, e and f). The crest-to-valley bottom toposequence (A-B) (Figures 4 and 5) length is approximately 1,500m, and has a relief difference of 100m, i.e. 470-370m. A basement of tillites, quartzites, mudstones, siltstones and shales underlies the area (see below, Figure 14). A prominent feature of the landscape is the deeply incised (12m) erosional gully formed by the creek (Figures 4c, d and f). Seventy five percent of the 450 mm annual rainfall falls in the winter growing season (May to October).

A georeferenced air photo was acquired and a DEM generated photogrammetrically for the supply of detailed terrain information. The resulting DEM featured 3m spatial resolution and sub-meter vertical accuracy.
Table 1. Categories of dry saline land soils, as defined by hydrology, landscape features and soil chemistry (adapted from Fitzpatrick et al., 2003)

<table>
<thead>
<tr>
<th>Hydrology</th>
<th>Soil/Landscape Feature</th>
<th>Dominant Soil Chemistry</th>
<th>Saline Soil Category Descriptor</th>
<th>Management Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater or Perched water</td>
<td>Primary dry saline land (Transient salinity) (natural)</td>
<td>Halitic</td>
<td>Primary, dry saline, topsoil, halitic G</td>
<td>See Table 2</td>
</tr>
<tr>
<td>Groundwater absent from root zone: salinity process driven by seasonal perched water table in root zone</td>
<td>Surface soil (Magnesia patch)</td>
<td>Sodic</td>
<td>Primary, dry saline, topsoil, sodic H</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsoil</td>
<td>Sodic</td>
<td>Primary, dry saline, subsoil, sodic H</td>
<td></td>
</tr>
<tr>
<td>Secondary dry saline land (Transient salinity) (induced)</td>
<td>Surface soil (Magnesia patch)</td>
<td>Halitic</td>
<td>Secondary, dry saline, surface soil, halitic G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsoil</td>
<td>Sodic</td>
<td>Secondary, dry saline, subsoil, halitic H</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eroded</td>
<td>Halitic</td>
<td>Secondary, dry saline, eroded, halitic E¹</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subsoil</td>
<td>Sodic</td>
<td>Secondary, dry saline, eroded, sodic H</td>
<td></td>
</tr>
</tbody>
</table>

¹ See Fitzpatrick et al. (2003)

Table 2. Generalised best management practices (BMPs) after drainage or disturbance for different classes of dry saline land (from Fitzpatrick et al. 2003)

<table>
<thead>
<tr>
<th>Soil Salinisation Category (Table 1)</th>
<th>Soil Texture</th>
<th>Indicators</th>
<th>Management Options in Sequence¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Sands/Loams</td>
<td>EC, pH</td>
<td>Mulch with coarse sand or organic matter. Drain to leach salts. Calcium application (gypsum). Vegetate with suitable species as soon as possible. May be used for agriculture.</td>
</tr>
<tr>
<td></td>
<td>Clays</td>
<td>EC, pH, CaCO₃, ESP or SAR, BD²</td>
<td>As for (G) Sands/loams but closer drain spacings will be required to leach salts</td>
</tr>
<tr>
<td></td>
<td>Sand/Clay</td>
<td>As above, subsoil BD</td>
<td>As for (G) Sands/loams but closer drain spacings will be required to leach salts</td>
</tr>
<tr>
<td>H</td>
<td>All</td>
<td>EC, pH</td>
<td>Drain to leach salts. Calcium application (gypsum). Vegetate with suitable species as soon as possible. May be used for agriculture.</td>
</tr>
</tbody>
</table>

¹ Most soils affected by salinity have nutrient deficiencies or imbalances. It is important, especially in eroded or scalded sites, that nutrient status is addressed when re-establishing vegetation. To minimise erosion and pugging, stock should be excluded from these areas.

² Many clayey subsoils have high bulk densities (BD) with poor hydraulic conductivity. These conditions cause difficulty in leaching salts and exploration by plant roots.

³ Sandy textures overlying clayey textures are called duplex soils.
**Soils**: Detailed soil information (i.e. draft soil map with accompanying detailed profile descriptions and chemical analyses) for the survey area was accessed from a previously unpublished CSIRO soil survey (Fitzpatrick et al., 2004). Initial soil mapping (Figure 5) was based on detailed fieldwork, soil sampling and laboratory analyses. This data was augmented by sampling additional soils (including profile descriptions and laboratory analyses) as part of the current study at key sites not previously sampled. As a consequence of the multi-factorial genesis of these soils, the present landscape is described as being pedologically complex – as depicted in the following range of soil types contained in the soil-mapping units (SMU) presented below:

- **SMU A**: *Brown Clay* (sometimes with subsoil expressed sodicity and salinity) – These soils are a moderate to strongly structured brown clay soil with field textures dominated by silt in the upper horizons. The soil is deep with what appears to be buried soils of generally redder colour (than the overlying brown clay) at depths of 1m or more; sodic subsoils with a pale A2 variant (Ab) may occur. This SMU occurs on the flat, overlying deep alluvium.

- **SMU B**: *Sodic Brown Clay* - These soils are a clay that may have a weak self-mulching surface and a gradational texture profile that may extend beyond 2.0m, but the underlying calcareous shales are at a mean depth of 1.6m and a range of 0.7m to 2.0m. These soils are restricted to the very gently inclined to moderately inclined slopes emanating from the low hills and rises overlying colluvium.

- **SMU C**: *Red Brown Earths* (sometimes with subsoil expressed sodicity and salinity) – These soils have a hard setting A horizon of light sandy clay loam to clay loam texture and a clear to sharp change to a dark reddish brown, strongly structured, medium to heavy clay B horizon. The solum is usually greater than 2m deep. A shallow variant (C-s) has been recognised for those profiles that are less than 0.5m to the C horizon. The majority of profiles are calcareous although there is considerable variation in depth to the calcareous layer(s), which may be soft, hard and nodular. This SMU occurs in the flat, overlying colluvium.

