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Regional Prediction of Soil Profile Acidity and Alkalinity

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Abstract

The Mount Lofty Ranges lie northeast of Adelaide, South Australia. Soils in the region are being degraded through soil acidification and alkalinisation, and the development of both potential and actual acid sulfate soils. These processes affect agricultural production and water quality. Soil testing and survey work in the area have shown significant acidification of acid sulfate and salt-affected soils in subcatchments. The spatial extent of these degraded soils has not been examined previously.

We have developed a method to determine the spatial distribution of soils with differing acidity and alkalinity (pH profiles) over an 80 km² region. The method involves using data from point, toposquence and subcatchment scales to develop simple mechanistic models and a geographic information system. We predicted soil profile pH classes for the 80 km² region and used these to plan the management of degraded soils. The data were also used as a soil degradation indicator for assessment of landscape quality at catchment and regional scale.

在阿德莱德东北方的劳伏特山区，土地的酸化和碱化以及硫酸性土壤的出现，影响水质和农作物产量。土壤分析与调查表明，该地区次级流域硫酸盐土壤和盐化土壤的酸化作用明显，不过，这些退化土壤的规模还未测定。我们采用一种方法来测量大范围（80平方公里）土地上不同酸碱度（pH值）土壤的空间分布。该方法采用收集到的点、坡面和次级流域不同尺度的数据，生成简单的机械模型和一个地理信息系统，预测了80平方公里内土壤的pH值等级，并以此制定退化土地的治理方案。该数据也作为土壤退化指标，用在流域和区域规模的景观质量评价工作中。

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THE UNDULATING, hilly landscape of the Mount Lofty Ranges, northeast of Adelaide, South Australia, supports agriculture ranging from extensive grazing to viticulture. A variety of soil and groundwater processes contribute to the development of soil acidity and alkalinity in the region. This soil degradation often occurs in specific parts of the landscape and is influenced by agricultural practices. For example, grazing and cropping of middle and upper slopes can lead to acidification in the upper parts of the soil profile. Alkaline, saline or sulfidic groundwaters can affect soil alkalinity and cause potential and actual acid-sulfate soils on lower slopes and valley floors. The chemistry and mineralogy of parent materials, especially Quaternary valley sediments and Cambrian metasediments containing pyrite, can also potentially influence soil acidity and alkalinity.

The objective of this study was to use mechanistic models and geographic information systems (GIS) to understand and predict spatially the processes that control soil profile pH in this landscape at point, toposquence, catchment and regional scales (80 km²). The main aim was to better identify and manage those parts of the landscape where water quality may be degraded or where soil acidification could be remediated by liming.

Materials and Methods

The study area

Initial work was based on the soil sampling and fieldwork of Fritsch and Fitzpatrick (1994). We took field samples, principally in the Herrmann subcatchment (139° 01' E; 34° 53' S; area about 2 km²) near Mount Torrens, about 50 km northeast of Adelaide. Sampling was also extended into the surrounding 80 km². We used the Herrmann subcatchment, with its detailed toposquences, to trial models designed to predict soil profile acidity and alkalinity over the broader region. Figure 1 of Chapter 21 shows the location of the areas concerned. The Overview provides some

background information about the region; Figures 2 and 5 of the Overview show its location.

Landscape, soils and agriculture

Much of the study area comprises undulating low hills with altitudes of 400–500 m and local relief about 30–50 m (Fig. 1). The climate of the area is Mediterranean, with a pronounced maximum rainfall in winter (May to August) and hot, dry summers (December to February). Annual rainfall is topographically controlled; it decreases from southwest to northeast across the region, from about 700 mm to 550 mm. Stream channels have a normal tributary pattern and mostly erode soils, bedrock or the alluvial soils and sediments of valley floors, sometimes to depths of 2–3 m. The Herrmann subcatchment drains to the east into the Murray River system. The larger 80 km² area contains a drainage divide with about one-third draining to the west to the Torrens River system and the remainder to the east, to the Murray River system. Subcatchments vary in size from 2 to 5 km².



