REGIONAL PREDICTION OF SALT-AFFECTED SOILS IN AN AREA OF COMPLEX SOIL PATTERNS IN SOUTH AUSTRALIA

Mark Thomas¹, Rob W. Fitzpatrick² & Graham S. Heinson³

¹CRC LEME, University of Adelaide and South Australian Department for Water, Land and Biodiversity Conservation, PMB 2, Glen Osmond, SA, 5064
²CRC LEME, CSIRO Land and Water, PMB 2, Glen Osmond, SA, 5064
³CRC LEME, School of Earth and Environmental Sciences, University of Adelaide, SA, 5005

INTRODUCTION

Shallow Non-groundwater Associated Salinity (shallow NAS), which is described in Fitzpatrick et al. (in prep.), is found in upland parts of landscapes that have no direct contact with saline groundwater watertables, unlike Groundwater Associated Salinity (GAS). GAS is characterised in terms of catchment-scale hydrological processes, and is managed accordingly. Conversely, shallow NAS is characterised by localised soil patterns, which are governed by soil-landscape processes at various scales.

Shallow NAS soils feature: (i) high exchangeable sodium percentage (ESP) (i.e., are "sodic" and feature excessive Na⁺ ions on the exchange complex); and, (ii) high soluble salt concentrations (i.e., are "saline", generally featuring Na⁺ and Cl⁻ ions, and measured by ECₑₛₑ), in the solum (i.e., A and B-horizons, typically < 1.2 m deep). In Australia, soils with ESP ≥ 5 are generally considered as being sodic (Rengasamy & Churchman 1999). These soils show signs of a decline in soil structure due to clay dispersion, which in turn creates waterlogging, hard-setting physical barriers to root growth, and poor gas transfer rates. Elevated ECₑₛₑ values (i.e. ≥ 2 dS/m) give rise to droughting and toxic conditions in soils, which affect crop growth (Soil Survey Division Staff 1993). When sodicity and salinity combine through shallow NAS, the harmful effects on crops are magnified. Shallow NAS is strongly associated with texture contrast soils, which feature sandy/loamy A-horizons over sodic clay B-horizons. These are very important agricultural soils in southern Australia.

According to Rengasamy (2002), approximately A$1,330 million of farm income is lost annually through shallow NAS in Australia. More locally, in the Northern Agricultural District (NAD) (302,000 ha) of South Australia, subsoil (i.e., 0.3-1.2 m) salts are a widespread problem. According to 1:100,000 scale State-wide soil mapping (Soil and Land Information 2002), > 15% of the NAD soils are affected by salinity (ECₑₛₑ ≥ 2 dS/m) and > 60% by sodicity (ESP ≥ 6). Most of the saline areas spatially overlap with the sodic areas in the mapping, indicating that a significant proportion of the NAD is affected by shallow NAS. However, shallow NAS soils are difficult to map by conventional field-based soil-landscape survey methods (e.g., Mcdonald et al. 1998) because they form complex patterns with no apparent visual surface clues (e.g., colour, texture) (Thomas et al. 2003). For this reason, shallow NAS has not been mapped in South Australia at scales suitable for farm management planning (1:5,000 or larger).

Our aim is describe a GIS-based regional digital soil mapping methodology to predict shallow NAS for a small regional study area in the NAD.

REGIONAL STUDY AREA

The small regional study area (2,300 ha) is in an upland farming zone of the NAD (Figure 1). The average annual rainfall is 450 mm, of which approximately 75 % falls during the winter. Winters are cool and summers are hot, giving rise to a temperate, Mediterranean-type climate. The predominant agricultural land use in the area involves wheat, barley, canola and sheep grazing rotations.

Figure 1: Map showing location of regional study area in Australia, featuring South Australia’s Northern Agricultural District and rainfall zones.
The regional study area landscape features a north-south ridge system flanked by broad (> 8 km) valleys draining south. From this we selected a regionally representative toposequence area (121 ha) on the east-facing flank of the ridge. The toposequence was 1.5 km long and had a 100 m relief difference. As a consequence of the multi-factorial genesis of the soils reflecting the variable parent material (interbedded tillites, shales, quartzites, mudstones and siltstones), the toposequence can be described as being pedologically complex (Fitzpatrick et al. 2003). Essentially, all land in the toposequence area, and most of the regional area, has been cleared of native vegetation.