- **SMU D**: similar profile characteristics to SMU C (*Red Brown Earths*) – These soils differ from SMU C soils in that they have a sporadic bleach of varying thickness and prominence. This SMU occurs on sloping to flat areas overlying colluvium / alluvium.

- **SMU E**: transitional to the *Brown Clays* of SMU A and SMU B (with a gradational texture) -- These soils have colours of the major horizons that are generally less red than the *Red Brown Earths*. The landscape position of soils of this SMU is generally near the transition from uniform profile forms to duplex. The gradational features in SMU E may have been enhanced by the cultivation practices resorting surface horizons.

- **SMU F**: *Rendzina* and *Terra Rossa* soils with low levels of salinity and sodicity – These soils comprise mainly shallow calcareous loams with calcrete fragments overlying mainly calcareous weathering siltstone with some very shallow, loamy topsoils (<0.1m) overlying massive calcrete. These shallow soils occur mainly on the crest and upper slopes, and
contain outcrops (40%) of mudstone, siltstone and partly carbonaceous shale (Figure 4b). These soils have formed in situ from fine sedimentary rocks (mudstones, siltstones and partly carbonaceous shales). The dominant vegetation is pasture. These soils are darker and browner than SMUs C, D, E and G.

- **SMU G: Red Brown Earths** (mostly with subsoil expressed sodicity and salinity) - The main morphological feature distinguishing these soils from the other Red Brown Earths is a lighter surface texture with accompanying poorer structure; the B horizons are strongly structured and medium to heavy clay texture; free lime is evident in the majority of profiles.

- **SMU Gully Edge:** The exposed soils at the gully’s edge (12m deep) are highly saline (EC<sub>se</sub> 360 dS/m), gypsiferous and sodic soils in some layers. Some carbonate-rich gravel bedding layers indicate the presence of alluvial fans in the profile.

- **SMU Gully Flat:** These soils are highly saline (EC<sub>se</sub> 4-140 dS/m) sulfidic hydrosols.

Figure 4a and b. Cootes study area's regional context (a) and landscape location with toposquence A-B marked (b). Inset, photo of study area looking from A to B, which is similar to photograph of transect (A'-A") shown Figure 5.
Figure 4c. Photograph of Cootes case study area, looking north east along selected transect from A to B, which is similar to aerial photograph showing transect (A’-A”) in Figure 5.

Figures 4d, e and f showing the “Freshwater Creek” deep (12m) erosion gully containing highly saline soils (edge of gully EC<sub>se</sub> 360 dS/m; bottom of gully EC<sub>se</sub> 4-140dS/m) in the Cootes study area.
Figure 5. Upper: soil map boundaries with Soil Map Units (SMU A to F) overlying a hill shaded aerial photo of the Cootes study area highlighted in yellow box with toposequence/transect described in Figure 14 highlighted with a red line. Lower: Enlargement of Cootes study area showing: (i) localities of geophysical survey points at 20 m intervals along survey lines with 50 m spacing (black dots), (ii) localities of soil profile sample points with morphological descriptions (green squares) and (iii) localities of soil profile sample points with morphological descriptions, chemical and physical soil data (red circles).
2.3 Site description of Munduney case study area

The Munduney case study area was selected because it is representative of typical landscapes with conditions (geology, climate, aspect and soil water regime) leading to the formation of surface expressed dry saline land (magnesia patches). This study area is located 20 km south of Jamestown at the “Munduney” property, operated by the University of Adelaide (Figures 6 and 7). The study area is on the north-west facing flank of a broad north-south valley system, which is drained southwards by the “Freshwater Creek” (Figure 6). The crest-to-valley bottom length is approximately 400m and has a local relief difference of approximately 80m. Prominent features of the landscape are two shallow interceptor drains constructed along contour lines to successfully manage recharge from rainwater and to control earlier soil erosion problems on the mid- and upper slopes (Figure 6a). An erosion gully exists at the bottom of the slope as a legacy of past erosion activity (Figure 6a).

Figure 6. Photograph of (a) the Munduney study area north-west facing landscape with dry saline land and (b) geophysical survey lines.
Figure 7. Photograph of (a) surface expressed dry saline land in scalded area (i.e. magnesia patch typical of the area) and (b) exposed weathered shale coated with salt efflorescences and carbonate at the Munduney study area.

Figure 7. Photographs soil profiles with surface expressed dry saline land exposed in the drainage ditch in Munduney study area.
A representative soil profile (Figures 7e and 7f) with surface expressed dry saline land was described according to McDonald et al. (1990) and soil and rock (Figure 7b) samples taken for laboratory analyses. EC1:5, pH1:5, pH (CaCl₂), major and total exchangeable cations, cation exchange capacity (CEC), and exchangeable sodium percentages (ESP) were measured on each soil horizon using standard techniques (Rayment and Higginson 1992). ECse was estimated from EC1:5 and soil texture to identify the salinity hazard and its affect on plants (Cass et al., 1996).

2.4 Electromagnetic induction principles

Traditional methods of measuring soil salinity involve soil sampling with an auger followed by analysis of a water extract in the laboratory (e.g. Rayment and Higginson, 1992). This procedure is slow, laborious and expensive. It is therefore desirable to use field methods that allow rapid, on-site diagnosis of salinity concentrations. The EM-38 and EM-31 electromagnetic induction soil conductivity sensors of Geonics Ltd has been developed for this purpose, as well as for rapid salinity mapping (e.g. Slavich, 1991). Both instruments are field portable, and comprise a transmitter and a receiver coil, a power supply, electronics and analogue display.