Figure 1. Undulating, hilly landscape of the study area, with eroding streamlines, perched wetlands (centre), sheep camps among groups of trees and agriculture that is mainly grazing and cropping on mid-slopes.

Soils of the middle and upper slopes in the study area mainly have sandy and loamy A horizons overlying clayey B horizons (Palexeralfs). Lower slopes, terraces and valley floors frequently have sodic (Natrixeralfs) and alluvial soils (Entisols), and wet soils (Aquents) in groundwater discharge areas with perched wetlands. Soils of the groundwater discharge areas are frequently saline and sulfidic—these are potential acid sulfate soils (Fitzpatrick et al. 1996). After oxidation of the sulfidic materials,

such soils become acid sulfate soils that contribute to degraded water quality through leakage of salts and acid weathering products. The clayey B horizons of sodic soils that have developed in areas where saline groundwater discharge has occurred often disperse and erode.

Land use in this area is predominantly sheep or cattle grazing on pasture. Increasingly, land is being used for more intensive purposes such as viticulture and cereal cropping. Commercial pine plantations have been established in areas of the Torrens River catchment, which is an important source of urban water supply.

Field soil sampling and mapping

Soil samples were obtained for three purposes:

- to establish boundaries for conventional soil mapping, using initial profile samples from toposequences within the Herrmann subcatchment and free sampling, largely as reported by Fritsch and Fitzpatrick (1994);
- to better characterise pH profiles that occur at specific points in the landscape that are subject to known acidification or alkalisiation processes, using samples principally obtained from the Herrmann catchment; and
- to provide verification data for the predicted soil profile pH classes across the broader, 80 km² area, mainly using archived samples from previous field projects of CSIRO Land and Water (formerly the Division of Soils).

Using these samples, we produced sets of nested study areas that included georeferenced soil pH values at points and in toposequences. Georeferencing was mainly achieved using a global positioning system with positional accuracy of about 5 m. However, the sites from which the archived soil samples were obtained had been located on 1:50,000 topographic maps with cadastral overlay positioning; thus, they could only be accurate to within 50 to 150 m.

Soil pH analysis and profile classes

Soil pH was measured by standard procedures (Rayment and Higginson 1992), using a 1:5 soil to water suspension (pH_w).

As a basis for prediction across the broader region, nine soil acidity and alkalinity profile classes were established initially. The classes were then simplified to five categories, matching the profile classes known to occur in the catchment area. Solum (A and B horizons) depths of about 1 m were considered, or less where profiles were shallow. The classes were constructed along the lines of Northcote's 'soil reaction trends' (Northcote 1979), with modifications to separate potential and actual acid sulfate soils. The simplification was based on the profile classes found in topographic sequences or related to a specific topographic position within the Herrmann subcatchment.

In practice, some similar profiles proved to be difficult to discriminate and were therefore combined. The final classification, described below, clearly indicates soils in need of remediation or protection from degradation. However, the neutral, moderately acidic and moderately alkaline classes are still difficult to distinguish because of poor pH buffering and their susceptibility to change as a result of agricultural practices. There are other classes in the 80 km² area, but they were not included because the basis for prediction was restricted to the most common classes in the region.

The five profile pH classes used for broad-scale prediction are listed below.

- *Class a.* Alkaline (pH_w > 7.5) or neutral (pH_w 6.5–7.5) throughout and associated with lower slopes and valley floors. This class contains both potential and actual acid sulfate soils that are associated with waterlogged or groundwater discharge areas and may be prone to erosion if vegetation is lost. If denuded, these soils may develop high sodicity, salinity and bulk density.

