



# Land Degradation Processes

Rob W. Fitzpatrick\*

## Abstract

This chapter describes how saline, sodic, acid and eroded soils are formed. Using simplified schematic diagrams based on Australian examples, we illustrate the major processes involved and show how some soils may act as precursors to land degradation. We use photographic examples from China to illustrate each degraded soil–landscape type. The chapter also discusses some of the differences between transient salinity and primary, secondary and seepage salinity.

本章阐述了土壤盐化、碱化、酸化以及土壤侵蚀的形成。针对澳大利亚的实例，以图例表格形式，简要展示了其中的主要作用过程，解释了有些类型的土壤可作为土地退化的前兆。用来自中国的照片材料说明退化土壤景观的各种不同类型。本章也探讨了暂时性盐碱化、原生盐碱化、次生盐碱化以及出渗盐碱化间的一些区别。

## Introduction

LAND degradation (soil salinity, sodicity, acidity and erosion) is the systematic decline in the quality of land resulting from a mismatch between land use and land quality. It is the consequence of different natural processes, but is usually accelerated by human activities. The result is declining function. Land undergoing degradation normally passes through three phases.

- Natural degradation is generally slow because a steady state develops between soil formation and soil degradation (usually loss). Natural degradation represents ‘inherent land quality’.
- Induced degradation results from inappropriate land use and management. Soils decline in quality, but productivity can be maintained by applying artificial nutrients and by appropriate soil management. Induced degradation happens more quickly than natural degradation.
- Desertification occurs when the degree of degradation is such that the resilience of the land is impaired. In unmanaged systems, desertification is indicated by changes in the quality and quantity of biomass and the biota. In agricultural systems, the degree of productivity reduction normally sets the stage for abandonment of the land. This is particularly

\*CSIRO Land and Water, PMB 2, Glen Osmond, SA 5064, Australia. Email: rob.fitzpatrick@csiro.au

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the case when levels of productivity can no longer be economically maintained through management.

In several dryland areas in China and Australia, salinity, waterlogging, erosion (water and wind) and other forms of land degradation are becoming severe and are expected to worsen. For example, water quality is declining because salts, nutrients and sediments are being transported into rivers, streams and dams. Native ecosystems, especially wetlands, are under threat, with loss of habitat and declining biodiversity and soil function. There are many causes of environmental degradation, but in both China and Australia by far the most all-encompassing is the clearing of native vegetation and its replacement with inappropriate agricultural practices. Improved agricultural production systems and restoration of native vegetation could help to restructure these landscapes to establish patterns of water use and ecological function similar to those of the original landscape before clearing. However, such restructuring depends on having a good understanding of the soil–water–landscape processes that are causing the problems.

The studies described in this volume summarise the results of a collaborative project between Chinese and Australian scientists to increase agricultural productivity and sustainability in certain regions of China and Australia. This chapter introduces the section on soils. It focuses on four major types of degradation — salinity, sodicity, acidity and erosion. The processes described are relevant to both Australia and China. The other chapters on soils focus on particular regions (Chapters 10, 12, 13 and 14) or particular processes (Chapters 9, 11 and 15).

In many areas, changes in components of water balance have led to severe changes in the physical and chemical characteristics of soils. In southern Australia, these changes occur particularly on

duplex soils — soils that have an abrupt textural boundary between the top layers and the relatively impermeable subsoil layers. Such soils occupy 80% of the high- to medium-rainfall zones of southern Australia, which include some of Australia’s prime agricultural (crops, meat, wool, dairy) and horticultural lands, as well as major catchments for regional water supplies. Thus, degradation of soil and water resources poses serious threats to land use and to the quality of water harvested and stored in regional water bodies.

## Salinity

Saline soils are those with relatively large amounts of soluble salts such as sodium chloride. Such soils occur naturally; this is referred to as primary salinity (Fig. 1).



**Figure 1.** Primary salinity in northern Hebei Province, China.

Secondary salinity results from human activities such as irrigation and land clearing in areas that are not irrigated (dryland salinity) (Ghassemi et al. 1995). Both primary and secondary salinity affect plant growth by causing dehydration.

Saline soils form under different environmental conditions and thus have diverse morphological, chemical, physical and biological properties. There is no universally accepted definition for saline soils:

the definition used depends on the discipline and the type of measurements taken. For example:

- hydrogeologists distinguish primary and secondary saline soils (e.g. Coram 1998; George et al. 1997a);
- plant and soil scientists use the distribution of salt-tolerant plant species and/or the approximate range of soil electrical conductivity (EC) levels to distinguish slightly, moderately or severely affected saline soils (e.g. Allan 1996); and
- scientists in other disciplines may use:
  - measurements of pH (3.5–8.5), exchangeable sodium percentage, the sodium adsorption ratio and EC to identify sodic–saline soils (e.g. Soil Survey Staff 1987);
  - measurements of pH (> 9), presence of sodium carbonate and high EC to distinguish alkaline saline soils; and
  - pH (< 3.5), presence of sulfur and high EC to distinguish acid sulfate saline soils (Fitzpatrick et al. 1996).