Briefly, both instruments operate in the same way, i.e. their transmitter coils are energised by an alternating current. The time-varying magnetic field arising from alternating currents induce small eddy current loops in the soil that generate secondary magnetic fields. The receiver coils measure these secondary magnetic fields. The ratios of the secondary to primary magnetic fields are directly proportional to the electrical conductivity (i.e. the apparent electrical conductivity [ECa], in deciSiemens/meter [dS/m]) of the soil material. Since most soil particles are poor conductors of electricity, it is primarily the water content/electrolyte concentration that gives rise to instrument response. Ideally the soil should be near field capacity throughout the depth of investigation at the time of measurement (e.g. Slavich, 1991). Despite this limitation, the technique has been shown to be a practical field method for diagnosing and delineating soil salinity problems (e.g. McNeill, 1980; Slavich, 1991).

2.4.1 EM-38 electromagnetic induction technique

Designed to be particularly useful for agricultural surveys measuring soil salinity, the EM-38 can cover large areas quickly because it is very lightweight and is only one meter long. The EM-38 provides rapid surveys with excellent lateral resolution. Measurements are obtained with the instrument placed on the soil surface. The EM-38 provides depths of exploration of approximately 0.75 to 1.5m in the horizontal and vertical dipole modes respectively. The current EM-38 electromagnetic induction survey was conducted using the vertical dipole (i.e. to 1.5m in depth).
2.4.2 EM-31 electromagnetic induction technique

The EM-31 instrument was designed to measure apparent electrical conductivity (ECa) in the regolith profile to an approximate depth of 5m when used at hip height. Like the EM-38 instrument, the EM-31 is portable and can cover large areas quickly on foot.

2.5 Volume magnetic susceptibility technique

Mineral magnetic techniques are a relatively recent development (post 1971) and have now become a very powerful and widely used research tool to characterise natural materials in landscapes (Thompson and Oldfield, 1986). Palaeomagnetic and mineral magnetic measurements have been most effectively applied to soils, soil parent materials, bedrock, river sediments and estuarine cores in studies of whole catchments. For example, mineral magnetic techniques have been used in a wide range of environmental studies such as sourcing sediments in reservoir catchments; establishing stream arm sediment contributions at river confluences; sourcing estuarine sediments; characterisation of soils; tracing overland soil movement; and identification of fire-induced magnetic oxides in soils and lake sediments. Soil magnetic properties can be used in conjunction with other pedological and mineralogical methods to trace sources of alluvium to measure the extent of erosion and deposition in eroding landscapes. These magnetic techniques can also be used for relative soil age dating and for the determination of soil and parent material discontinuities (e.g. evidence for buried soil layers).

Magnetic susceptibility measurements can detect the presence of iron oxides in soils at lower concentrations than other methods such as X-ray diffraction analyses. In soils, their magnetic properties reflect the varied magnetic behaviour of the bulk of soil minerals present. In many soil samples, the magnetic susceptibility is largely determined by the ferrimagnetic mineral present such as magnetite and maghemite (Table 3). Other major soil constituents may also affect magnetic susceptibility values. Quartz, calcium carbonate, orthoclase, organic matter and water are diamagnetic and, in most soils, these dilute the magnetic properties. In extreme cases, such as pure silica sands and pure limestone, the diamagnetic component will have a significant effect on the magnetic susceptibility of the sample. Paramagnetic soil minerals are those rich in iron but low in ferrimagnetic properties. They may make a significant contribution to bulk magnetic susceptibility. Antiferrimagnetic minerals will also increase magnetic susceptibility values. Of these, goethite and hematite are the most abundant (Table 3) and therefore can make an important contribution to the magnetic properties of soils.

Magnetic susceptibility is essentially a measure of how "magnetisable" a mineral is (Thompson and Oldfield, 1986). Volume susceptibility, \( \kappa \), is defined by the relation, \( \kappa = M/H \), where \( M \) is the volume magnetisation induced in a material with susceptibility, \( \kappa \), by an applied field, \( H \). Mass specific magnetic susceptibility, \( \chi \), is the volume susceptibility divided by the sample density, \( \chi = \kappa/\rho \), and has units of m³kg⁻¹. The ferrimagnetic Fe oxides, such as
magnetite, maghemite, titanomagnetite and titanomaghemite, commonly dominate the magnetic signature of a soil, rock or sediment. These minerals have strong, positive mass specific magnetic susceptibilities of the order of 20,000 to 50,000 x 10^{-8} m^3kg^{-1}. They are attracted to the weak magnetic field of a hand magnet, which provides a useful field test for their presence in a sample. In contrast, the other Fe oxides have magnetic susceptibilities in the order of 20 to 100 x 10^{-8} m^3kg^{-1}. These values are comparable to or slightly greater than those of other common soil minerals and are not particularly diagnostic. Fifteen oxides, hydroxides, and oxyhydroxides of Fe have been recognised (Table 3). Of these, twelve occur naturally, but only eight are common in soils or other surface environments. The magnetic susceptibility of a mixed-mineral sample is influenced by the composition, size and shape of the ferrimagnetic crystals, but it is primarily determined by their concentration. Thus, magnetic susceptibility measurements from a set of related samples commonly show a positive, linear relationship to magnetite or maghemite content (e.g. da Costa, et al., 1999).

