Soil-regolith models of soil-water landscape degradation: development and application

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9 Soil–Regolith Models of Soil–Water Landscape Degradation: Development and Application

Rob W. Fitzpatrick* and Richard H. Merry*

Abstract

Soil degradation (salinity, sodicity, waterlogging and acidity) in the high rainfall catchments in the Mount Lofty Ranges and Dundas Tablelands is a growing concern to property holders because of the rapid increase in waterlogged saline scalds. The objective of this study was to develop a systematic approach to constructing soil–regolith models that describe, explain and predict soil–water landscape degradation processes in a specific region.

The 'descriptive model' uses toposequences (soil landscape cross-sections) to describe the basic soil–regolith features and direction of soil water and solute movement. Here, we suggest that it is also necessary to produce models to explain and predict the relationships and behaviour of the soil–regolith system under study. Such models could explain and predict the processes giving rise to the vast range of complex and poorly understood saline, sodic and acid sulfate soils in catchments. Toposequence and catchment scales are the most suitable for constructing such models because each of the vertical and lateral changes can be linked to hydrological, physicochemical and biomineralogical processes.

This chapter describes several case studies that illustrate how the different types of soil–regolith model have been used to describe and predict degradation processes in salt-affected soils and adjacent stream waters, and to assist in generating maps at catchment and regional scales using geographic information systems. They have also been used to produce soil–landscape and vegetation field keys, which provide details of land-use options that can help to prevent the irreversible spread of saline and sodic conditions.

在劳伏特山区和邓达斯高原降水丰富的流域里，土地的快速退化（盐化、碱化、酸化以及渍涝），引起农场主的日益关注。本研究试图系统地构建土壤－风化层模型，以便解释和预报某个特定地区土壤－水分景观退化的过程。该描述性的模型用坡面层次（截面土壤景观）来描述基本的土壤－风

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化层特征，以及土壤水分和溶解物的移动方向。对于被研究的土壤－风化层系统，也有必要建造模型，以便解释和预报其间的关系和变化情况。对于导致流域大量出现复杂，人们了解甚少的盐碱化、酸化土壤的作用过程，这些模型可以作出解释、预报。因为每一个垂直方向或水平方向的变化都与水文、物理化学以及生物矿物过程有关，所以这样的模型最适合为一个坡面或者一个流域而建造。本章给出许多具体的研究实例，以说明不同类型的土壤－地表模型是如何解释、预测盐化土壤及其毗邻河流的退化过程，如何为采用地理信息系统在流域和区域范围制图提供辅助的。这些模型也可为土地保护组织制作野外土壤景观和植被的图例，详细提供土地利用的可能方式，以助于防止盐碱化的不可逆扩展。

FOUR questions frequently asked by the users of land resource information are:

- What soil properties are changing spatially with time?
- What are the most suitable approaches for characterising, monitoring, predicting and managing soil changes?
- What tools are required to make suitable predictions about soil and landscape conditions and sustainable land use?
- To what extent do soil processes and soil management influence water quality?

These four questions can be solved by integrating pedological, hydrological, biogeochemical and mineralogical data to develop various types of models that can identify and predict soil-landscape processes. This information can then be used to underpin and develop strategies for managing both spatial and temporal soil changes. Pedology is an integrative and extrapolative science because it builds an organisational framework to quantify and explain spatial variability within landscapes. It also provides a template, via mechanistic models, to understand biogeochemical processes at regional and global scales. Consequently, pedology provides an excellent framework for the extrapolation of spatial variability from detailed components of soils (hand specimens and horizons) to soil profile, toposequence, catchment, regional and global scales.

The objective of this chapter is to discuss the toposequence approach as a vehicle for presenting results of spatially-based conceptual models that can be used to develop:

- *descriptive models* to assess catchment-scale variability of saline, sodic and acid sulfate soils in order to develop practical solutions for ameliorating soils at farm scale (see Chapter 21);
- *explanatory models* to understand the relationships and behaviour of saline soil processes (including potential saline and acid sulfate soils) that can take into account changes in land management; and
- *predictive models* to predict changes in saline soils caused by drainage (e.g. erosion), which result in development of either sodic or acid sulfate soils.