The definition is further complicated by the fact that salinity can be transient (i.e. not associated with a permanent saline groundwater table).

In Australia, most studies of salinisation processes focus on primary and secondary salinity (e.g. George et al. 1997a; Coram 1998; Macumber 1991) or the processes occurring in sodic soils (described below) (e.g. Isbell et al. 1983; Naidu et al. 1995; Rengasamy and Sumner 1998; Shaw et al. 1998).

The soluble salts found in saline soils are of three types: chlorides, sulfates and carbonates. Most saline soils in Australia have high amounts of chloride salts (Isbell et al. 1983). However, in parts of the Mount Lofty Ranges (Fitzpatrick et al. 1996), Dundas Tableland and the North China Plain (Fig. 2) extensive areas of saline soils also contain sulfate salts (Fig. 1) and sulfides at depth (Fig. 2).

Saline soils with high amounts of carbonates of sodium (sodium bicarbonate) may also occur and are usually associated with coarse-textured materials. These saline soils often exhibit a whitish surface crust when dry (Fig. 1).

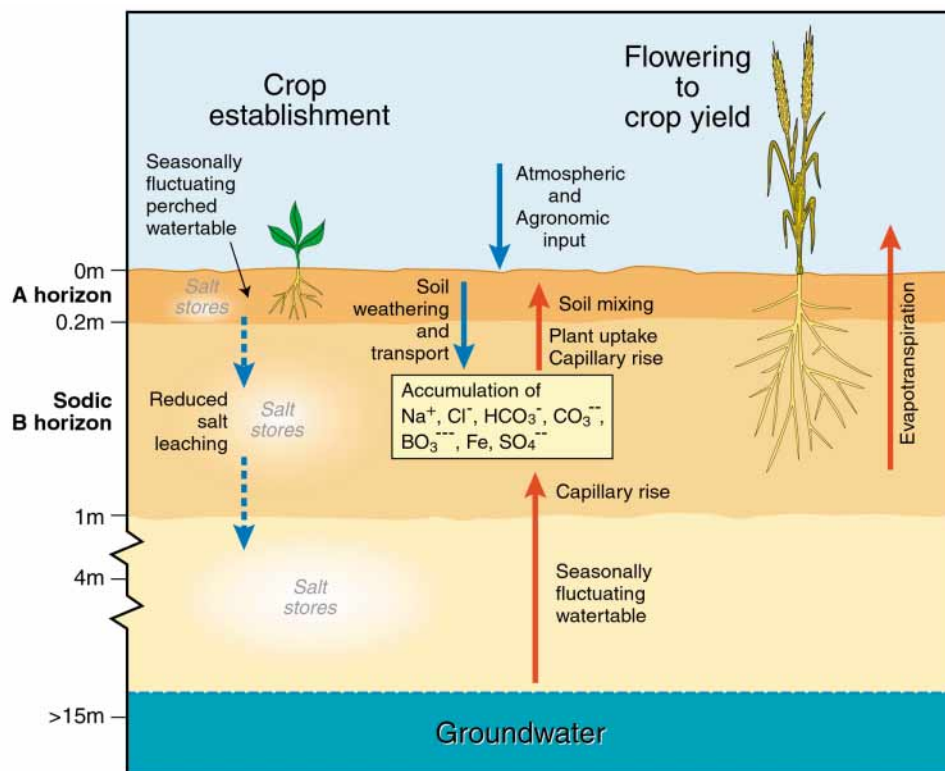


**Figure 2.** Saline sulfidic (black mud) soil near Yangcheng Reservoir, coastal zone on the North China Plain, Hebei Province.

High salinity (as defined by high EC) dehydrates plant cells because the dissolved salts decrease the osmotic potential of soil water. Water flows from the high osmotic potential (low salt concentration in plant cell) to low osmotic potential (high salt concentration in soil). Thus, plants cannot extract water from soil when the soil solution has a lower osmotic potential than the plant cells. The effect on plants is similar to drought stress, with reduced plant growth and often death. For many crops, yields are reduced when the soil extract EC reaches 4 dS/m (US Salinity Laboratory Staff 1954) and decline proportionately as EC levels increase above that level. Some crops, such as sugar beets, are tolerant to EC levels between 4 and 8 dS/m. At an EC of 16 dS/m the growth and yields of most crops are affected. Figure 3 shows the hydrological processes and salinity development commonly found in cropping systems in Australia.

