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

Mark Thomas[1], Rob W. Fitzpatrick[2] & Graham S. Heinson[3]

[1]CRC LEME, University of Adelaide and South Australian Department for Water, Land and Biodiversity Conservation, PMB 2, Glen Osmond, SA, 5064
[2]CRC LEME, CSIRO Land and Water, PMB 2, Glen Osmond, SA, 5064
[3]CRC 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 $EC_{se}$), in the solum (i.e., A and B-horizons, typically < 1.2 m deep). In Australia, soils with ESP $\geq$ 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 $EC_{se}$ values (i.e. $\geq$ 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$1,330 million of farm income is lost annually through shallow NAS in Australia. More locally, in the Northern Agricultural District (NAD) (302,000 ha) of South Australia, subsoil (i.e., 0.3-1.2 m) salts are a widespread problem. According to 1:100,000 scale State-wide soil mapping (Soil and Land Information 2002), > 15% of the NAD soils are affected by salinity ($EC_{se} \geq 2$ dS/m) and > 60% by sodicity (ESP $\geq$ 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 cli-mate. The predominant agricultural land use in the area involves wheat, barley, canola and sheep grazing rotations.

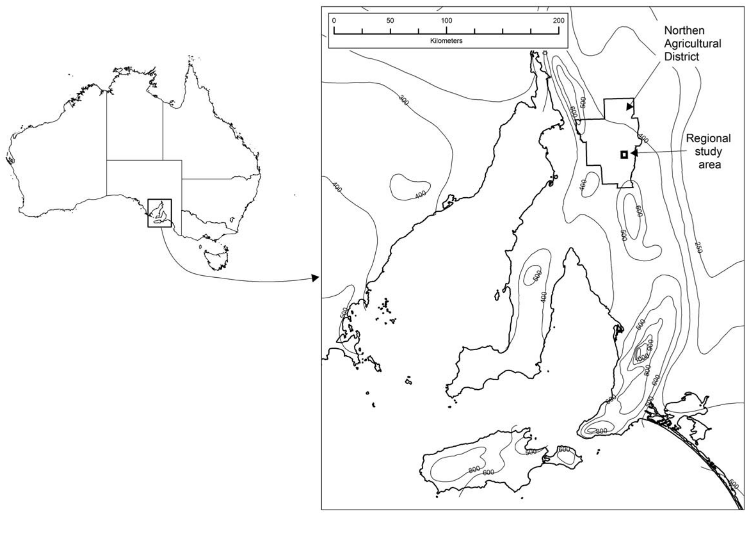


**Figure 1:** Map showing location of regional study area in Australia, featuring South Australia's Northern Agricultural District and rainfall zones.

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 $m^2$) 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 assesses/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 $m^2$) 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 $m^2$) investigations*

At plot scale (100 $m^2$), 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 $EC_{se}$, 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 ($EC_{se}$ 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 ($EC_{se}$ 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.