### Table 3. The oxides, hydroxides and oxyhydroxides of iron (from Bigham et al. 2002)

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Formulas</th>
<th>Hydroxides</th>
<th>Formulas</th>
<th>Oxyhydroxides</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hematite</td>
<td>α - Fe2O3 †</td>
<td>Bernalite</td>
<td>Fe(OH)3</td>
<td>Goethite</td>
<td>α - FeOOH</td>
</tr>
<tr>
<td>Maghemite</td>
<td>γ - Fe2O3</td>
<td>Ferrhydrite</td>
<td>Fe5HO8.4H2O</td>
<td>Lepidocrocite</td>
<td>γ - FeOOH</td>
</tr>
<tr>
<td>Magnetite</td>
<td>Fe3O4</td>
<td>Green rust</td>
<td>§see below</td>
<td>Akaganéite</td>
<td>β - FeOOH-Cl</td>
</tr>
<tr>
<td>Wüstite</td>
<td>FeO</td>
<td>Feroxyhyte</td>
<td>δ' - FeOOH</td>
<td>Schwertmannite</td>
<td>Fe8O8(OH)6SO4</td>
</tr>
<tr>
<td></td>
<td>β - Fe2O3 ‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>δ - Fe2O3 ¶</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Minerals that have been reported as naturally occurring in soils are in **bold**. Minerals in normal type occur under more restricted conditions.
‡ Greek letters (α, β, γ etc.) are used to distinguish minerals or compounds that have the same chemical composition but different structures.
§ Refers to a group of compounds with the basic Fe(OH)2 structure. Charge arising from partial oxidation of Fe(II) is balanced by various interlayer anions, typically Cl−, SO4^{2-}, and CO3^{2-} as per: Fe(II)1-xFe(III)x(OH)2(Cl−, SO4^{2-}, CO3^{2-}).
¶ Formulas given without corresponding mineral names indicate compounds that have been synthesised in the laboratory but have not been found as naturally-occurring, inorganic phases.

Many studies have documented that the magnetic susceptibility of surface soil is commonly higher than that of underlying materials (e.g. Thompson and Oldfield 1986). This “magnetic enhancement” can result from: (i) simple accumulation of primary ferrimagnetic minerals (e.g. maghemite) that are resistant to weathering or transport; (ii) burning of the soil and the conversion of goethite, hematite or lepidocrocite to maghemite; (iii) neoformation of maghemite or magnetite from the soil solution; (iv) accumulation of ferrimagnetic minerals through atmospheric deposition; and (v) cultivation of abrasive soils (Fitzpatrick and Riley, 1990).
Volume magnetic susceptibility determinations were conducted in the field using a Bartington magnetic susceptibility instrument model MS2 (Bartington Instruments Ltd., Oxford, England) equipped with a MS2D probe, which determines concentrations of magnetic materials in the top 60 mm.

2.6 Ground-based surveys using EM-38, EM-31 and VMS geophysical techniques

EM-38, EM-31 and VMS surveys were conducted simultaneously at the Cootes’ property in a key area of 121ha (Figure 5). The survey was carried out over a grid comprising 975 GPS-located sample points along 16 x ~1,000m crest-to-valley (west-east) transects, 50 m apart (north-south). An along-transect sampling interval for 20 m was used (Figure 5).

EM-38, EM-31 and VMS surveys were conducted at the Munduney property in a key area comprising 2 ha (Figures 6 and 7). The surveys were conducted along four contour transects that were approximately 20m apart, with along-transect sampling conducted at 10m intervals, with 82 sample points being GPS-located (Figure 6).

Using a GIS the three geophysical surveys were co-registered to the GPS locations and individually interpolated by Ordinary Kriging to generate GIS surfaces for each survey.

The Munduney survey lines were plotted graphically for visual assessment and interpretation, and are discussed in the following section.
3. RESULTS AND DISCUSSION

3.1 Soil and landscape data

3.1.1 Subsoil expressed dryland saline land: Cootes case study area

Using SMU mapping as a basis, the study area was divided into a number of “landscape soil units” (LSUs) based on similarities in: topography, soil-regolith morphology (soil texture, structure); zones of salt accumulation; and hydrology (i.e. groundwater and freshwater flows). These, with the laboratory analysis data (clay %, EC\text{se} and ESP), are shown in Figure 8, overlaid on a 3-D aerial photo drape of the study area. Also shown are the locations of soils (“a” and “b” from < 0.3m, and “c” at 1.0 m) and taken for mineralogical (powder X-ray diffraction) analysis.

The LSUs that have been identified are described as follows:

- **LSU 1**: Crests, upper north-south oriented ridges and topographic highs along west-east oriented spurs; shallow calcareous loams with very low salinity and sodicity (Rendzina and Terra Rossa soils) interspersed with outcropping (i.e. 5-50% surface cover) shales and siltstones.

- **LSU 2**: High slopes intruding up drainage and gully lines to the west-east oriented spurs and upper north-south oriented ridges: saline/sodic clay soils with gradational texture profile and weak self mulching surface.

- **LSU 3**: Lower slopes intruding up drainage or gully lines; Red Brown Earths with subsoil expressed sodicity and salinity; strong texture contrasts between leached upper layer loams above sodic clay layers (see profile data, Figure 8). B horizons are strongly structured and medium to heavy clay texture; free lime is evident in the majority of profiles.

- **LSU 4**: Flat alluvial plain; deep moderate to strongly structured sodic clays (sometimes with subsoil expressed sodicity and salinity) with thin leached A horizons; field textures dominated by silt.

- **LSU 5**: Gully Edge: Highly saline (EC\text{se} 360 dS/m), gypsiferous and sodic soils on steeply inclined slopes with some carbonate-rich gravel bedding indicting alluvial fans

- **LSU 6**: Gully Flat: Highly saline (EC\text{se} 4-140 dS/m) sulfidic hydrosols.
Figure 8. 3-D aerial photo drape of the Cootes study area with landscape soil unit boundaries, laboratory data and XRD sampling locations (a), (b) and (c) indicated.
3.1.2 Surface expressed dryland saline land: Munduney case study area

Dry saline land with surface expression (magnesia patches) is associated with upper slopes of undulating to rolling rises and low hills in the Munduney study area (Figures 6a,b; 7a and 9). The regional distribution of dry saline land magnesia patch soils are shown in the hill shaded map (Figure 9; red, 10-50% affected; pink, 2-10% affected; green, <2% affected), together with areas showing the modelled drainage and pyritic/sulfidic geological units. These landscapes are associated with shallow, saline, greyish brown, powdery calcareous silty loams that, within one metre, become more silty with depth and grade to weathering calcareous siltstone bedrock containing pyritic/sulfidic minerals (Figures 7b, c, d). The near-surface, slowly permeable, weathering calcareous siltstone tends to restrict drainage of saline soil water. Evaporation subsequently strongly concentrates salts in the topsoil.