## Sodicity

Sodic soils, like saline soils, contain relatively large amounts of sodium, but in this case the sodium is present as ions, not as salts. A soil is considered to



**Figure 3.** Hydrological processes and salinity development commonly found in cropping systems in Australia (from Fitzpatrick et al. 2001).

be sodic when the adsorbed sodium reaches a concentration where it starts to affect soil structure (Rengasamy and Sumner 1998). Sodic soils can result from drainage by erosion gullies or directly from the weathering of parent materials over thousands of years (Isbell et al. 1983).

Sodic soils have poor structure and low permeability, with adverse effects on plant growth (Fig. 2). Permeability allows water, gases (oxygen and carbon dioxide) and solutes to circulate easily to and from plant roots, which promotes plant growth. However, if a hard sodic dispersed clay layer occurs on the soil surface (Fig. 4) or close to the soil surface (e.g. the B horizon in Figs 3 and 5) it can act as a barrier to root development. The hard soil restricts root growth to either the cracks or topsoil above the claypan because movement of water, nutrients, and gases is too slow in sodic B horizons. In fact, when dry, the B horizon can be so hard that it is also a physical barrier to root penetration. The overall

effect on plant growth is one of stress similar to that caused by extremely dry or saline conditions.

The rate and amount of downward percolation of salts are primarily controlled by soil texture and subsoil layer permeability. In coarse-textured horizons, water flows more quickly and the average pore diameter is larger than in fine-textured soils. Decreased water storage is directly related to greater pore diameter. As a result, deep percolation of water and salts is more likely to occur in coarse-textured soils. In some localities in Australia and China, relatively coarse-textured soils overlay impermeable sodic clay horizons. Under these circumstances, percolation leads to lateral flow of water and solutes along the surface of the impermeable layers. If the contact between the two different layers approaches the soil surface along a hill slope, as often happens, the laterally moving water will create a wet spot that eventually becomes saline as the water is evaporated (Fig. 6).



**Figure 4.** Sodicty development in surface soils. (Note damage to root development under the hard, dense, slowly permeable plate.)



**Figure 5.** Sodicty subsoil formation. (Note that root development is restricted to the A1 horizon because roots find it difficult to penetrate the prismatic Bt horizon.)

## Transient Salinity

Transient salinity is the term used for salinity that is not associated with a permanent saline groundwater table. Different forms of transient salinity are expressed in the subsoil and at the soil surface.

### Transient salinity with subsoil expression

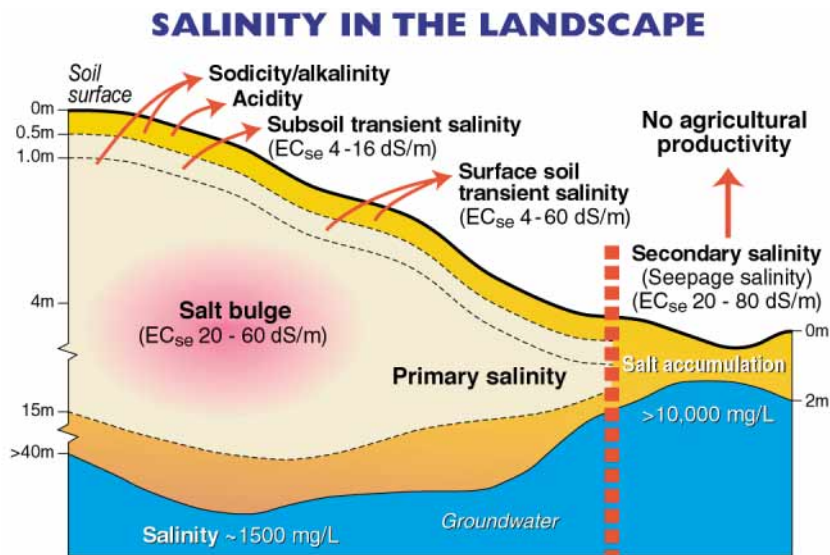
A recent survey of sodicty soils in the South Australian wheat growing regions indicated slow accumulation of salts in the subsoil layers in small

amounts that could be detrimental to crops. This phenomenon of ‘subsoil transient salinity’ in the root zones of sodicty soils is different from the ‘secondary’ or ‘seepage’ salinity found in association with rising saline groundwater tables (Rengasamy and Sumner 1998; Shaw et al. 1998). When the upper layers of soil are sodicty, water infiltration is very slow, because dispersed clay clogs soil pores. If the subsoils are sodicty, downward movement of water is restricted, causing temporary waterlogging in the subsoil and the development of a ‘perched watertable’. Salts accumulate above the perched watertable during the wet season and in the sodicty subsoils following drying, due to water uptake by plant roots and evaporation. Although the rate of salt accumulation is not great, over time it can be detrimental to crops. Subsoil transient salinity fluctuates with depth and with season as the balance between downward and upward fluxes changes.