Materials and Methods

The study area

Initial work was based on soil sampling and fieldwork in the Herrmann subcatchment near Mount Torrens, about 50 km northeast of Adelaide, South Australia (Fritsch and Fitzpatrick 1994). The Overview provides some background on the region and Figure 5 of the Overview shows its location. Figure 1 of Chapter 21 shows the location of the areas concerned. The landscape of much of the study area is undulating low hills; the altitude ranges from 400 to 500 m and local relief from about 30 to 50 m. The climate is Mediterranean, with most rain falling in winter (May to September) and hot, dry summers (December to February).

Soil–regolith models to describe, explain and predict landscape degradation

Salt-affected and waterlogged soils form under different environmental conditions and have diverse morphological, chemical, physical and biological properties. These soils can be grouped based on the types of electrolytes causing the salinity or their chemical and physicochemical properties (Szabolcs 1991). Three main types of characteristics are used:

- salt content, composition and distribution in the profile and (in some cases) also in the groundwater;
- exchangeable sodium percentage and sodium adsorption ratio (sodic soils); and
- pH conditions and the existence of sodium carbonate (alkaline sodic and saline soils).

Of all the continents, Australia has the highest proportion of salt-affected soils in relation to total surface area (Szabolcs 1991). Sodic and saline soils occupy almost 2 million and 0.39 million km^2, respectively (Northcote and Skene 1972). The sodic:saline ratio of 5.17 is 4.4–10.3 times that reported for other continents, and is consistent with the high proportion of sodium present in soil solutions and groundwaters. In Australia, most sodium-affected soils are the result of past inundations by brackish water, possibly supplemented by cyclic salt. The result is that in subsoils, Cl^- is the dominant anion and exchangeable Mg^{2+}:Ca^{2+} ratios are high.

The effects of adsorbed Na^+ on clay dispersion are most pronounced in the B horizon of dense alkaline subsoils, which comprise over 86% of Australian sodic soils (Northcote and Skene 1972). The impact of soil sodicity on the environment is an important land degradation issue in Australia. Both primary and secondary sodification can cause undesirable changes in soil structure, severe hillslope erosion, waterlogging and erosion of downstream watercourses.

Generally speaking, Australian soil-landscapes are extremely variable and complex; this is partly due to the great age of much of the continent. In adjacent landscape positions, one can be confronted with deeply weathered soils that contain ancient stored salt juxtaposed with very youthful soils on partly weathered rocks that are generating salt as a result of contemporary weathering processes. Much work has been done on the hydrogeology of dryland saline areas and soil sodicity, but there is little published material on the development of comprehensive biogeochemical and physical process models of saline and acid sulfate soils. One reason for the lack of data is that, until recently, saline and acid sulfate soils were not considered suitable for agricultural production. There is also little published information on the dynamics of saline, sodic and acid sulfate soils, in particular whether the changes are reversible if saline soils develop into sodic soils after drainage.

Soil–regolith models are a simplification or abstraction of the processes that may occur in a particular toposequence system under study so that the information can be more easily handled either manually or mentally for a specific purpose (e.g. Dijkerman 1974). Several kinds of simplification or abstraction may be used; for example, in creating models that describe, explain or predict particular aspects of soil–regolith processes. Because more than one kind of simplification or abstraction is often used to design models, different models are not necessarily mutally exclusive. Here, we will show that the descriptive model is the precursor or framework for developing the explanatory model, which in turn is used to help develop the predictive model.

A systematic approach to describe topo-sequences: descriptive soil–regolith models

Chapter 21 provides a summary of how we described soils in toposequences and linked these soil-landscape features to the main soil and water processes operating within the landscape via toposequences.

In the toposequence shown in Figure 1, red soils of the middle and upper slopes principally have better drained, sandy and loamy A horizons overlying clayey B horizons (Palexeralfs). Lower slopes, terraces and valley floors frequently have more poorly drained, yellowish sodic (Natrixeralfs) and alluvial soils (Entisols), and wet, grey coloured soils (Aquents) in groundwater discharge areas. Discharge areas frequently support perched wetlands.