- *Class b.* Moderately acidic surface ($\text{pH}_w < 6.5$), neutral or alkaline in the subsoil. This class includes soils affected by subsoil sodicity and alkalinity, which are prone to clay dispersion, salinity and gully erosion.
- *Class c.* Neutral ($\text{pH}_w 6.5\text{--}7.5$) throughout. These soils were commonly shallower than 1 m and little affected by degradation or agricultural development.
- *Class d.* Moderately acidic ($\text{pH}_w < 6.5$) throughout. These soils were typically Palexeralfs of middle and upper slopes; they may be more acidic in the upper 10–20 cm due to agriculture and may be underlain by very acidic saprolite.
- *Class e.* Very acidic ($\text{pH}_w < \text{about } 5$) throughout most of the profile. This class is similar to Class d, but is considerably more acidic and likely to limit agricultural production through aluminium toxicity and nutrient deficiency. Liming of these soils should be considered a priority.

Figure 2 shows some typical pH profiles from the Herrmann subcatchment.

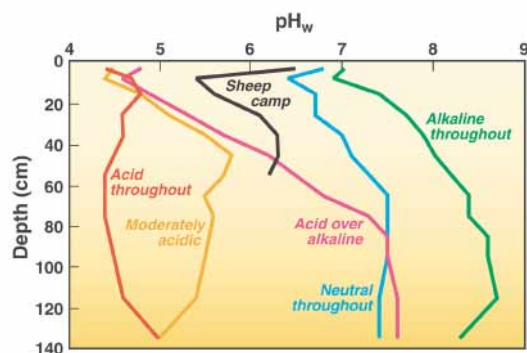


Figure 2. pH_w profile types found in the Herrmann catchment.

Spatial relationships

We used point data for profiles, hydrology and elevation to develop toposequences that were spatially matched with conventional soil maps for

both a detailed (0.2 km^2) key area within the northeastern part of the Herrmann subcatchment and the subcatchment itself. The toposequence shown in Figure 3 illustrates the topographic relationships between soil pH profile and position in the landscape—the upper slope positions have acidic soil profiles and the lower slopes and valley floors have neutral and alkaline soil profiles. The pedological processes known to be operating in the area are long-term weathering and agricultural acidification on the middle and upper slopes; and salinity, alkalinisation, sodification and development of saline and acid sulfate soils on the lower slopes (Fritsch and Fitzpatrick 1994; Fitzpatrick et al. 1996). Conventional mapping units were allocated to the appropriate pH class using both point and toposequence information, as shown in Figure 4 for the Herrmann subcatchment. These ‘nested’ maps and toposequences were then used to develop relationships as a basis for GIS prediction of soil pH profile over the 80 km^2 .

The principal toposequence types were constructed from soil data at point sites; hydrology and elevation data; and structural analysis (Fritsch and Fitzpatrick 1994). Using the point data, linear weighted index models were derived for each of the different scales or areas of interest—subcatchment key area, subcatchment or region—depending on the availability of GIS data, as outlined below. We developed smaller scale, linear weighted models using data for the detailed parts of the catchment that were not available over the whole region.

The data used to develop the models and maps at the different scales are listed below (see also Fitzpatrick et al. 1999 for further detail).

- *Key area scale (0.2 km^2).* Data were vegetation class maps developed from air photos and forward-looking infrared (FLIR) remote sensing, digital elevation models (DEMs) and soil mapping (not shown, see Fitzpatrick et al. 1999 and Chapter 21, this volume).