Generally the accumulated salts in the cereal-growing regions of southern Australia are sodium chloride. However, these salts may also include sodium carbonate and bicarbonate when soil becomes alkaline with a pH > 9.0 (i.e. alkaline-sodicty saline soils) Studying salt accumulation in sodicty subsoils in more detail will allow us to model this phenomenon and predict when and where it will occur.

### Transient salinity with surface expression

The most extreme case of salt accumulation occurs when values range from 4 to 60 dS/m at the soil surface, often with salt efflorescences. These high levels of salt prevent crops from growing and can make the soil susceptible to scalding and erosion. This salinity is due to the localised mobilisation of salts by throughflow above slowly permeable sodicty B horizons to topographic depressions. This so-called ‘surface soil transient salinity’ can occur in a variety of soil types and at all positions in undulating landscapes. It was first reported locally by Herriot (1942) and is commonly referred to as ‘magnesia’ patches in South Australia because of the



**Figure 6.** Landscape salinity, illustrating the development of primary salinity, salt bulges, subsoil transient salinity, surface soil transient salinity and secondary salinity (from Fitzpatrick et al. 2001).

presence of high magnesium, as well as sodium (in other words, magnesium is a natural part of the evaporation sequence).

## Primary, Secondary and Seepage Salinity

### Primary salinity

Primary salinity is caused when salts leach from the soil due to natural processes, eventually leading to the accumulation of salts in the groundwater, sometimes at levels of 2000 to 20,000 mg/L (Fig. 6). As long as the watertable is below 5 m, saline groundwater does not usually affect vegetation. Primary highly saline soils are usually found in foot slopes and topographic depressions, and near springs where the saline groundwater is naturally shallow (less than 1.5 m deep) (Figs. 1 and 6).

#### *Salt stores in the regolith*

Over many thousands of years, salt has been accumulating in older landscapes from the large quantities (20–200 kg/ha/year) of salt blown in from the ocean by wind and rain (e.g. Hingston and Gailitus 1976; Peck and Hurle 1976). In addition,

salts have been generated by the weathering of rocks during soil formation and the leaching of connate salts trapped in the original sediments. For any particular situation, however, salinisation processes will depend on geology, climate, vegetation and changes superimposed by agriculture. For example, before agriculture in Australia, salts were leached down the profile by rain and accumulated within or below the root zones of native vegetation (Allison et al. 1990; Figs 3 and 6). In semiarid conditions there was not always sufficient rainfall to leach all incoming salts to the groundwater. The clay layers in deep subsoils often hindered the movement of water and salt, and a 'bulge' of salt accumulated at depths of 5–10 m (Fig. 6). Groundwater tables were usually 30 m or more below the surface and the quality of groundwater was frequently good ( $< 2000$  mg/L salt). This is the present situation in the upper parts of the landscape in many cropping regions.

### Secondary salinity

Secondary salinisation often follows land clearing, which causes groundwaters to rise and areas of primary saline soils to expand (Fig. 6). In Australia, the introduction of agriculture and the replacement

of perennial native vegetation with annual species have resulted in increased drainage, thereby disturbing the existing equilibrium of groundwater levels. This may ‘recharge’ the groundwater, resulting in raised groundwater pressures in low-lying discharge areas. The increased recharge may then discharge into low-lying areas and rivers (e.g. Wood 1924; Dyson 1990; Nulsen 1993; George et al. 1997b). At 2 m depth, the rate of salinisation is such that we can observe saline conditions in surface soils.

### Seepage salinity

Salinity can occur through capillary rise from deeper (7 m) saline groundwater tables on silt loam soils. As water moves into the upper layers there will be a net mass flow of salt in solution in addition to capillary action bringing salts higher in the profile, closer to the evaporating surface or plant roots. This type of salinity is usually called seepage salinity. Over the past four decades it has affected an estimated 2.5 million ha of land and is predicted to increase fourfold over the next three to four decades (Coram et al. 2001).

## Acidity

Soil acidity is a severe soil degradation problem that can greatly reduce the production potential of farming systems. Most occurs in productive agricultural zones. It causes production losses within paddocks, and also long-term and offsite effects, including:

- poor water use by plants (leading to higher recharge and erosion);
- increased leaching of nutrients and aluminium; and
- the irreversible breakdown of layer silicate minerals in soils.

