8 Land Degradation Processes

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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

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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

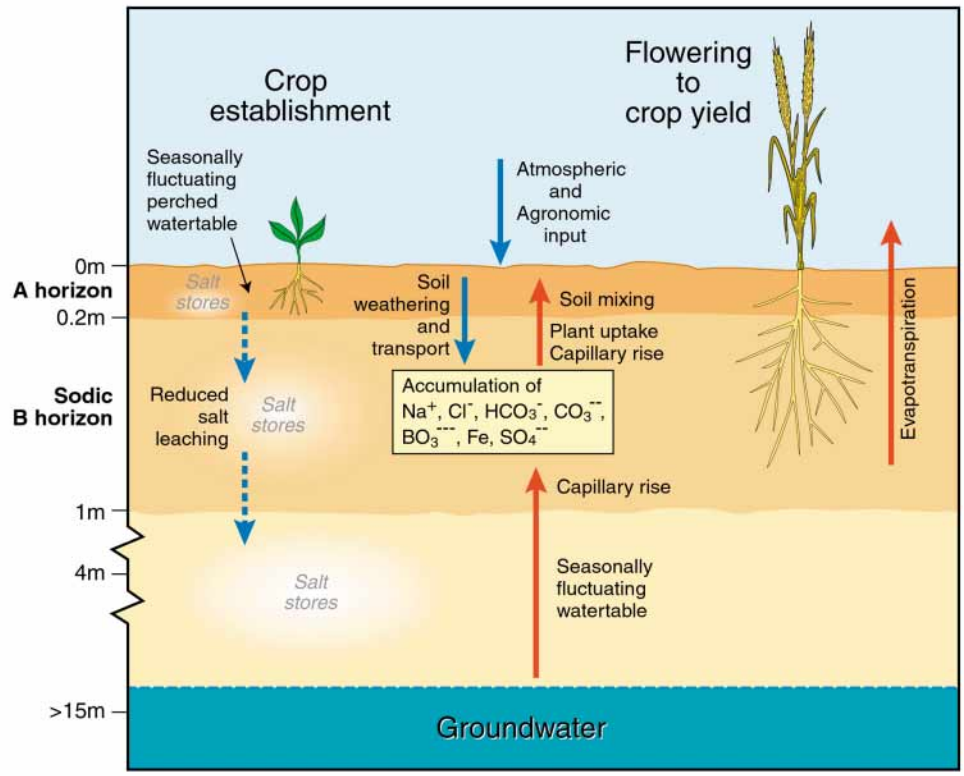

Figure 3. Hydrological processes and salinity development commonly found in cropping systems in Australia (from Fitzpatrick et al. 2001).

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. Sodicity development in surface soils. (Note damage to root development under the hard, dense, slowly permeable plate.)

Figure 5. Sodic 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 sodic 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 sodic 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 sodic, water infiltration is very slow, because dispersed clay clogs soil pores. If the subsoils are sodic, 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 sodic 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-sodic saline soils) Studying salt accumulation in sodic 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 sodic 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

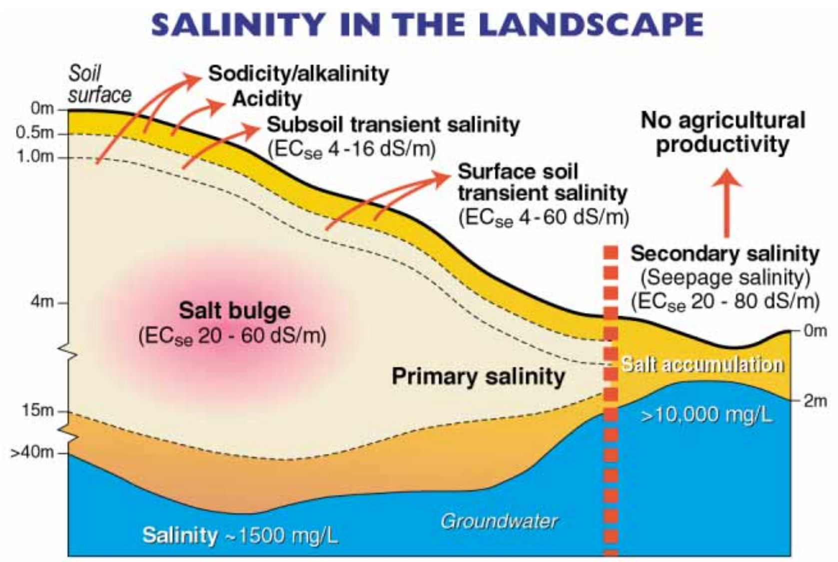

Figure 6. Landscape salinity, illustrating the development of primary salinity, salt bulges, subsoil transient salinity, surface soil transient salinity and secondary salinity (from Fitzpatrick et al. 2001).