Tables 4–6 present physical and chemical (pH, electrical conductivity, ESP and carbonate content) from soil horizon data for representative soil profiles in the study area. Mineralogical data is presented in Appendix 1. The soil photographed in Figure 7f, was classified according to Isbell (1996) as a Hypervescent, Paralithic, Hypercalcic Calcarosol; medium, slightly gravelly, loamy/silty, moderate.

Table 4. Particle size data and soil texture of shallow calcareous silty loam.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Clay %</th>
<th>Silt %</th>
<th>Fine Sand %</th>
<th>Coarse Sand %</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>11</td>
<td>40</td>
<td>37</td>
<td>1</td>
<td>Fine silty loam</td>
</tr>
<tr>
<td>5-20</td>
<td>12</td>
<td>40</td>
<td>37</td>
<td>1</td>
<td>Fine silty loam</td>
</tr>
<tr>
<td>20-35</td>
<td>7</td>
<td>33</td>
<td>37</td>
<td>3</td>
<td>Find silty loam</td>
</tr>
</tbody>
</table>

Table 5. Electrical conductivity, pH, organic carbon, sulfur and carbonate carbon of shallow calcareous silty loam.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>EC&lt;sub&gt;se&lt;/sub&gt; dS/m</th>
<th>EC (1:5 soil:water) dS/m</th>
<th>pH</th>
<th>pH (0.01M CaCl&lt;sub&gt;2&lt;/sub&gt;)</th>
<th>Organic C %</th>
<th>Total S %</th>
<th>CO₃ as CaCO₃ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>2.9</td>
<td>0.3</td>
<td>8.4</td>
<td>7.8</td>
<td>2.0</td>
<td>0.03</td>
<td>6.2</td>
</tr>
<tr>
<td>5-20</td>
<td>16.9</td>
<td>1.6</td>
<td>8.2</td>
<td>8.0</td>
<td>1.1</td>
<td>0.02</td>
<td>8.5</td>
</tr>
<tr>
<td>20-35</td>
<td>15.7</td>
<td>1.3</td>
<td>9.2</td>
<td>8.5</td>
<td>0.5</td>
<td>0.02</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Table 6. Exchangeable cations, cation exchange capacity and ESP of shallow calcareous silty loam.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Exchangeable Cations cmol/kg</th>
<th>CEC (NH₄)</th>
<th>ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ca  Mg Na K Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>9.7  1.1  0.2  0.7 11.7</td>
<td>9.1</td>
<td>1.8</td>
</tr>
<tr>
<td>5-20</td>
<td>7.1  1.6  0.5  0.4 9.6</td>
<td>7.6</td>
<td>6.8</td>
</tr>
<tr>
<td>20-35</td>
<td>3.5  1.2  1.8  0.2 6.7</td>
<td>3.7</td>
<td>49.1</td>
</tr>
</tbody>
</table>
3.2 Geophysical data: EM-38, EM-31 and VMS

The EM surveys were conducted for the Cootes case study area using an EM-38 for the vertical dipole mode (Figure 10a), EM-31 (Figure 10b) and VMS (Figure 9c). The EM-38 determines subsoil conductivity at approximately 1.5m deep, and the EM-31, the regolith conductivity to
approximately 5m deep. VMS is measured at the soil surface. Figure 10 shows high response values in red, medium values in yellow-turquoise, and low values in dark blue. Conductivity values are generally strongly related to salt content (ECa).

### 3.2.1 Subsoil expressed dry saline land: Cootes case study area

Figure 10a (EM-38) displays three zones of relatively high subsoil conductivity. Feature “m” in LSU 2 is likely to represent an area of near-surface mineralisation. LSU 3 displays regions of conductivity associated with sloping areas that are not in near-surface (i.e. <1.5m) drainage zones. These regions are likely to represent subsoil salts, and are indicative of the subsoil form of dry saline land discussed earlier. This variable pattern shows the importance of micro relief and the structure of near surface geology on near surface drainage patterns, and hence subsoil dry saline land expression.

The EM-38 (Figure 10a) high conductivity zones are strongly correlated with VMS (Figure 10c) showing magnetic minerals near the soil surface, which can also contribute to the high conductivity. Moderate conductivities are displayed throughout LSU 4 areas, and are likely to be associated with low salt concentrations in the subsoil (see Figure 9 profile data) (Thomas et al., 2003).

By contrast, the EM-31 plot (Figure 10b) shows deeper regolith (approximately 5m) conductivity in all LSUs, especially in the drainage zones on sloping areas, and throughout LSU 4. Values ranged from ‘very low’ (<20 mS/m) in the more resistant knolls to ‘very high’ (>150 mS/m) at the NE discharge zone into the deep gully (Figure 10b). Conductivity values increased with distance downslope from the major knolls – as would be expected due to deeper, and perhaps, moister soils. Looking from the western ridge there appears to be a crescent of higher conductivity (100-150 mS/m) zones following the ‘break of slope’ areas. However high values are also found in the upper sections of the gullies leading up to the ridge. A large proportion of high conductivity response on the sloping areas is probably associated with conductive basement rock or the deposition of magnetic colluvial material. In the sloping area drainage zones, the highly conductive regolith pattern is likely to reflect magnetic colluvial material and/or salt accumulation. These salts are likely to have been washed down from upper-slope areas, or from below in saline groundwater.