Soil acidification can be determined by assessing the pH of a soil, which determines the concentration of hydrogen ions or acid in the soil. The pH is measured using a logarithmic scale: soils at pH 7 are

neutral, those of pH < 7 are considered acidic. Soil acidity is not thought to restrict the growth of most crops or pasture until the pH drops to < 5.5–6.0 (pH<sub>w</sub>) or < 5.0–5.5 (pH<sub>Ca</sub>).

Development of acidity in soils is a natural process, especially in the high rainfall regions of southern Australia. Some soils are inherently acidic because of the high rates of leaching in these regions. Even in lower-rainfall cropping areas, some soil types have become acidic because they have no free lime in the profile. As soils become more acidic, plants and crops that cannot tolerate acidic conditions do not flourish, so productivity and yields decline. When conditions become severely acidic (e.g. pH < 4, such as in inland acid sulfate soils), biogeochemical processes start to break down the layer silicates in the soil, releasing aluminium, iron and manganese. This may lead to mineral toxicities and nutrient imbalances.

The natural rate of acidification is accelerated by the use of acidifying fertilisers, nitrogen fertilisers, the removal of agricultural products and nitrate leaching. The management of soil acidity involves the following requirements at the farm level:

- recognising paddock indicators of soil acidity
- monitoring soil pH
- knowing crop and pasture tolerances to acidity
- treating paddocks that have acidity problems.

Acid soils can be ameliorated by applying liming material or other types of neutralising agent, growing acid-tolerant plants or reducing the rate of acidification.

## Erosion

Soil erosion by wind and water is a worldwide environmental problem that seriously threatens sustainability of agriculture. A recent study showed that the direct and indirect annual cost of erosion may be as high as \$400 billion worldwide. This

translates to roughly \$80 per year for every person on Earth. Some of the most eroded regions of the world—including the Loess Plateau in China (e.g. Xianmo Zhu and Mei'e Ren 2000; Lindstrom et al. 1990; Li and Lindstrom 2001; Figs. 7 and 8)—are located in semiarid areas where drought is a serious threat to sustainable agriculture.



**Figure 7.** Erosion gullies on the Loess Plateau, China.



**Figure 8.** Erosion gullies and terraces on the Loess Plateau, China.

The Loess Plateau is the thickest, most complete, loess deposition in the world (Figs. 7 and 8). The formation of the Loess Plateau is in essence the process of loess accumulation. Loess deposits and the Paleosols contained in them have a loose and porous structure, which has frameworks composed of sands and other coarse particles, filled with fine

particles and microaggregates and strengthened by clayey materials. Such a porous medium is very susceptible to water erosion if not protected by plants. This is why soil and water losses are so severe in the Loess Plateau region. Without the protection of vegetation and stabilisation by root systems, raindrops impact and destroy the porous soil structure and cause a dramatic decrease in soil permeability. Improper tillage practices have also damaged the soil structure and reduced soil resistance to water erosion, often leading to severe soil erosion. Removal of natural vegetation and inappropriate land use leads to reduced soil permeability and an increase in soil water erosion. This is the main reason for high sediment loads in the Yellow River. Consequently, severe soil erosion is not a geological process, but a result of improper land use.

In areas with high erosion due to improper land use, research on wind erosion (Fig. 9) and water erosion, and on soil and water conservation and dryland farming, have led to the development of agricultural systems that could be sustainable. For example, comprehensive management schemes and reforestation of watersheds can result in water conservation and reduced wind and water erosion. Such improved productivity will raise farmers' income. The Loess Plateau is an example of this type of approach.



**Figure 9.** Wind erosion in northern Hebei Province, China.

In southern Australia, various incision and deposition cycles of sheet and streambank erosion have occurred in high winter rainfall areas (> 600mm) (Fitzpatrick et al. 1996). These erosion features may be associated with sodic soils (Natraqualfs or solodised solonetz soils) undergoing recent alteration caused by rising saline–sulfatic groundwater tables due to land clearing following European settlement approximately 120 years ago. Surface and subsurface pedological features, soil chemical, physical and hydrological measurements and remote sensing were used to study the age, onset and development of erosion in several key catchments in southern Australia (e.g. Prosser 1996). Aquic, saline and sulfidic conditions occur in seepage areas where saline and sulfatic groundwater rises to the surface from semiconfined aquifers. The almost bare surface that is formed is subjected to drastic alteration of soil structure during cycles of drying and wetting (Fitzpatrick et al. 1996). On drying, salts and iron minerals concentrate and crystallise at the surface by evaporation to form cemented impermeable soil materials. On wetting, salts are dissolved by rising groundwater and overland flow occurs. Rising saline water also flocculates clay particles, giving rise to low soil strength in the topsoil.