Soil colour as a key indicator in developing descriptive soil–regolith models

Soil colour can provide a descriptive indicator of redox status, and this relates to soil aeration, organic matter content and fertility. As described by Fitzpatrick et al. (1999b) and others, indicators of

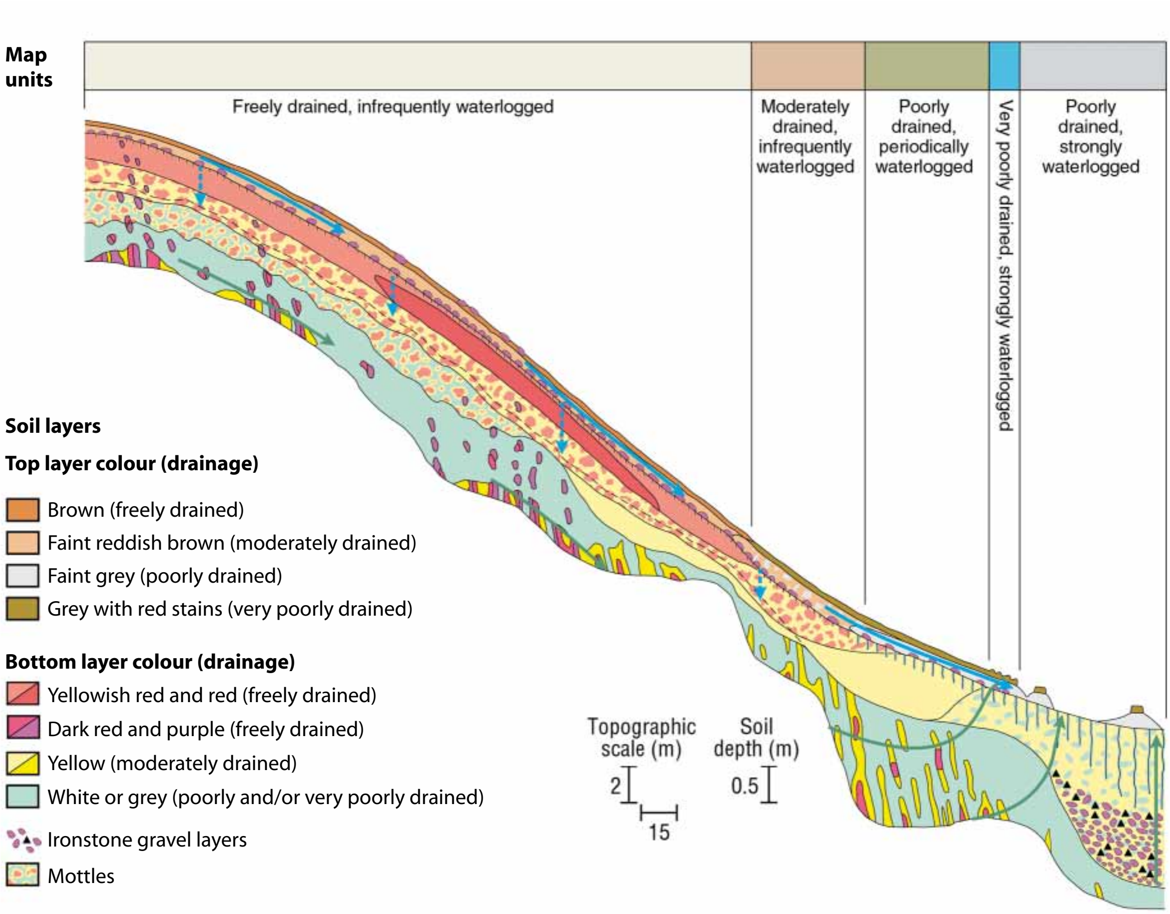

Figure 1. Descriptive soil–regolith model showing direction of perched fresh water flow and ground water flow. Modified from Fritsch and Fitzpatrick (1994).

good soil conditions for most forms of plant growth include the following:

- dark brown colours near the surface, often associated with high levels of organic matter, well-aggregated soil and above-average nutrient levels; and
- bright yellowish and reddish colours in subsoils, usually indicating oxidised conditions, suggesting good drainage. These coloured iron oxides also contribute to soils having good aggregation because of their strong surface charge properties. Aggregated soil materials are porous and contain sufficient air and water for root development.