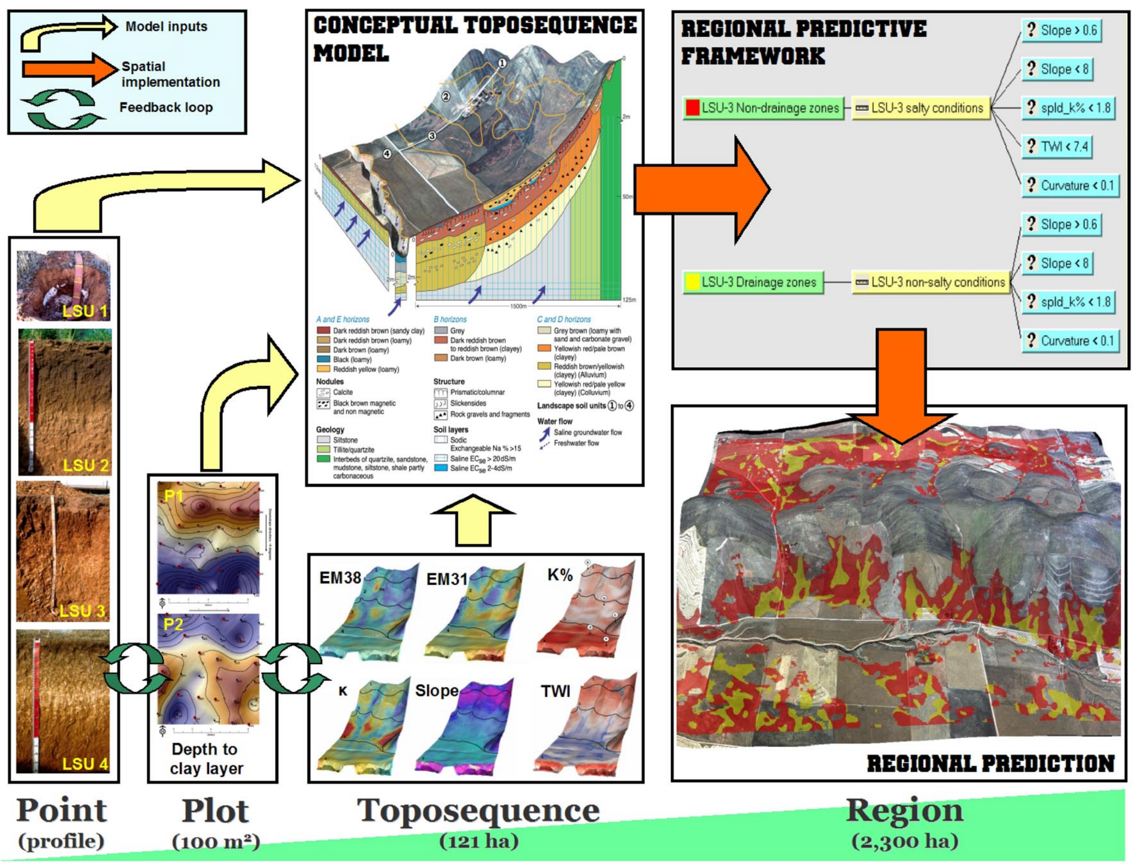


**Figure 2:** Links between point, plot and toposequence scale investigations and the construction of the *explanatory* CTM. The regional predictive framework shows the numeric thresholds for the GIS prediction. The regional predictions for shallow NAS (red areas)/non-shallow NAS (yellow areas) in LSU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