Saline sulfidic soils form in seepage areas with saline sulfatic aquifers and shallow watertables. The high sulfide and salt concentrations lead to the complete breakdown of soil structure and soil strength. Consequently, such seepage areas are highly prone to sheet erosion. Sheet erosion is produced by overland flow and controlled by salt concentration, which restricts the growth of the vegetation cover and reduces the structural stability of the topsoil. The saturated zone increases up the slope because

of increased throughflow and overland flow and restriction of throughflow. The reasons for the restriction in throughflow include rising saline/sulfidic groundwaters, clay dispersion and iron oxide blockage of soil pores. Such conditions give rise to accelerated sheet erosion, which forms shallow incision zones and a thin deposition zone.

## Conclusion

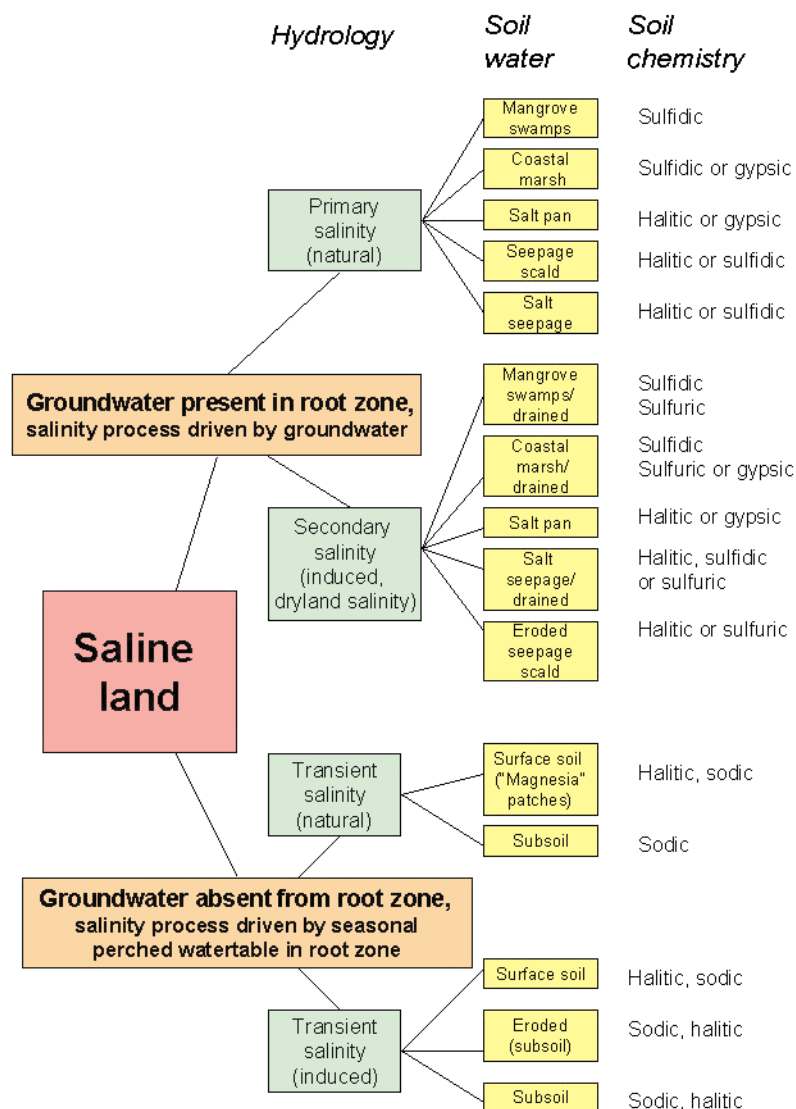
The three most important features that cause saline soils to differ are:

- hydrological status (presence or absence of groundwater);
- natural (primary) or induced (secondary) status; and
- soil chemical status (sodicity or type of soluble salt).

Several workers have attempted to categorise dryland saline soils using hydrology and water status (e.g. SCAV 1982 and Williams and Bullock 1989). We have further modified this concept and also included soil chemical status (Fig. 10). The important soil chemical features are halitic (sodium chloride dominant), gypsic (gypsum or calcium sulfate dominant), sulfidic (iron pyrite dominant), sulfuric (sulfuric acid dominant), and sodic (high exchangeable sodium on clay surfaces). Most of these terms are defined in Isbell (1996).

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**Figure 10.** Categories of dryland saline soils as defined by hydrology, soil water status and soil chemistry (from Fitzpatrick et al. 2001).

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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, physico-chemical 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

\* CSIRO Land and Water/Cooperative Research Centre for Landscape Environments and Mineral Exploration, PMB 2, Glen Osmond, SA 5064, Australia. Email: rob.fitzpatrick@csiro.au

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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, toposquence, catchment, regional and global scales.