**METHODS AND MATERIALS**

Our approach was to combine multiscale soil and hydrological process models to predict, using a GIS, shallow NAS in the regional study area. The multiscale analyses were undertaken using field survey and laboratory methods, which were conducted at point (profile), plot (100 m²) and toposequence (121 ha) scales. The resulting datasets were used to display the main soil, regolith, geological and hydrological features in the toposequence using a cross-sectional, graphic format called a Conceptual Toposequence Model (CTM). At this stage the model was used to assess/display toposequence-scale soil-landscape variability, i.e., as a descriptive CTM (Fitzpatrick & Merry 2002) specifically related to shallow NAS toposequence expression. With the introduction of soil-landscape process knowledge from the multiscale investigations (e.g., solute transport pathways, shallow NAS zone processes), the descriptive CTM was transformed into an explanatory CTM (Fitzpatrick & Merry 2002). The final stage of the methodology involved spatially implementing the explanatory CTM, via a GIS, to make the regional shallow NAS predictions.

As discussed, three papers in preparation combine to fully document the whole regional predictive approach. In the first, Fitzpatrick et al. (in prep.) refine soil salinity concepts and definitions, and propose generic soil-process models. In the second, Thomas et al. (in prep.-a) describe at the point (profile), plot (100 m²) and toposequence (121 ha) scales, soil-landscape investigations to construct the soil and hydrological processes models. They also document the conceptual toposequence modelling in the regionally representative, shallow NAS-affected toposequence. In the third, Thomas et al. (in prep.-b) discuss the development and implementation of the regional predictive framework, via the conceptual toposequence modelling, to achieve the regional shallow NAS predictions.

**Multiscale surveys and analyses**

The multiple survey and analytical techniques used, and their scales and modes of application, are summarised in Table 1. Figure 2 is closely linked to Table 1 as it displays conceptually how the multiscale analyses and models connect to construct the explanatory CTM via the “model input” arrows and feedback loops. Figure 2 also highlights the links between the explanatory CTM and the GIS-based regional predictive framework, and the resulting regional shallow NAS predictions. Here we summarise the key outputs from the multiscale analyses, and briefly discuss the models that were developed.

**Point scale (profile) investigations**

Point scale surveys and analyses were used to determine spatial relationships between soil physico-chemical properties and to map the soils of the regionally representative toposequence area. Four landscape soil units (LSUs) were identified (Figures 2 and 3) (Thomas et al. 2003). Analysis of profile physico-chemical data showed that shallow NAS was confined to the LSU 3-types of soils on lower colluvial/alluvial slope landscape areas (Fitzpatrick et al. 2003).

**Plot scale (100 m²) investigations**

At plot scale (100 m²), we focused our investigations on morphological and chemical properties at the contact between the A and B-horizons by incorporating 3D GIS techniques (Figure 2). These investigations were conducted in two plots inside the LSU 3 soil area; one from a good crop yielding area (P1) and the other from a poor crop yielding area (P2) (Figures 2 and 3). The key soil properties investigated included ECₐₑ, CEC, ESP and magnetic susceptibility.

No strong relationships were identified between the A and B-horizon contact shape and plot soil patterns. However, P1 (the good crop yielding area) generally had a thicker A-horizon (0.16-0.34 m) and was less saline (ECₐₑ 0.4-0.7 dS/m), whereas P2 (the poor crop yielding area) generally had a thinner A-horizon (0.10-0.18 m), and was more saline (ECₐₑ 0.7-1.4 dS/m). By taking landform positions into account (Figures 2 and 3) during interpretation of these findings, we were able to determine that P1 was likely to be more agriculturally productive because of the combination of: (i) a higher water holding capacity (thicker A-horizon); and, (ii) a higher rate of freshwater flushing (leaching salts from the solum into downslope areas) due to the low-lying landscape position.
Toposequence (141 ha) investigations

At toposequence scale (141 ha), investigations focused on the relationships between landform (based on terrain wetness index (TWI) and slope), surface and subsoil salt concentrations/clay distribution (EM38), soil-regolith salinity/clay distribution (EM31), surface volume magnetic susceptibility (κ) and surface mineralogy (airborne radiometric K%) in the toposequence area (Figure 2). The electromagnetic induction (EMI) techniques (EM38 and EM31) revealed strong soil-landscape patterns, which were visually linked to the landscape-wide distribution of shallow NAS and hydrological patterns (Figure 2) using 3D GIS techniques and soil data (e.g., Figure 3). We also found that κ patterns strongly correlated with those of EM38, which in turn linked to landscape drainage patterns. Our interpretation for these observations was that high EM38 values/high κ values corresponded with low solum freshwater flushing zones in the TWI coverage (Table 1). Wetness index patterns and soil data (Figure 3) confirmed this relationship. Thus, we concluded that EM38 and κ patterns were pedogenic expressions of solum freshwater flushing patterns.

Thomas et al. (2003) demonstrated the link between topsoil clay mineralogy and soil types. In that study they reported that airborne radiometric K% could be used to regionally map the boundary between the LSU 4 and LSU 3 soils (Figs. 2 and 3).