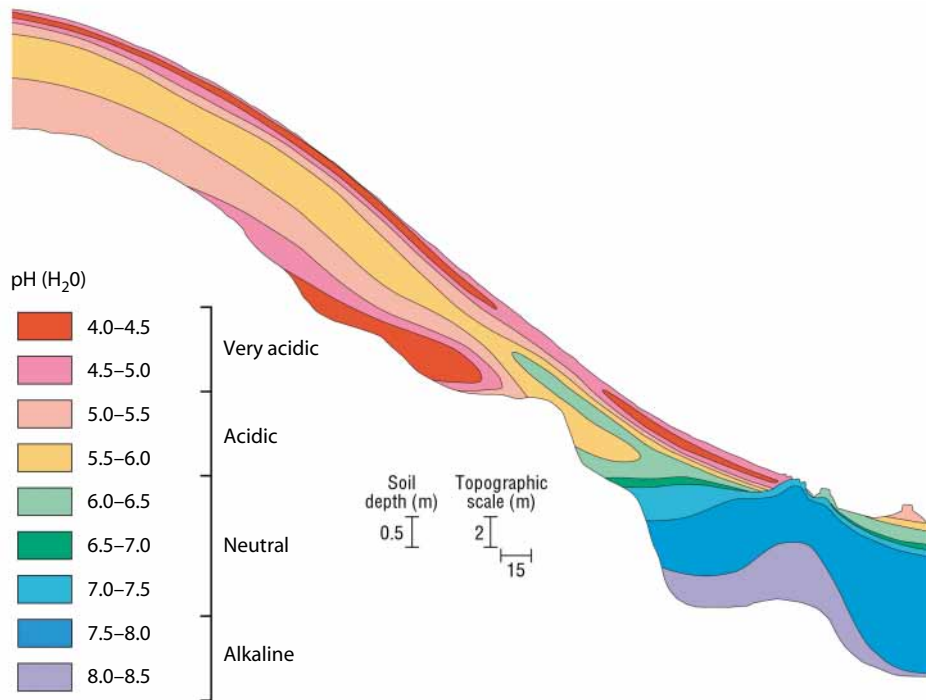


Figure 3. Acidity and alkalinity of soil layers along a typical toposequence from the Herrmann catchment.