The objective of this chapter is to discuss the toposquence 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<sup>2</sup>, 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<sup>-</sup> is the dominant anion and exchangeable Mg<sup>2+</sup>:Ca<sup>2+</sup> ratios are high.

The effects of adsorbed Na<sup>+</sup> 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 mutually 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.

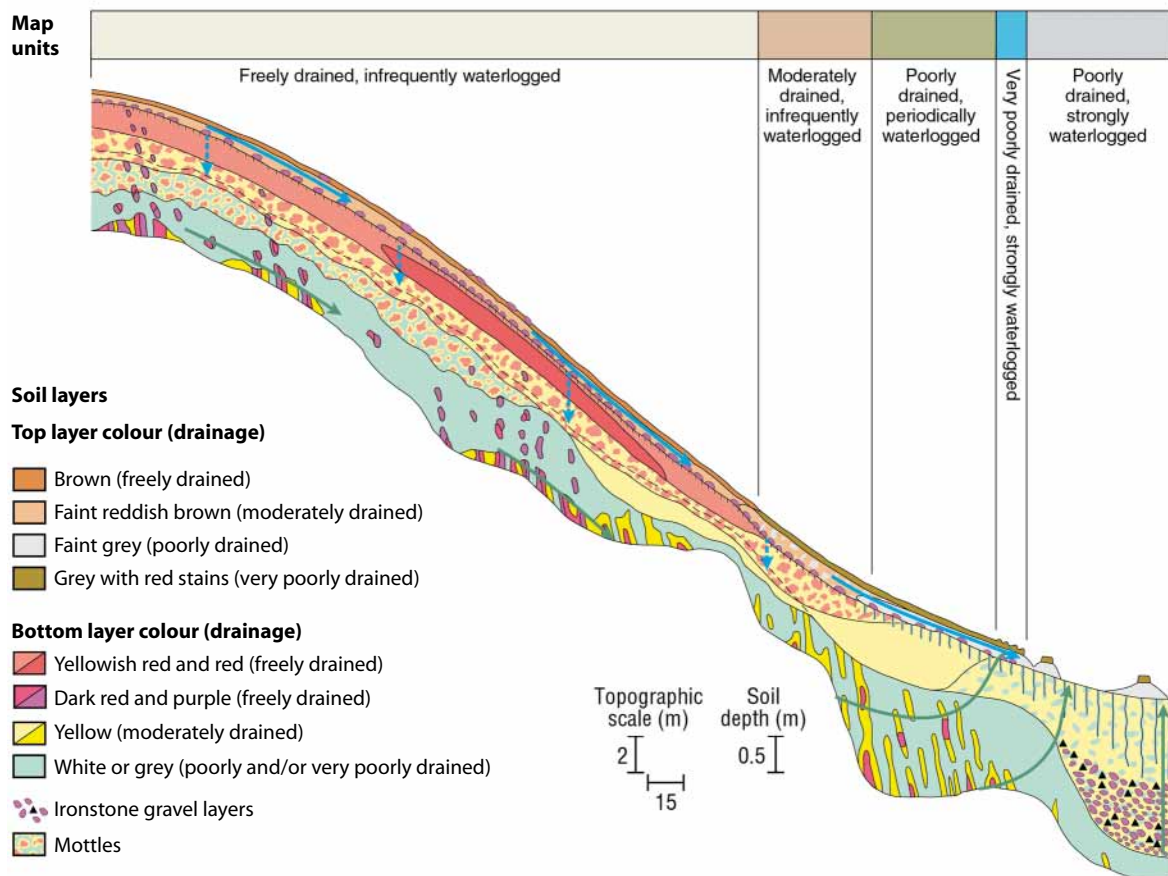
**A systematic approach to describe toposequences: descriptive soil–regolith models**

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).