Descriptive indicators of poor soil conditions include:

- mottles (blotches or specks) with dull yellow and orange colours in a grey, bluish or olive coloured material, indicating prolonged lack of soil aeration (seasonal or permanent waterlogging);
- rust-coloured specks and iron precipitates along fine roots, indicating prolonged or permanent waterlogging;
- very pale grey or white colours, indicating possible considerable leaching, low organic matter and low fertility;
- pale dense subsurface layers overlying dense clays (usually with mottled colours), indicating a perched watertable on the clay; and
- black mottles with the smell of hydrogen sulfide or mercaptan gases, which develop through anaerobic decay of organic matter, indicating severe waterlogging.

Figure 1 shows the distribution of these soil colour indicators in a toposequence.

Across large areas, it is expensive to monitor watertable depths (using piezometers or dipwells) to estimate water duration in soils. The field instrumentation installed down the toposequence is used to verify and quantify pathways and loads of water flow. Soil colour is a useful indicator for recognising and delineating waterlogged soils. 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 waterlogging can occur without any evidence on the surface. In Figure 1, we used mostly soil colour (together with other morphological, chemical and mineralogical indicators) and hydrology measurements (Cox et al. 1996) in the toposequence to construct the two-dimensional linkages that describe water flow paths and development of salinity (descriptive soil–regolith models).

Explanatory soil–regolith models

The descriptive model (Figure 1) was used to construct the explanatory soil-landscape model, which attempts to explain the contemporary geochemical dispersion and erosion processes present in the lower parts of the toposequence (Fig. 2).

In the catchments of the Mount Lofty Ranges and the Dundas Tableland, the codominant anions in saline groundwaters and soils are SO_4^{2-} and Cl^-. Chapter 11 describes the type of land degradation occurring in this particular landscape.

Predictive models

Development of potential acid sulfate soils

In many parts of inland Australia, the saline groundwater is rich in SO_4^{2-}, which can seep up through the soil, along with other ions in solution like Na^+, Mg^{2+}, AsO_4^{3-}, I^- and Cl^-. The SO_4^{2-} then concentrates by evaporation and forms various mineral precipitates within and on top of the soil (Figs 2 and 3a). The combination of rising sulfate-rich groundwaters, anaerobic conditions associated with saturated soils, agricultural activity and a fractured rock geology rich in iron and sulfur can lead to the formation of saline soils with potential and actual acid sulfate soil conditions (Fitzpatrick et al. 1996, 2000). If the soil is wet and contains sufficient organic carbon, anaerobic bacteria use the oxygen associated with the SO_4^{2-} ions during the assimilation of carbon in organic matter. This process produces pyrite (FeS_2) and forms 'sulfidic materials'. The pyrite-enriched soils are termed potential acid sulfate soils because they have all the ingredients necessary to produce acid sulfate soils (Figs 2 and 3a).

Development of acid sulfate soils

Acid sulfate soils result when activity from animals, drainage works or other disruptions exposes the pyrite in the previously saturated soils to oxygen in the air. When this happens, pyrite is oxidised to sulfuric acid (H_2SO_4) and various iron sulfate-rich minerals, and acid sulfate soils form (Fig. 3b). When sulfuric acid forms, the soil pH can drop from neutral (pH 7) to less than 4 (we have measured values as low as 2) to form a 'sulfuric horizon' (Fig. 3b). The sulfuric acid dissolves the clay particles in soil, causing basic cations and associated anions (e.g. Na^+, Mg^{2+}, Ca^{2+}, Ba^{2+}, Cl^-, SO_4^{2-}, SiO_4^{4-}), trace elements, and metal ions such as iron and aluminium to be released on the soil surface and in stream waters.