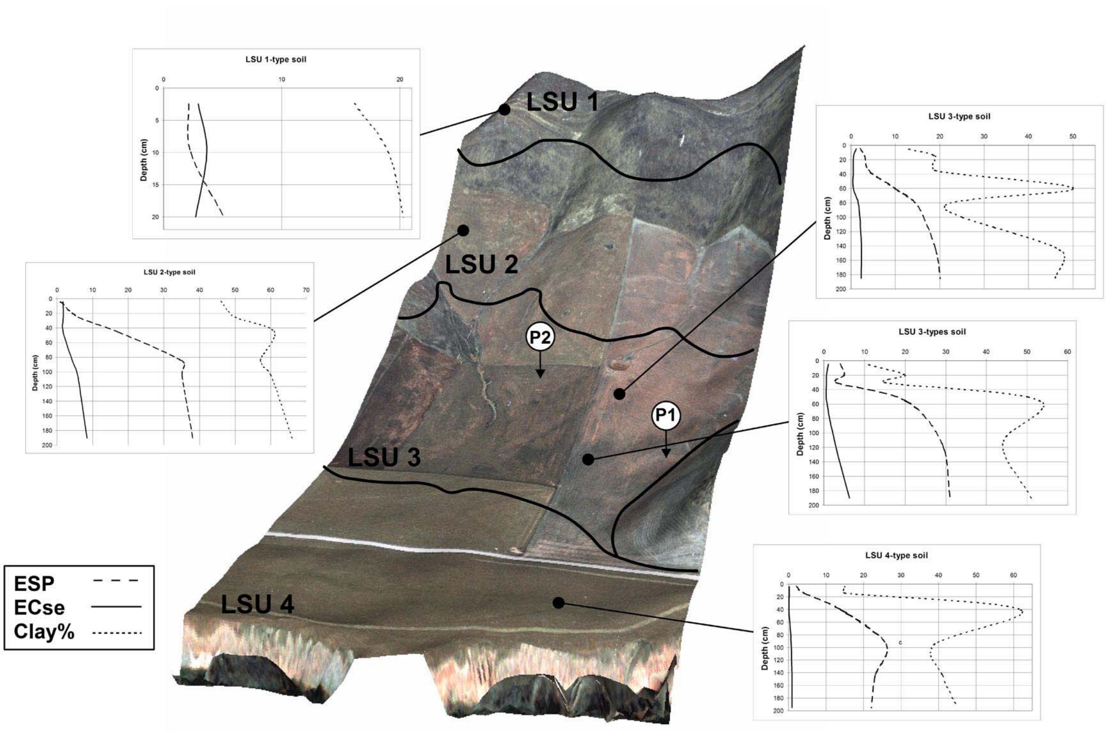


**Figure 3:** 3D aerial photo drape of the toposequence area with landscape soil unit boundaries, selected profile datasets showing ESP, $EC_{se}$ and clay% by depth, and P1 and P2 sites indicated.

**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.

| Method | Instrument/ technique | Application | Potential soil-landscape attributes derived | Units / type | Key references | Application scale: Point (profile) | Plot (100 $m^2$) | Toposequence (121 ha) | Regional (2,300 ha) |
|---|---|---|---|---|---|---|---|---|---|
| Electromagnetic induction (EMI) | EM38 | Electromagnetic induction of soil-regolith profile; on foot, field-based | Combined soil profile salinity, texture and moisture; <1.5 m | Apparent EC ($EC_a$; dS/m) | (Mcneill 1980; Sudduth *et al.* 2001) | | • | • | |
| | EM31 | | As above, plus including regolith and bedrock >6m | | | | | • | |
| Magnetic susceptibility | Bartington ME2B, dual frequency sensor | Mass magnetic susceptibility of soil layers; laboratory-based | Magnetic iron oxides [magnetite ($\alpha$ - $Fe_2O_3$) and pedogenic maghemite ($\gamma$ - $Fe_2O_3$)]; soil-landscape/pedogenic processes, especially local wetting/drying conditions, leaching, burning | $\chi$ | (Dearing 1999; Evans and Heller 2003) | | • | | |
| | Bartington ME2E, loop sensor | "Bulked" surface volume magnetic susceptibility (< few cm's); on foot | | $\kappa$ | | | • | • | |
| | Bartington ME2F, probe sensor | High spatial resolution surface volume magnetic susceptibility (< few cm's); on foot | | | | | • | | |
| Gamma radiometrics | Regional airborne survey | Regional geochemical image of topsoil (K, Th, U, total count); GIS | Regional/toposequence soil-landscape process; mineral weathering; mineralogy; soil types | % (K), ppm (Th, U and total count) | (Dickson and Scott 1997; Minty 1997; Wilford *et al.* 1997) | | | • | • |
| | GR-320 spectral radiometer | High spatial resolution geochemical survey of topsoil (K, Th, U, total count); on foot | Soil-landscape processes; geochemical weathering history; local geochemical patterns | | | | | • | |
| Physico-chemical analysis | Extractive / digestive physico-chemical analysis | Multiple (>30) analyses; accurate | Soil chemistry, soil physical measurements; multiple other attributes | Various | (Rayment and Higginson 1992) | • | • | • | • |
| | Mid Infrared (MIR) analysis | Multiple (>30) analyses; predictive, low cost, rapid | | | (Janik *et al.* 1998) | | • | | |
| | X-ray diffraction (XRD) | X-ray diffraction; accurate fine texturing | Clay mineralogy | | (Olson *et al.* 2000) | • | | • | |
| Digital terrain analysis | Aerial photographs; digital elevation models (DEMs) | Terrain attributes; soil-landscape methodology; 3D GIS overlays | Slope; curvature; terrain wetness index (TWI); terrain based 3D renderings | GIS raster | (Burrough and Mcdonnell 2000; Wilson and Gallant 2000) | • | | • | • |
| Soil-landscape survey | Yield map | Yield | Soil-landscape processes; farm planning | GIS vector | (Mcdonald *et al.* 1998; Schoeneberger *et al.* 2002) | | • | • | |
| | Soil survey method | Soil classification; soil-landscape methodology; soil mapping | Pedogenic processes; soil hydrology; land capability; soil mapping; multiple soil-landscape properties, field texture, etc… | Models; GIS raster | | • | • | • | • |