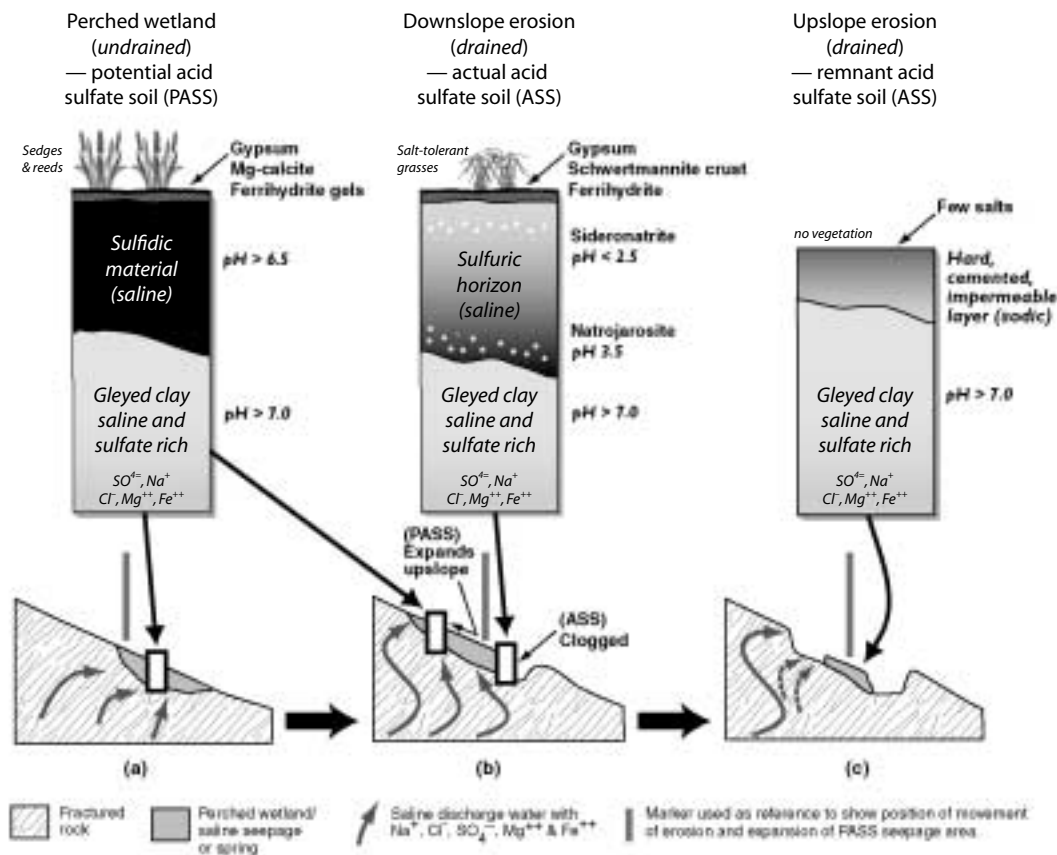
In the catchments of the Mount Lofty Ranges and the Dundas Tableland, the codominant anions in saline groundwaters and soils are  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$ . Chapter 11 describes the type of land degradation occurring in this particular landscape.

### Predictive models

#### *Development of potential acid sulfate soils*

In many parts of inland Australia, the saline groundwater is rich in  $\text{SO}_4^{2-}$ , which can seep up through the soil, along with other ions in solution like  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{AsO}_4^{3-}$ ,  $\text{I}^-$  and  $\text{Cl}^-$ . The  $\text{SO}_4^{2-}$  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





**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  $\text{Cl}^-$  as the dominant anion and  $\text{Na}^+$  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 (B<sub>tn</sub>, 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).

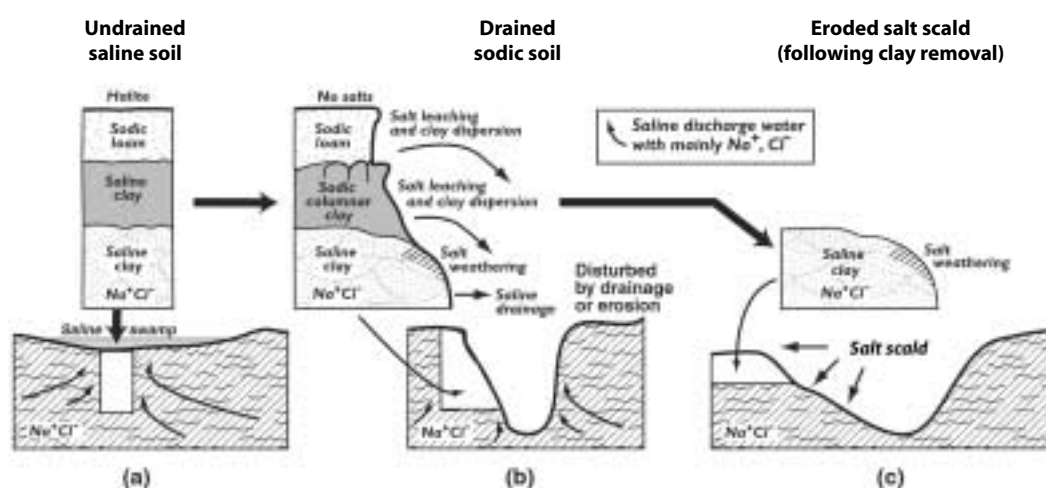
### Changes in decomposition and transformation rates of soil minerals

When saline soils are leached, salt efflorescences 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<sup>2</sup> 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).

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