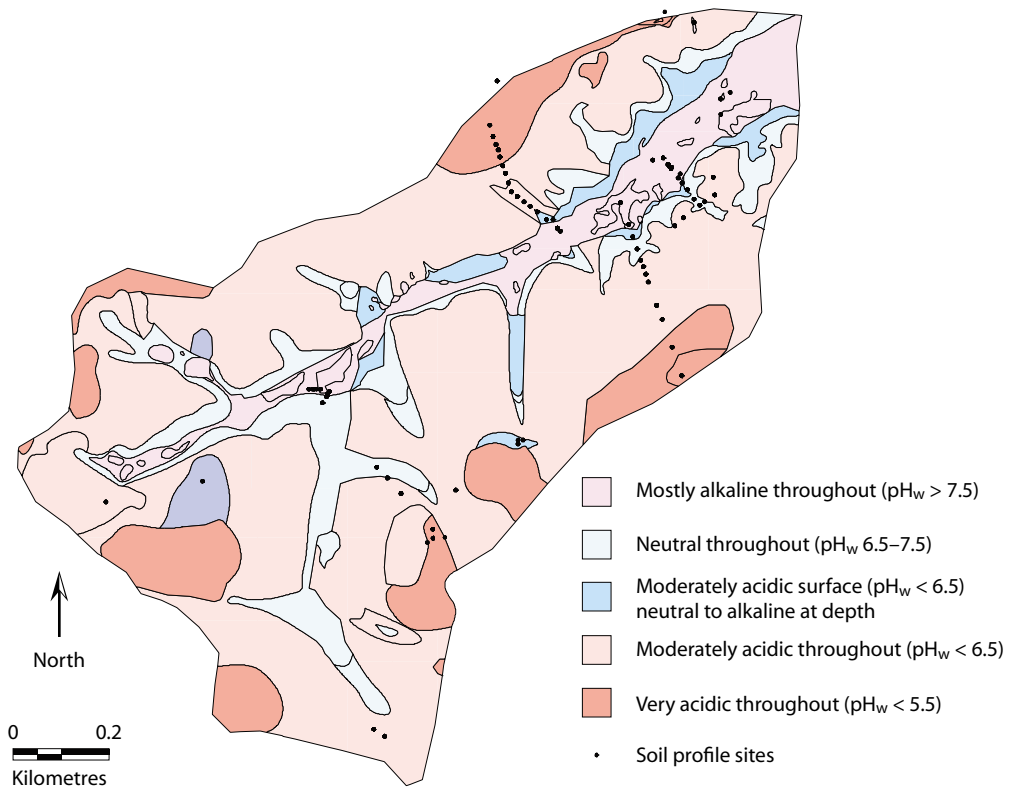


Figure 4. Conventional soil map of the Herrmann catchment (2 km²) with soil units allocated to soil profile pH_w classes. Some point sample and toposequence locations are marked.

- *Subcatchment scale (2 km²)*. Two maps of soil pH class were developed at subcatchment scale (Figs 4 and 5). The map shown in Figure 4 was developed from conventional soil map boundaries, using toposequence and point pH profile data. Because the most reliable pH class data were obtained from subcatchment scale or below, the linear weight indexing used to model at that scale (Fig. 5) was adjusted for best fit with the conventional map (Fig. 4). The model was developed using a topographic index and land unit mapping of soil acidity classes at the 1:50,000 scale (compiled by D.J. Maschmedt of Primary Industries and Resources, South Australia). The topographic index was derived using the procedure of Hutchinson and Dowling (1992). The index can be represented as $\ln(A_s/\tan \beta)$, where A_s is the specific catchment area and $\tan \beta$ the local slope angle evaluated on a cell-by-cell basis from the DEM. The land unit mapping included both soil type

and geology of the parent material — data that exist for the entire agricultural area of South Australia.

- *Region scale (80 km²)*. The map of the modelled best estimate of soil profile acidity and alkalinity for the larger region (Fig. 6) was generated by extrapolation of the model that produced Figure 5, using the same input data.

Verification of prediction of soil acidity/alkalinity profiles

To verify the models, we used two different approaches. First, because the same models were used to generate maps at the subcatchment and regional scales, we could verify the models to some extent by comparing the distribution of profile classes at the subcatchment scale (Fig. 5) with the conventional soil map (Fig. 4). Table 1 shows the results of this comparison.