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 $EC_{se}$ 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/$EC_{se}$ 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.

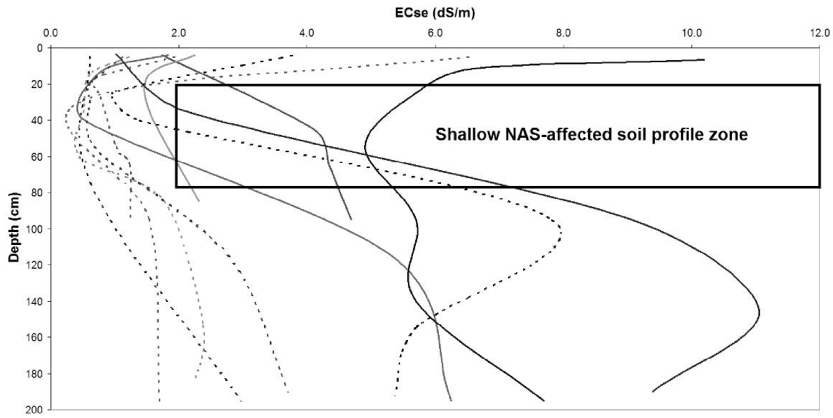


**Figure 4:** Profiles from plot scale investigations from LSU 3 shallow NAS predicted areas (solid lines) and profiles from LSU 3 non-NAS predicted areas (dotted lines) are plotted.

## 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.

Acknowledgements: We acknowledge the Cootes and Ashby families for access to their farmland.

## REFERENCES

BURROUGH P.A. & MCDONNELL R.A. 2000. *Principles of Geographical Information Systems*. Oxford University Press Inc., New York.

DEARING J.A. 1999. Magnetic Susceptibility. *In:* WALDEN J., OLDFIELD F. & SMITH J. eds. *Environmental Magnetism; a practical guide.* Quaternary Research Association, London, pp. 35-62.

DICKSON B.L. & SCOTT K.M. 1997. Interpretation of aerial gamma-ray surveys - adding the geochemical factors. *AGSO Journal of Australian Geology & Geophysics* **17**, 187-200.

EVANS M.E. & HELLER F. 2003. *Environmental Magnetism: Principles and Applications of Enviromagnetics*. Academic Press, Burlington, Massachusetts.

FITZPATRICK R.W. & MERRY R.H. 2002. Soil-regolith models of soil-water landscape degradation: development and application. *In:* MCVICAR T.R., RUI L., FITZPATRICK R.W. & CHANGMING L. eds. *Regional water and soil assessment for managing sustainable agriculture in China and Australia.* Australian Centre for International Agricultural Research, Canberra, pp. 130-138.

FITZPATRICK R.W., THOMAS M., DAVIES P.J. & WILLIAMS B.G. 2003. Dry saline land: an investigation using ground-based geophysics, soil survey and spatial methods near Jamestown, South Australia.