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_w) or < 5.0–5.5 (pH_{Ca}).

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 terrasetts 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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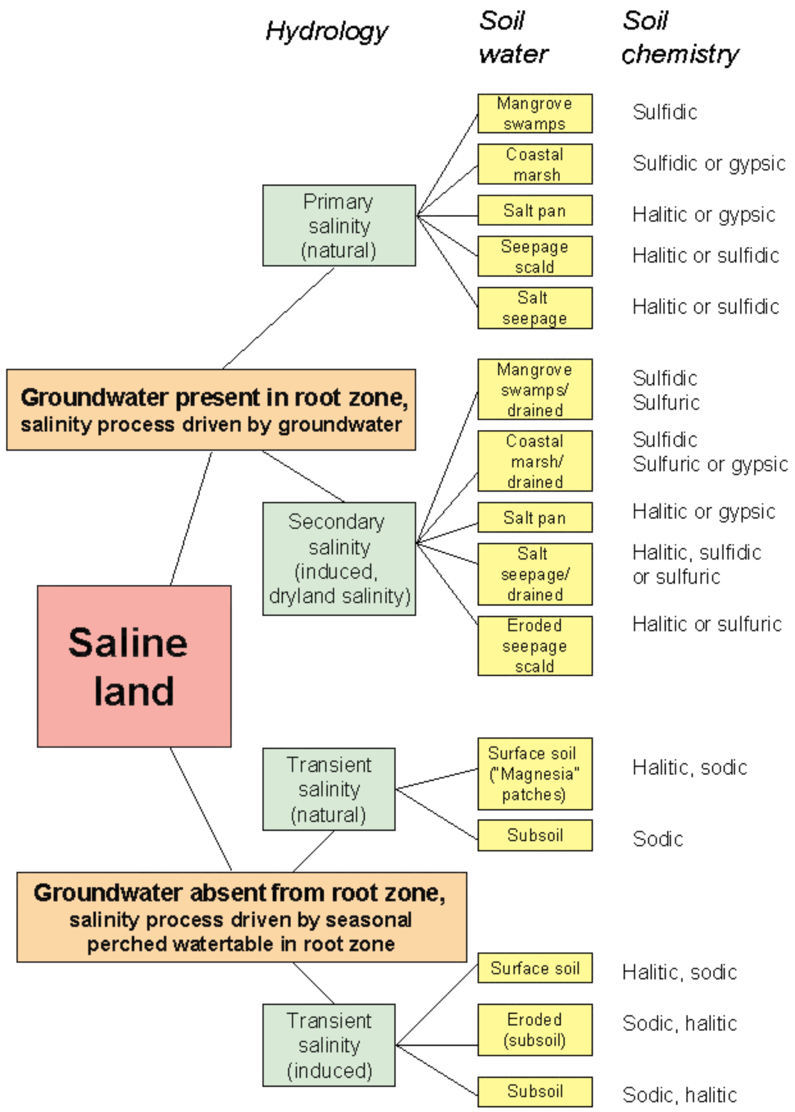

Figure 10. Categories of dryland saline soils as defined by hydrology, soil water status and soil chemistry (from Fitzpatrick et al. 2001).

References

Allan, M.J. 1996. Method for assessing dryland salinity in Victoria. Technical Report No. 34. Bendigo, Centre for Land Protection Research, Department of Conservation and Natural Resources.

Allison, G.B., Cook, P.G., Barnett, S.R., Walker, G.R., Jolly, I.D. and Hughes, M.W. 1990. Land clearance and river salinisation in the Western Murray Basin, Australia. Journal of Hydrology, 119, 1–20.

Coram, J. ed. 1998. National Classification of Catchments for land and river salinity control. A catalogue of groundwater systems responsible for dryland salinity in Australia. Report for the Rural Industries Research and Development Corporation, compiled by the Australian Geological Survey Organisation. Publication no 98/78 ISBN 0 6425 7884 2

Coram, J.E., Dyson, P.R., Houlder, P.A. and Evans, W.R. 2001. Australian Groundwater Flow Systems Contributing to Dryland Salinity. A Bureau of Rural Sciences Project for the National Land and Water Resources Audit's Dryland Salinity Theme. 77.

Dyson, P.R. 1990. The development, dynamics and management of groundwater systems and dryland salinity in the Uplands of south eastern Australia. In: Management of Soil Salinity in Southeastern Australia. Aust. Soc. Soil Sci., Riverine Branch, 253–267.