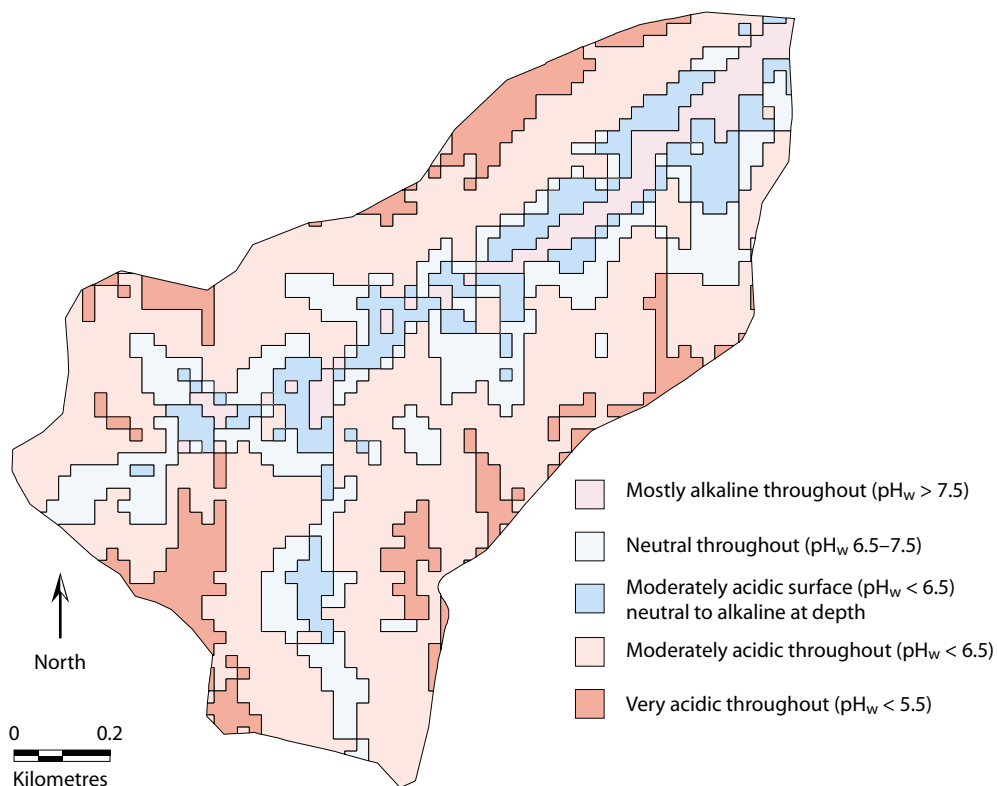


Figure 5. Modelled distribution of soil pH_w profile classes in the Herrmann (2 km²) catchment. The modelling relied heavily on the GIS linear weighting index. Compare the spatial structure of Figure 4 and Figure 5.

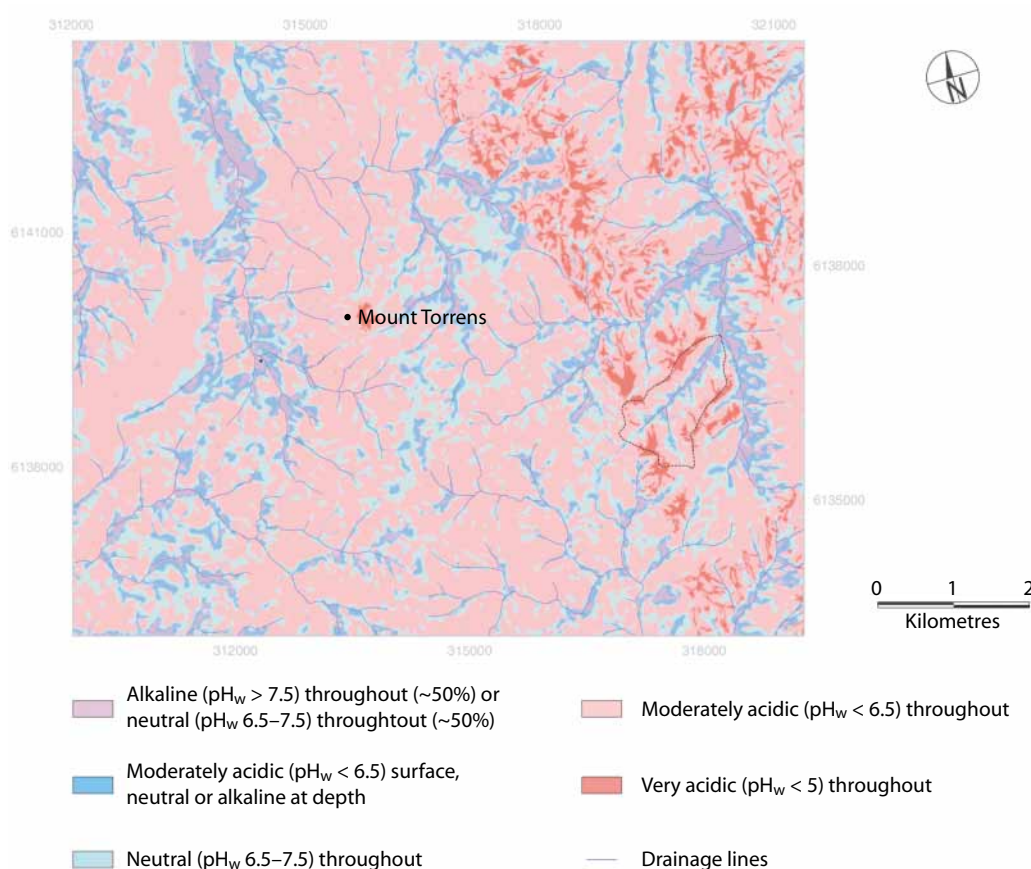


Figure 6. Best estimate of distribution of soil profile acidity and alkalinity classes for the 80 km² study region.