CSIRO, Adelaide.
FITZPATRICK R.W., THOMAS M. & RENGASAMY P. in prep. Non-groundwater associated salinity (NAS) in an area of complex soil patterns in South Australia: Definitions and generic soil-landscape models.
FRITSCH E. & FITZPATRICK R.W. 1994. Interpretation of soil features produced by ancient and modern processes in degraded landscapes. I. A new method for constructing conceptual soil-water-landscape models. *Australian Journal of Soil Research* **32**, 889-907.
JANIK L.J., MERRY R.H. & SKJEMSTAD J.O. 1998. Can mid infrared diffuse reflectance analysis replace soil extractions? *Australian Journal of Experimental Agriculture* **38**, 681-696.
MCDONALD R.C., ISBELL R.F., SPEIGHT J.G., WALKER J. & HOPKINS M.S. 1998. *Australian soil and survey handbook*. Australian Collaborative Land Evaluation Program, Canberra.
MCNEILL J.D. 1980. *Electrical conductivity of soils and rocks*. Geonics Ltd., Ontario, pp. 22.
MINTY B.R.S. 1997. Fundamentals of airborne gamma-ray spectrometry. *AGSO Journal of Australian Geology & Geophysics* **17**, 39-50.
OLSON C.G., THOMPSON M.L. & WILSON M.A. 2000. Phyllosilicates. *In:* SUMNER M.E. ed. *Handbook of Soil Science*. CRC Press, Boca Raton, Florida, pp. F77-F123.
RAYMENT G.E. & HIGGINSON F.R. 1992. *Australian laboratory handbook of soil and water chemical methods.* Inkata Press, Melbourne.
RENGASAMY P. 2002. Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Australian Journal of Experimental Agriculture* **42**, 351 - 361.
RENGASAMY P. & CHURCHMAN G.J. 1999. Cation exchange capacity, exchange cations and sodicity. *In:* PEVERILL K.I., SPARROW L.A. & REUTER D.J. eds. *Soil analysis: an interpretation manual*. CSIRO Publishing, Collingwood, Victoria, pp. 147157.
SCHOENEBERGER P.J., WYSOCKI D.A., BENHAM E.C. & BRODERSON W.D. 2002. *Fieldbook for describing and sampling soils*. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE., USA.
SOIL AND LAND INFORMATION 2002. *Land Resource Information - Northern Agricultural Districts of South Australia*. SaLI Group, The Department of Water, Land and Biodiversity Conservation, Adelaide, South Australia.
SOIL SURVEY DIVISION STAFF 1993. *Soil survey manual*. U.S. Government Printing Office, Washington.
SUDDUTH K.A., DRUMMOND S.T. & KITCHEN N.R. 2001. Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. *Computers and Electronics in Agriculture* **31**, 239-264.
THOMAS M., FITZPATRICK R.W. & HEINSON G.S. 2003. Mapping complex soil-landscape patterns using radiometric K%: a dry saline land farming area case study near Jamestown, SA. In: ROACH I.C. ed. *Advances in Regolith*. CRC LEME, pp. 411-416.
THOMAS M., FITZPATRICK R.W. & HEINSON G.S. in prep.-a. *Dry saline land in an area of complex soil patterns in South Australia: Identification and variability at plot and toposequence scales*.
THOMAS M., FITZPATRICK R.W. & HEINSON G.S. in prep.-b. *Dry saline land in an area of complex soil patterns in South Australia: Identification and variability at regional scales*.
WILFORD J.R., BIERWIRTH P.N. & CRAIG M.A. 1997. Application of airborne gamma-ray spectrometry in soil/regolith mapping and applied geomorphology. *AGSO Journal of Australian Geology & Geophysics* **17**, 201 - 216.
WILSON J.P. & GALLANT J.C. 2000. Digital terrain analysis. *In:* WILSON J.P. & GALLANT J.C. eds. *Terrain analysis: principles and applications*. John Wiley & Sons Inc., New York, pp. 1-27.