As the regolith structure declines due to the accompanying sodicity, soils become clogged with clay and mineral precipitates and lose their permeability and groundcover. This prevents the groundwater below from discharging and forces it to move sideways or upslope (Fig. 3b). Soil around the clogged area eventually erodes, sending acid, metal ions and salts into waterways and dams, while a new area of potential acid sulfate soil develops upslope or adjacent to the original acid sulfate soil zone. If pugging by cattle or other activities continue to disturb the soil around the newly degraded area, it continues to expand (Fig. 3b). Bare, eroded, saline scalds surrounding a core of slowly permeable, highly saline, eroded acid sulfate soils (Fig. 3c) occur if these processes express on the surface of the soil. These saline landscapes are characterised by slimy red or white ooze and scalds with impermeable iron-rich crusts, and have been reported in South Australia, southwestern Victoria (Dundas Tableland), the Western Australian wheatbelt, the

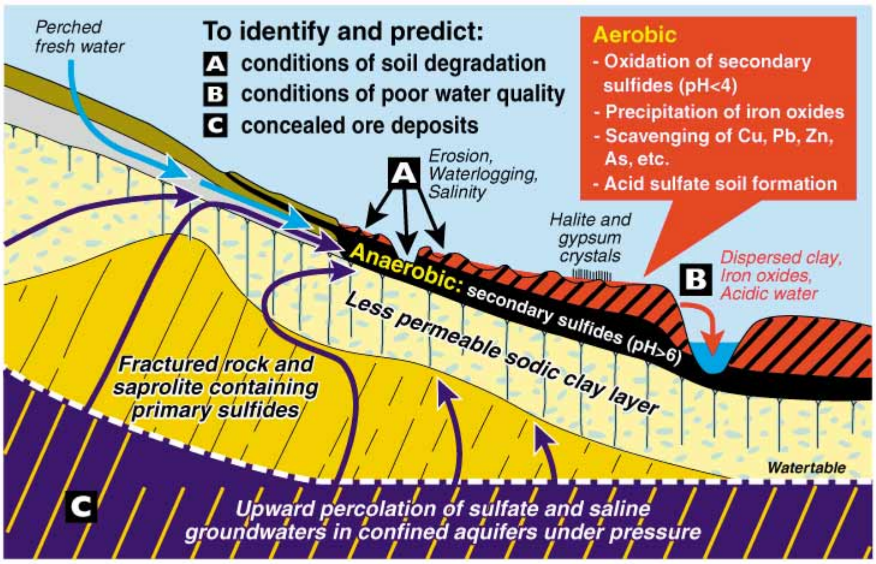

Figure 2. Explanatory soil–regolith model showing geochemical dispersion and erosion processes in saline landscapes and formation of secondary sulfides in potential acid sulfate soils in a perched wetland and actual acid sulfate soil along drainage lines.