Conceptual toposequence model construction

Fritsch & Fitzpatrick (1994) and Fitzpatrick & Merry (2002) detail the construction and interpretation of CTMs. Figure 2 illustrates the connections and feedback loops (i.e., multiscale extrapolation/verification sequences) involved in the process of constructing the CTM through the spatial and conceptual integration of the multiscale investigations. In Figure 2, the CTM highlights the connections between: landform; parent material (geology); the four soils (LSUs 1 to 4); soil morphologies (horizons and structure); and soil-landscape hydrology (structure, nodules and water flow). Salt/solute pathways and processes (saline and sodic), which influence the expression of shallow NAS in the landscape, are also highlighted by the explanatory CTM.

Figure 2: Links between point, plot and toposequence scale investigations and the construction of the explanatory CTM. The regional predictive framework shows the numeric thresholds for the GIS prediction. The regional predictions for shallow NAS (red areas)/non-shallow NAS (yellow areas) in LSU 3 soils is shown, overlaying a draped 3D rendition of the regional aerial photograph.
Regional prediction methodology

Given that we discovered that shallow NAS only featured in LSU 3 soils, and that our multiscale investigations revealed that not all LSU 3 soils were affected by shallow NAS, we focussed on the following two classes in our regional shallow NAS prediction methodology: LSU 3, shallow NAS affected; (i.e., "LSU 3 salty conditions"; Figure 2); and LSU 3 (i.e., "LSU 3 non-salty conditions", Figure 2).

Our approach was to extrapolate soil and hydrological patterns associated with shallow NAS from easily accessible and low-cost regional coverages. The extrapolation of these patterns was achieved through the spatial implementation of regional predictive framework (Figure 2). This procedure involved:

- Using soil data and knowledge from the explanatory CTM to identify regional coverages that have patterns that spatially corresponded with LSU 3 soils and shallow NAS and hydrological process patterns;
- Defining threshold values from these coverages that lend numeric expression to the patterns, "captured" in the form of a rules-based regional predicative framework (Figure 2); and,
- Spatially implementing the rules-based regional predicative framework via a GIS.

From the multiscale investigations, we identified the following regional coverages that corresponded with shallow NAS soil and hydrological patterns:

- Slope;
- Airborne radiometric K%;
- TWI; and,
- Plan curvature.

The final numeric model defining the predictive thresholds is presented in the regional predictive framework in Figure 2. Spatial implementation of the regional predictive framework was achieved using a GIS. The result is presented in the regional prediction in Figure 2.

Functionally, the regional predictive framework (Figure 2) uses slope to discriminate LSU 3 from LSU 2 soils, and airborne radiometric K% to discriminate LSU 3 from LSU 4 soils. In the LSU 3 areas, TWI drainage thresholds further discriminate between salt accumulation and salt flushing zones (i.e., LSU 3 shallow NAS vs. non-shallow NAS). Profile curvature is used to filter out convex landscape positions (e.g., crests and ridges) in LSU 3 areas.
Table 1: Summary of methods showing survey and analytical techniques used, their scale and mode of application, and key references.