The LSU 3/4 boundary forms a prominent contrasting conductivity feature. The high conductivity throughout most of LSU 4 is likely to reflect the hydraulic barrier - caused by the low sodic clay permeability - which traps and concentrates up-slope regolith salts. Perhaps after a considerable time in storage the salts seep out of the gully face, evidenced by high EM-31 conductivity zones and laboratory data. The high values along the edges of the main eastern creek bank or edge of the erosion gully (LSU 5) is indicative of salt discharge via throughflow and evaporative concentration within the soil profile (see Figure 14).
Figure 10. EM-38 (a) and EM-31 (b) and VMS (c) surveys overlaid on a 3-D aerial photo drape of the study area and Landscape Soil Units (1-4). High response values are in red, medium values in yellow-turquoise, and low values in dark blue.
3.2.2 Surface expressed dryland saline land: Munduney case study area

The Munduney EM-38, EM-31 and VMS field data for each survey transect were plotted together so that the datasets can be easily compared (Figures 11 and 12). High EM-38 responses were associated with the strongly saline (EC_{se} >3 dS/m) reddish and yellowish soils that have silty loam top and subsoils overlying shallow weathered siltstone in topographic highs. In contrast, low EM-38 responses were recorded in less saline grey and eroded soils in topographic lows that overlie near-surface and outcropping bedrock. The VMS responses strongly matched the EM-38 patterns (i.e. high correlation: r^2 = >0.77) for line 4, which correspond to the saline red and yellow silty loam soils overlying shallow bedrock in topographic highs (Figure 13). The lower VMS for the less saline grey soils in the low lying area associated with waterlogging and reducing (i.e. de-magnetising) soil conditions, and where the salts from these soils have been leached from the profile via through flow. However, for lines 1, 2 and 3 r^2 values were 0.21, 0.36 and 0.46 respectively and corresponded with survey lines corresponding with shallower, near-surface weathered rock, unlike line 4 (i.e. r^2 = >0.77), which corresponded with deeper soil profiles.

The EM-31 detected salt stores at depth in the low-lying areas only. Because the EM-38 and VMS detects near surface features (< 1.5m) and the EM-31 detects depth at approximately 5m, it was not surprising that the EM-31 patterns did not match those of the EM-38 (Figures 11 and 12). The main features shown in these figures are a series of high and low EC_{a} values. The ‘highs’ of the EM-38 plots correspond with areas of salt storage or accumulation; whilst the large ‘lows’ appear to be associated with very localised topographic lows (or depressions) where the soils are more leached by rainwater flushing through the subsoil. These trends, although exploratory in nature, are reasonably cohesive, given the minimal sampling carried out.

3.3 Integration of landscape-soil and geophysical data

Soil-regolith process models are a simplification or abstraction of the mechanisms that occur in a particular geological-pedological cross-section or toposequence under study so that it can be more easily handled either physically or mentally for a specific purpose (e.g. Dijkerman 1974). Several kinds of simplification or abstraction may be used; for example, in creating conceptual models that describe, explain or predict particular aspects of soil–regolith processes. Here, we use topographic, soil and ground-based geophysics data to construct a 3-D soil-landscape process models to explain salt storage and salt mobilisation in these complex landscapes affected by dry saline land salinity.
Figure 11. EM-38, EM-31 and VMS data for transect lines 1 (above) and 2 (below).
Figure 12. EM-31, EM-38 and VMS data for transect lines 3 (above) and 4 (below).
3.3.1 Whole-of-landscape 3-D process model for Cootes study area

3.3.1.1 Construction of soil-landscape process model

Colour photographs of typical soil profiles from each LSU occurring in different parts down the landscape slope or toposequence are shown in Figure 14. To understand the lateral linkages and relationships between soil-regolith, geology and hydrology down landscape slopes, we used the systematic structural approach (Fritsch and Fitzpatrick 1994) to identify and describe, by depth interval, all similar soil-regolith features (i.e. soil components with similar consistency, colour, textural and structural patterns, and physico-chemical and mineralogical properties). Similar soil-regolith features were grouped into fewer soil-regolith layers using nested or concordant relationships to group soil-regolith features, and discordant relationships to separate them and draw boundaries around similar features to link them down the toposequence, and map them at toposequence scale in cross section (Figure 14).

Each soil-regolith layer displayed in the cross section or toposequence were linked to soil-regolith and hydrological processes (e.g. water flow paths, salinity and sodicity). In Figure 14, we used mostly soil-regolith colour (together with other morphological, chemical and mineralogical indicators) and geology in the toposequence to construct the 3D linkages that describe water flow paths and development of salinity (descriptive soil-regolith models). Some visual indicators are obvious (e.g. occurrences of thick black accumulations of organic matter on soil surfaces) but some are more subtle (e.g. subsoil mottling patterns). Subsoil expressed salinity and sodicity can occur without any evidence on the surface. In Figure 14 cross hatching and shading represents soil...
sodicity and salinity with the thick dark blue arrows indicating salt groundwater flow and broken blue arrows freshwater flow.

Interpretations of the ground-based geophysical data, together with soil survey patterns and topographic (DEM) information were also used as a basis for developing and constructing improved whole-of-landscape process model with three-dimensional architecture displaying groundwater and fresh surface water flow systems. The process model incorporates a 3D-aerial photograph drape of the study area with boundaries of landscape-soil units (LSU) including photographs of representative soil profiles for each LSU, geology and cross-section of a typical toposequence showing the main morphological, saline and sodic soil-regolith features/layers (Figure 14).

3.3.1.2 Application of the soil-landscape process model

The EM-38 and EM-31 surveys of the Cootes study area have revealed a highly variable pattern of electrical conductivity especially when draped over topography (i.e. in 3D, Figures 10a and b). Similarly, the VMS survey has shown a variable pattern for soil magnetic properties (Figure 10c). Briefly, LSU 1-type soils are shallow loams on the crest or ridge, interspersed with outcropping (i.e. 5-50% surface cover) shales and siltstones. LSU 2-type soils are saline/sodic clays on steep upper slopes. LSU 3-type soils are on lower colluvial/alluvial slopes, and demonstrate strong texture contrasts between the leached upper layer loams above sodic clay layers (ref. Fig. 2 profile data). LSU 4-type soils are deep alluvial sodic clays with thin leached A horizons.