In the second approach, we collated archived data for 35 soil profiles with data for five profiles sampled as part of this project. Because the archived data were from sites georeferenced from a 1:50,000 scale topographic map, the positional accuracy is likely to be lower than the data collected for this project. Therefore, we drew a circle of scaled radius 100 m on the modelled regional map (Fig. 6), centred on the location obtained from the topographic map, and compared the classes that we predicted would occur within that circle with the profile used for verification.

Results and Discussion

Soil pH profiles and processes

Soils of the slopes and crests usually showed strong acidification in their A horizons (e.g. Fig. 2). This acidification is due to normal agricultural processes

such as nitrate leaching of legume-fixed or fertiliser nitrogen, and removal of alkaline products such as hay, fodder or cereal grain. In samples taken to verify predictions in areas with sheep camps, we found that profiles were more alkaline than adjacent, moderately acidic soil profiles. This effect occurs because sheep camps, which are frequently located on or near hill crests, are the source of substantial alkaline input into the soil and thus result in near-neutral surface soils overlying acidic subsoils (Fig. 2). However, we did not include the location of sheep camps in our predictions because camps are not always related to particular features of the landscape or vegetation. Although terrain, remote sensing and vegetation analysis can identify sheep camps, such an exercise is probably not warranted because the aggregate area of the camps is quite small and they can be managed at a farm level.

The deeper subsoils in the middle and upper slopes on some parent materials were also highly acidified between 1 and 2 m and into the saprolite, illustrated in Figures 2 and 3. This is believed to result from soil formation on parent materials that contain significant sulfide minerals, either in bands or dispersed through the regolith. Oxidation of these sulfides has resulted in acidic profiles that are strongly weathered. These parent materials have been mapped as the Talisker Calc-Siltstone (containing the Nairne Pyrite Member), the Tapanappa and other unnamed formations of

Table 1. Comparison of areas of modelled soil pH profile classes (Fig. 5) (a to e) for the subcatchment (2 km²) scale with map classes developed from conventional soil mapping (Fig. 4).

Conventional soil mapping	Modelled soil classes	Area (m ²)	Area (%) ^a
Class a (alkaline throughout)	a	52,519	43
	b	41,361	
	c	23,151	
	d	5,045	
	e	18	
Class b (acidic surface, neutral to alkaline at depth)	a	2,866	36
	b	22,404	
	c	14,795	
	d	17,816	
	e	4,670	
Class c (neutral throughout)	a	5,502	36
	b	41,205	
	c	58,949	
	d	59,720	
	e	128	
Class d (moderately acidic throughout)	a	1,840	70
	b	33,780	
	c	146,113	
	d	554,168	
	e	52,512	
Class e (very acidic throughout)	c	1,162	51
	d	84,770	
	e	90,127	

^a Indicates the percentage of the area allocated to a profile class by the model that coincides with the same class allocated from conventional soil mapping

Cambrian age that occur in a broad band in the eastern Mount Lofty Ranges and on Kangaroo Island (Belperio et al. 1998). This pyrite is also the likely source of most of the sulfur of the potential and actual acid sulfate soils found associated with perched and relict wetlands in the study area (Fitzpatrick et al. 1996).

On the lower slopes, soils were frequently alkaline (Fig. 3). The principal cause of alkalinity is the accumulation of sodium salts that results from concentration by evapotranspiration, and the subsequent development of sodic clays. Magnesian calcites are sometimes observed in these valley floor soils; they develop from evaporative concentration from groundwaters, sometimes in wetlands (Fitzpatrick and Merry 1999).