<table>
<thead>
<tr>
<th>Method</th>
<th>Instrument/ technique</th>
<th>Application</th>
<th>Potential soil-landscape attributes derived</th>
<th>Limits (m)</th>
<th>Key references</th>
<th>Application scale</th>
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</thead>
<tbody>
<tr>
<td>Electromagnetic induction (EMI)</td>
<td>EM38 Electromagnetic induction of soil-regolith profile; on foot, field-based</td>
<td>Combined soil profile salinity, texture and moisture; &lt;1.5 m</td>
<td>Apparent EC (EC_a; dS/m)</td>
<td>As above, plus including regolith and bedrock &gt;6m</td>
<td>(Meneill 1980; Suduth et al. 2001)</td>
<td>Regional (2,300 ha)</td>
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<td></td>
<td>EM31</td>
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<tr>
<td>Magnetic susceptibility</td>
<td>Bartington ME2B, dual frequency sensor</td>
<td>Mass magnetic susceptibility of soil layers; laboratory-based</td>
<td>Magnetic iron oxides [magnetite (α - Fe_3O_4) and pedogenic maghemite (γ - Fe_3O_4)]; soil-landscape/pedogenic processes, especially local wetting/drying conditions, leaching, burning</td>
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<td></td>
<td>Bartington ME2E, loop sensor</td>
<td>&quot;Bulked&quot; surface volume magnetic susceptibility (&lt; few cm^3); on foot</td>
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<td></td>
<td>Bartington ME2F, probe sensor</td>
<td>High spatial resolution surface volume magnetic susceptibility (&lt; few cm^3); on foot</td>
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<td>Gamma radiometrics</td>
<td>Regional airborne survey</td>
<td>Regional geochemical image of topsoil (K, Th, U, total count); GIS</td>
<td>Regional/toposequence soil-landscape process; mineral weathering; mineralogy; soil types</td>
<td>% (K), ppm (Th, U and total count)</td>
<td>(Dickson and Scott 1997; Minty 1997; Wilford et al. 1997)</td>
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<td></td>
<td>GR-320 spectral radiometer</td>
<td>High spatial resolution geochemical survey of topsoil (K, Th, U, total count); on foot</td>
<td>Soil-landscape processes; geochemical weathering history; local geochemical patterns</td>
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<td>Physico-chemical analysis</td>
<td>Extractive / digestive physico-chemical analysis</td>
<td>Multiple (&gt;30) analyses; accurate</td>
<td>Soil chemistry, soil physical measurements; multiple other attributes</td>
<td>Various</td>
<td>(Rayment and Higginson 1992)</td>
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<td></td>
<td>Mid Infrared (MIR) analysis</td>
<td>Multiple (&gt;30) analyses; predictive, low cost, rapid</td>
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<td></td>
<td>X-ray diffraction (XRD)</td>
<td>X-ray diffraction; accurate fine texturing</td>
<td>Clay mineralogy</td>
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<td>Digital terrain analysis</td>
<td>Aerial photographs; digital elevation models (DEMs)</td>
<td>Terrain attributes; soil-landscape methodology; 3D GIS overlays</td>
<td>Slope; curvature; terrain wetness index (TWI); terrain based 3D renderings</td>
<td>GIS raster</td>
<td>(Burrough and McDonnell 2000; Wilson and Gallant 2000)</td>
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<td>Soil-landscape survey</td>
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<td>Soil-landscape processes; farm planning</td>
<td>GIS vector</td>
<td>(Medonald et al. 1998; Schoeneberger et al. 2002)</td>
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<td></td>
<td>Soil survey method</td>
<td>Soil classification; soil-landscape methodology; soil mapping</td>
<td>Pedogenic processes; soil hydrology; land capability; soil mapping; multiple soil-landscape properties, field texture, etc…</td>
<td>Models; GIS raster</td>
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Validation of the LSU shallow NAS/non-shallow NAS predictions was undertaken using soil profile data from the point (profile) scale investigations from LSU 3 predicted areas. Figure 4 shows these, in which EC_a is plotted against depth. Here, 5 profiles from shallow NAS predicted areas (dotted lines), and 6 from non-shallow NAS predicted areas (solid lines) are plotted. The box inside the graph ("shallow NAS-affected soil profile zone") defines shallow NAS soils according to soil depth/EC_a thresholds (Fitzpatrick et al. in prep.). All profiles that intersect this box are shallow NAS-affected soils.

Figure 4 shows that all profiles from shallow NAS predicted areas (solid lines) intersect with the box, thus all have been correctly classified. All except for one profile from non-shallow NAS predicted areas (dotted) do not intersect with the box, making all except for one correctly classified as non-shallow NAS.
Of the 2,300 ha regional study area, the regional predictive methodology classified 40% (744 ha) as being LSU 3 soils. Of this area, 75% of the area (654 ha) was classified as shallow NAS and 25% (190 ha) as non-shallow NAS.

**Figure 4:** Profiles from plot scale investigations from LSU 3 shallow NAS predicted areas (solid lines) and profiles from LSU 3 non-NAS predicted areas (dotted lines) are plotted.

**CONCLUSIONS**

We have drawn together the themes of three papers in preparation, which, when combined, document the steps involved in the development of a GIS based regional methodology to predict shallow NAS. We have demonstrated the links between multiscale investigations to develop an explanatory CTM that highlights shallow NAS processes (e.g., salt/solute flows). In turn the explanatory CTM was used to develop a GIS-based framework for regional shallow NAS spatial predictions. The regional methodology is based on easy-to-acquire, cost-effective GIS coverages (DEM and regional airborne radiometric K%). Using this predictive methodology we show that, of the selected 2,300 ha high value farming region, approximately 30% (i.e., 75% of LSU 3 soils) is affected by shallow NAS.

New insights have been gained into the role of soil-landscape factors, like regional landform and drainage patterns, in governing the distribution of shallow NAS patterns at the toposequence scale. We have also demonstrated the value of combining, through GIS-based 3D terrain techniques, multiple: (i) geophysical surveys (e.g., terrain, EMI and κ); (ii) detailed field and laboratory data; (iii) airborne radiometric K%; and, (iv) terrain modelling in developing soil-landscape models that underpin digital soil mapping methods that are likely to support farming decisions in landscapes with complex soil patterns.

Further work will investigate how our regional methodology to predict shallow NAS can be adapted for another high value farming area in a higher rainfall zone in South Australia.

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**REFERENCES**


CSIRO, Adelaide.