In SLU 1, the upper north-south ridge has low ECa values (EM-38 and EM-31), as do the west-east spurs leading down from the ridge (Figures 10a and b). The intervening areas (gullies with various degrees of definition as drainage lines) have slightly higher ECa values but these are interrupted in a north-south direction with lower conductivity ‘troughs’. The troughs could be due to coarse-textured colluvium or could represent remnants of vertically dipping shales, now covered with colluvium (Figure 15). Regardless of which is the true answer, the troughs would have considerable hydrological significance. The 3-D perspective emphasises the crescent of higher conductivity around the lower slopes of the main north-south ridge and the intrusion to higher elevations up the main gullies.

The ECa patterns displayed from both the EM-38 and EM-31 surveys generally indicate higher conductivity areas across the lower slopes of the landscape. However, where the EM-31 shows higher conductivities in the drainage zones of LSUs 2 and 3, the EM-38 and VMS shows lower relative values in the drainage zones (Figures 10a, b and c). The high ECa values (>150 mS/m) observed high in the landscape (Line 11 – Appendix 2) from the EM-31 survey may suggest that the source of electrical conductivity is related to magnetic minerals at depth rather than just an accumulation of soluble salts. In general, electrical conductivity values tend to increase downslope in most landscapes, even though they may show peaks and troughs along the way. However this is
not always the case in this area (e.g. compare Lines 10 and 11 with Lines 6 to 9 in Appendix 2). The high values in elevated positions indicate the presence of electrically conductive material i.e. most likely salts or magnetic minerals in these soil types. East-west cross sections (Appendix 2) of the landscape reveal considerably more variability in EM-31 electrical conductivity than is shown in the contoured data of Figure 10. Practically all transects exhibit a series of ‘peaks’ and ‘troughs’ – some more so than others (e.g. Lines 11 to 14) but also further north at Lines 4 & 5 (Appendix 2). Such troughs may be interpreted as indicating the presence of ‘preferred’ pathways for the downward movement of water i.e. a surrogate measure of recharge. It is possible that this explanation might also be true in this area but that interpretation is confounded by the possible presence of magnetic minerals in the slope colluvium (Figure 10c). A third explanation, given the near vertical bedding of the underlying shales, is that the troughs may reflect a zone of increased weathering (and leaching) between different layers of the shale material (Figure 15). The apparent continuity of troughs from transect to transect (Appendix 2) would lend support to this hypothesis, particularly if the shale is within a few meters of the land surface.

Other, electrically non-conductive, rock material is also present in the landscape (“m” in Figure 10a). This is shown quite clearly as a large trough on the eastern sector of Line 1 and it carries through at least to Line 4 (Appendix 2). The trough corresponds with a topographic high on Line 1 that diminishes in magnitude until it has disappeared before reaching Line 4. A further, similar example occurs on Lines 15 and 16 where transects passed over a long east-west spur (Appendix 2). A north-south transect, relatively high in the landscape at Easting 278755, demonstrates the higher electrical conductivities in the re-entrant valleys and also a ‘high’ well up the slope of the southernmost spur encountered along Lines 15 and 16.

The conductivity patterns from Figure 10, combined with soil profile data (ESP, salinity and clay %) in A and B horizons in Figure 8, suggest that soil-landscape patterns with LSU 3-type soils up-slope of LSU 4-type soil are likely to be indicative of landscapes prone to dry saline land formation and salt entrapment. Dry saline land soils are typically associated with upland soils that exhibit vertical (i.e. down profile) and lateral (i.e. down slope) impediments to drainage (mainly in LSU 3). Subsoil expressed dry saline land is associated with soils that have a sodic clay B-horizon (Btn). The sodic clay condition acts to hamper vertical drainage of soil water, forcing it to move laterally down slope (Figure 14 – see arrows in LSU 3). As the water moves over the Btn horizon it accumulates and transports salts from the up-slope topsoil where they become concentrated in the upper clay horizon and / or in seasonally wet patches, e.g. at break of slope and in topographic lows. Here salts become seasonally concentrated in subsoils as water evaporates or is used by plants. The concentration of salts may vary from time to time at depth in response to changes in seasonal rainfall / soil hydraulic conditions, explaining the “transient” nature of salinity that has been observed on poor plant growth in affected areas.
Figures 10a and b show a clear divide between a high electrical conductivity zone associated with LSU 3 to the west and low conductivity with LSU 4 to the east of the main road (Figure 14). The area to the west (LSU 3) is largely influenced by colluvium and that to the east largely influenced by alluvium (i.e. approaching the main creek line with variability that is reminiscent of a typical alluvial plain) as illustrated in Figure 14. The low conductivity divide may represent a north-south bed of siliceous material, with a surface expression best seen on Line 1 (Appendix 2) as a distinct knoll or it may simply represent the divide between colluvial outwash from the western ridge and alluvium from the (now deeply incised) creek system (Figure 14).

The high EC\textsubscript{a} values (EM-38 and EM-31) in the easternmost sector (LSUs 5 and 6) are consistent with saline groundwater and soluble salt discharge into the deeply incised creek line (Figures 10a, b and c; 14).

In summary, the descriptive 3-D whole-of-landscape process model characterizes the catchment-scale variability of relict (past geomorphological processes in development of rock weathering and erosion) and current (saline, sodic and sulfidic soils) soil forming processes and helps develop a better understanding of the salt storage and flow paths. The model also explains the contemporary geochemical dispersion and erosion mechanisms present in the lower parts (erosion gully) of the toposequence (Figure 14). The model illustrates some of the pedological, geological, mineralogical and hydrological processes involved in catchments between Jamestown and Spalding. In particular, the model explains salt storage and salt mobilisation in this complex landscape that is affected by both dry saline land and dryland salinity (i.e. groundwater induced, occurring in the lowest part of the landscape/ in the erosion gully with stream salinity).