Prediction of pH profile

The GIS-based models were able to predict soil pH profiles at scales useful for land management. Verification indicated that the predictions were acceptable, especially where soils were acidic or alkaline throughout. Although saline, sulfidic soils were contained within Class a soils, their distribution was influenced by proximity to the pyritic parent materials mentioned above. Therefore, it is important to use geological data in the generation of the model at this scale. Soils that are acidic throughout (Class e) and generally in need of lime treatment are clearly associated with the older, more stable and weathered parts of the landscape. They were efficiently predicted using the topographic index and existing land unit maps containing geological information. Similarly, these predictors successfully identified alkaline and sodic soils of lower slopes and valley floors.

For the 80 km² region, the correct class or a neighbouring class was usually predicted. The inclusion of the DEM-based topographic index at this scale allowed us to link pH profile class with topographic position more reliably than by using conventional 1:50,000 acidity-class mapping.

Verification of models

Two approaches were used to verify the models. The first compared the areas of each soil pH profile class provided by the modelled data with the conventionally mapped areas of the Herrmann subcatchment (Table 1). For each conventionally mapped class other than Class c, the soil class predicted by the model was the same as the most common profile type in the mapping unit. For each conventionally mapped class, the next most common class (second in area, apart from Class c) predicted by modelling was always the class most similar to the predominant class. The modelled data were much more closely related to the subtleties of topography than was possible using conventional mapping, and real boundaries are usually continuums rather than sharp breaks. Therefore, the modelled spatial distributions of profile classes are considered more reliable than conventional soil mapping and point sampling.

The second approach of verification involved the comparison of soil profile data from 40 sites distributed across the larger region. A difficulty arose because the historical material used was georeferenced from 1:50,000 topographic maps. Soil pH profile classes were predicted for an area of 100 m radius, centred on the verification site as originally located from a topographic map. Of the 40 sites, 20 were the same class as the most common profile classes predicted for the 100 m radius circle; 11 had the same verification profile as the modelled subdominant class; 5 were in the adjacent class; and 4 were in another minor class. For all verification sites where the locations were approximate, the model always predicted the same pH class within the 100 m radius circle. These data also suggested that the mostly 'alkaline throughout' soil class (Class a) would probably not exist on parent rocks older than Cambrian in the western part of the region. This should be further investigated; if it is found to be true, the predictive model should be modified.

Conclusions

Where toposequence trends in soil profile pH were evident, GIS was able to predict soil profile pH types over relatively large regions with good effectiveness and to highlight those areas requiring specific management. Verification of the predictions indicated that the methodology was useful in identifying very acidic profiles requiring liming programs, or alkaline and sodic profiles requiring gypsum application and drainage management. Related work predicting the location of waterlogged and groundwater discharge areas (Davies et al. 2000) is also important as it helps to identify soils affected by alkaline and saline groundwaters, and potential acid sulfate soils that develop in wetlands. The spatial distributions of these acidic, alkaline and wetland soils are clearly related to topography and the geology of parent materials.

Soils with profile pH values in the moderately acidic, neutral or moderately alkaline range were less well discriminated. The pH values of the upper part of these soil profiles are more likely to be affected by agricultural management because they are usually less well buffered against pH change; they are also less likely to need lime or gypsum application.

Although the process of transfer of alkalinity by stock is well known, we were not aware of the number of sheep camps in this area and the extent to which they were contributing to soil alkalinisation. The sheep camps require farm-level management to preserve soil fertility and conserve remnant vegetation.

The approach to prediction of the properties of soils in landscapes described here is expected to add value to existing land-unit mapping, improve regional planning of management of soil degradation processes and be a useful tool in agricultural extension. Strategic liming of selected parts of catchments has been shown to be effective in their management (see, for example, Adams and Evans 1989) with potential to improve plant and animal productivity and stream water quality.

Acknowledgments

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