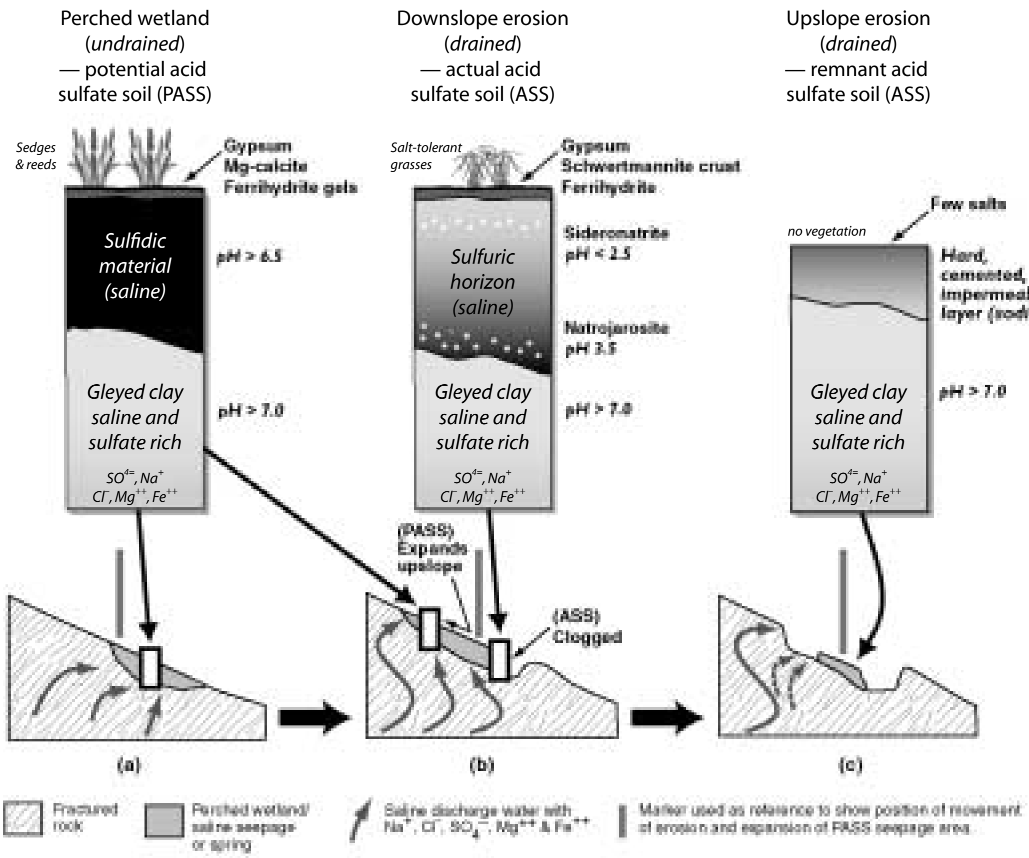

Figure 3. Predictive soil–regolith model showing the progressive transformation of saline potential acid sulfate soils in a perched wetland, via actual acid sulfate soils to eroded highly saline acid sulfate soils.

Yass valley in New South Wales and southeastern Queensland. While these reports suggest that saline acid sulfate soils are widely spread, the full extent, nature and severity of the problem are still unknown. This is because the discovery of saline inland acid sulfate soils is relatively recent (Fitzpatrick et al. 1996), although the problem has been studied in coastal areas since the 1980s.

Development of saline soils

In Australia there are extensive areas of naturally saline soils. The secondary saline soils that form following land clearing are more closely associated with processes leading to dryland salinity. Most of the saline soils found in Australia contain Cl^- as the dominant anion and Na^+ as the dominant cation (Fig. 4a). The accumulation of this stored salt is generally believed to originate from the ocean via rainfall and marine deposition in earlier geological periods (Isbell et al. 1983). Following the clearing of upland areas, saline seepages develop rapidly on slopes because of rising saline groundwater tables. When saline soils dry out, halite (sodium chloride) is often the main salt efflorescence formed (Fig. 4a). However, there is little information available on the nature of the soils and the salts that they contain.

Changes in salinity and development of sodicity

Sodic soils are believed to have developed from saline soils by freshwater leaching. Secondary sodic soils are known to develop from the drainage of saline soils (Fig. 4b). However, the formation of ‘naturally’ sodic soils is more uncertain: such soils could have formed directly from the weathering of certain parent materials thousands of years ago and may not necessarily have developed from saline soils (Isbell et al. 1983). A case study conducted in the Mount Lofty Ranges of South Australia illustrated that a sodic soil with an exchangeable sodium percentage of more than 15% could develop from a saline soil (EC_{se} > 8 dS/m) when it was drained following the formation of a nearby erosion gully. Figure 4b illustrates freshwater leaching of a saline soil (Fritsch and Fitzpatrick 1994). The studies in the Mount Lofty Ranges have demonstrated the important interrelationships between salinity and sodicity in the context of soil–water–landscape processes and the flocculation and dispersion of clay particles (Fitzpatrick et al. 1994).

Changes in the mobility of colloids and clays

Freshwater throughflow in loamy or sandy surface horizons of drained saline soils in discharge areas leads to the development of sodic layers and to lateral movement of colloids into streams (Fig. 4b; Fitzpatrick et al. 1994). Such processes usually predominate in texture-contrast soils (duplex soils) in which dense, sodic, columnar B horizons (Btn, where 'B' is the subsoil horizon, 't' indicates clay accumulation and 'n' a sodic condition) occur. These layers restrict the downward movement of water, leading to waterlogging, tunnel erosion and enhanced lateral movement of water as surface runoff and as shallow groundwater flow in sloping land. Eventually a saline scald is formed (Fig. 4c).