The model identifies a complex palaeovalley system (SLU 4 and 5 derived from alluvium), which provides new insights (see below) into the soil-regolith, geological and hydrological features associated with salt stores in both upland soil surface features and in low-lying valley-fill sediments.

The combined EM-31/EM-38 and topographic pattern (Figures 10a and b) describe the true underlying physical and magneto/chemical variation that exists in this landscape. Therefore, types of soil-landscape pattern expressed in areas with similar environmental conditions (e.g. climate, geology, land use) is likely to be a useful predictor of where dry saline land issues are likely to occur in the landscape. If so, the ability to predict these patterns will be important in managing these areas more effectively.

The higher conductivities in LSU 3 may be due to soluble salts, transported magnetic material, or a combination of both. Only more targeted sampling and detailed laboratory analyses will determine that factor and no final conclusion should be drawn until that process is carried out.
Figure 14. Whole-of-landscape 3-D process model for Cootes case study area showing (i) 3D-aerial photograph drape of study area with boundaries of landscape-soil units (LSU), (ii) photographs of representative soil profiles for each LSU, (iii) geology, (iv) cross-section of typical toposequence showing the main morphological, saline and sodic soil-regolith features/layers and (v) groundwater and fresh surface water flow paths.
4. CONCLUSIONS AND FURTHER WORK

For the two research sites each dominated by either subsoil expressed or surface expressed (magnesia patch) dry saline land, EM-38, EM-31 and VMS used in combination shows strong promise for obtaining high intensity, non intrusive, spatially continuous soil information. These three geophysical techniques - together with topography and soil survey data - have been used to: (i) produce maps showing the aerial extent of dry saline land and (ii), construct a colour cross-sectional diagram or model to show the various saline and sodic soil horizons/layers and water flow pathways (Figure 15).

Figure 15. Whole-of-landscape 3-D process model for Cootes case study area showing (i) EM-38 map partly draped over the 3D-aerial photograph drape of study area with boundaries of landscape-soil units (LSU), (ii) photographs of representative soil profiles for each LSU, (iii) geology, (iv) cross-section of typical toposequence showing the main morphological, saline and sodic soil-regolith features/layers and (v) groundwater and fresh surface water flow paths. The EM-38 map designates high conductivity values in red (subsoil expressed dry saline land), medium values in yellow-turquoise and low values in dark blue.
Presently, the EM-38 method appears to be the method of choice for quick characterisation of dry saline land in the Jamestown region. This technique has proven very successful for detection of shallow lateral changes in the apparent electrical conductivity (ECa) of soils (Figure 15). The EM-38 map and cross-section shows that subsoil expressed dry saline land is confined mainly to Landscape Soil Unit 3, where salts have preferentially accumulated. The accumulation of these salts in this part of the landscape can be explained by the barrier to onward (down-slope) drainage formed by the sodic clays at the surface of Landscape Soil Unit 4, blocking the flushing of sloping area salts out of the catchment. However, within Landscape Soil Unit 3, it is evident that subsoil salt concentrations are lower in areas within near-surface subsoil drainage areas due to the higher rates of freshwater flushing experienced (Figure 15). This topographic flushing pattern is repeated at a finer scale in surface expressed dry saline land at the Munduney study area where marked reduction in ECa was measured in drainage lines. These studies highlight the usefulness of EM-38 as a broad precursory investigative tool that can be used to direct and focus the more costly and time-consuming detailed soil surveys.

These geophysical techniques (EM-38, EM-31 and VMS) - in conjunction with terrain information and soil analyses - have been used to successfully help interpret discreet soil-landscape patterns that have been attributed to dry saline land forming conditions. However, to confirm these interpretations more quantitative work is required (e.g. geomorphologic mineralogical and geochemical characterization).

Further work should also involve exploiting the regional perspective offered by linking ground-based data to airborne geophysics and other regional scale data sets (soil mapping, terrain and geology) to extrapolate the established patterns of dry saline land for focus study areas. Thomas et al. (2003) describes some preliminary work using this approach by featuring airborne K% gamma radiometrics in mapping soil-landscape patterns in the Jamestown study area.

Finally, the conceptual toposequence model that we have “constructed” for the Cootes case study area provides a powerful tool for communicating salt storage and salt mobilisation knowledge for this complex landscape affected by dry saline land and dryland salinity, and a framework for determining optimal patterns of regional land use and land management. We anticipate that the model developed here could be applied to landscapes in the region with similar environmental conditions (e.g. geology, rainfall, land use, topography, soils, etc.) to highlight whole-of-landscape salt storage and mobilisation mechanisms.
5. ACKNOWLEDGMENTS

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6. REFERENCES


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## APPENDIX 1: Mineralogical data

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D = Dominant; CD – co-dominant; M = Minor; T = Trace
APPENDIX 2: EM 38, EM-31 and Volume magnetic susceptibility data
Cootes survey - Line 1
### Munduney survey - Line 2

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- **Eca (mS m⁻¹):** The values range from 0 to 100 mS m⁻¹.
- **VMS (x10⁻⁸ m³ kg⁻¹):** The values range from 10 to 400 x10⁻⁸ m³ kg⁻¹.
Munduney survey - Line 3

![Graph showing water quality parameters across different locations.](image-url)
Munduney survey - Line 4

Eca (mS m⁻¹)

VMS (x10⁻⁸ m³ kg⁻¹)

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VMS versus EM38

\[ y = 2.415x + 81.85 \]

\[ R^2 = 0.4169 \]
$y = 3.3074x + 57.727$

$R^2 = 0.7765$