Changes in decomposition and transformation rates of soil minerals

When saline soils are leached, salt efflorescenses on the soil surface are dissolved (Fig. 4b). Salt crystals develop at depth in sodic soils where saline groundwater discharges through the subsoil clay layer into the gully. This causes the banks to erode (salt weathering; Figs 4b and 4c). As shown in Figures 3a and 3b, when the potential acid sulfate soils undergo changes, different salt and iron minerals form because of differences in pH and salt concentrations (Fitzpatrick et al. 1996; Fitzpatrick and Self 1997). In the final stage of the acid sulfate soil formation, a hard soil layer remains, with few salts (Fig. 3c).

The acidification process accelerates the decomposition and formation of minerals in the soils and underlying rocks and can cause an increase in salinity and carbonate (Fitzpatrick and Merry 1999). Where salinity has surface expression, unsightly scalds develop; they are devoid of vegetation and contribute to poor quality water in the catchment.

Changes in greenhouse gas emissions

Saturated, saline soils are potential sources of greenhouse gases that have not been adequately researched. In a recent study of an area of about 80 km^2 in South Australia, Fitzpatrick et al. (1999a)

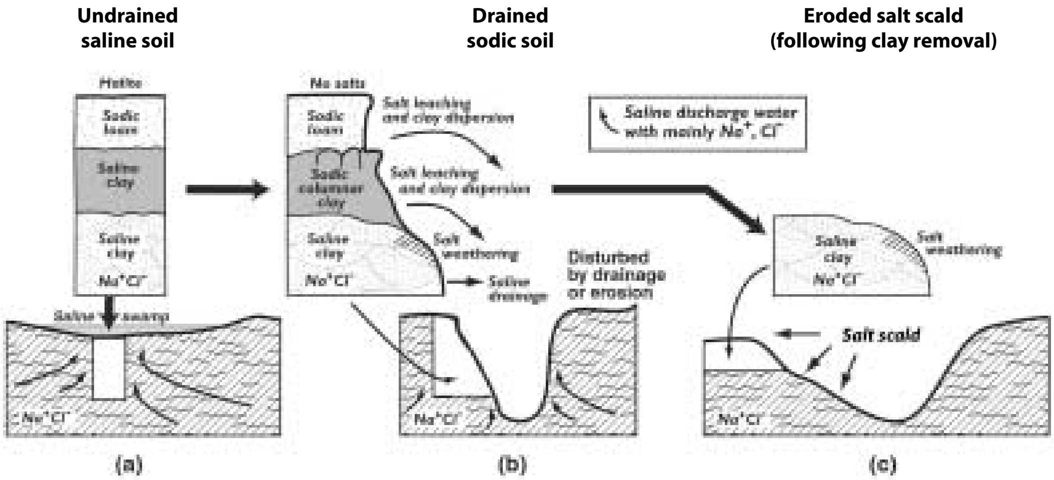

Figure 4. Predictive soil–regolith model showing the progressive transformation of saline soils, via sodic soils, to saline soils in salt scald.

used geographic information systems (GIS) to estimate that more than 10% of the area was strongly waterlogged and poorly drained, and a further 27% periodically waterlogged. A high proportion of the area was also characterised by saline discharge or potential acid sulfate soils. Depending on seasonal conditions, redox status and the nature of groundwaters (sulfidic, sulfatic or oxygenated), greenhouse gases such as carbon dioxide, nitrogen oxides and methane may be emitted. Drainage of these sites may decrease production of these greenhouse gases (Fitzpatrick and Merry 1999).

Conclusions

A systematic approach has been developed for constructing soil–regolith and water process models, which describe the toposequence system under study (descriptive model), and explain or predict the relationships and behaviour of the toposequence system under study (explanatory and predictive models). These models can be useful in generating maps at catchment and regional scales using GIS (see Chapters 11 and 21), and in producing practical soil-landscape and vegetation field keys from which to determine land-use options for preventing the irreversible spread of saline and sodic conditions (see Chapters 26 and 29).

Acknowledgments

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