Fitzpatrick, R.W., Fritsch, E. and Self, P.G. 1996. Interpretation of soil features produced by ancient and modern processes in degraded landscapes: V Development of saline sulfidic features in non-tidal seepage areas. Geoderma, 69, 1–29.

Fitzpatrick, R.W., Rengasamy P., Merry R.H. and Cox J.W. 2001. Is dryland soil salinisation reversible? National Dryland Salinity Program. web site http://www.ndsp.gov.au.

Ghassemi, F., Jakeman, A.K. and Nix, H. A. 1995. Salinisation of land and water resources: human causes, extent, management and case studies. Chapter 2: Australia (143—212); Chaper 3: China (213—239). University of New South Wales Press Ltd, Australia and CAB International, UK.

George, R.J., McFarlane, D.J. and Nulsen, R.A. 1997a. Salinity threatens the viability of agriculture and ecosystems in Western Australia. Groundwater, 5, 6–21.

George, R.J., Speed, R. and Commander, P. 1997b. Hydrogeological models used for dryland salinity research and management: Western Australia. Unpublished paper prepared for the Conceptual Models Workshop held at the Australian Geological Survey Organisation in Canberra, 7 October 1997.

Herriot, R.I. 1942. The reclamation of highland 'Magnesia' patches, a preliminary note on work being conducted at Mt Bryan East. South Australian Journal of Agriculture, 94–95.

Hingston, F.J. and Gailitis, V. 1976. The geographic variation of salt precipitated over Western Australia. Australian Journal of Soil Research, 14, 319–335.

Isbell, R.F., Reeve, R. and Hutton, J.T. 1983. Salt and Sodicity in Soils: an Australian viewpoint. Division of Soils, CSIRO, 107–111. Melbourne, CSIRO/London, Academic Press.

Li Yand Lindstrom, M.J. 2001. Evaluating Soil Quality—Soil Redistribution Relationship on Terraces and Steep Hillslope. Soil Science Society of America Journal, 65,1500–1507.

Lindstrom, M.J., W.W. Nelson and T.E. Schumacher. 1990 Soil movement by soil tillage as affected by slope. Soil Tillage, 17, 225–254

Macumber, P.G. 1991. Interactions between Groundwater and Surface Systems in Northern Victoria. Victoria, Dept Conservation and Environment.

Naidu, R., Sumner, M.E. and Rengasamy, P. eds. 1995. Distribution Properties and Management of Australian Sodic Soils. Melbourne, Australia. CSIRO Publishing. 351.

Nulsen, R.A. 1993. Changes in soil properties. In: Reintegrating Fragmented Landscapes. New York, Springer-Verlag, 107–145.

Peck, A.J. and Hurle, D.H. 1976. Chloride balance of some farmed and forested catchments in south-western Australia. Water Resources Research, 9, 648–657.

Prosser I. 1996. Thresholds of channel initiation in historical and Holocene times, Southeastern Australia. In: Anderson, M.G. and Brooks, S.M., eds, Advances in Hillslope Processes. John Wiley & Sons. 687–708.

Rengasamy, P. 2000. Transient salinity in the root zones of sodic soils. Crop Science Society of South Australia, Newsletter No.187.

Rengasamy, P. and Sumner, M.E. 1998. Processes involved in sodic behaviour. In: Sumner, M.E. and Naidu, R., eds, Sodic Soils: Distribution, Properties, Management and Environmental Consequences. Oxford University Press, 35–50.

SCAV (Soil Conservation Authority of Victoria) 1982. Salting of non-irrigated land in Australia. Government Printer, Melbourne, Victoria.

Shaw, R.J., Coughlan, K.J. and Bell, L.C. 1998. Root zone sodicity. In: Sumner, M.E. and Naidu, R., eds, Sodic Soils: Distribution, Properties, Management and Environmental Consequences. Oxford University Press, 95–106.

Soil Survey Staff 1987. Sodic, sodic-saline, and saline soils of North Dakota. Miscellaneous Publication, Soil Conservation Service, United States Department of Agriculture, Bismarck, North Dakota.

US Salinity Laboratory Staff 1954. Diagnosis and improvement of saline and alkali soils. United States Department of Agriculture, United States Government Printing Office, Washington DC.

Williams, B.G. and Bullock, P.R. 1989. The classification of salt-affected land in Australia. CSIRO Division of Water Resources, Technical Memorandum 89/8.

Wood, W.E. 1924. Increase of salt in soil and streams following the destruction of the native vegetation. Journal of the Royal Society, Western Australia, 10, 35–47.

Xianmo Zhu and Mei'e Ren. 2000. The Loess Plateau- Its Formation, Soil and Water Losses, and Control of the Yellow River, Soil erosion and dryland farming Ed John M. Laflan. CRC Press, New York. 1–5.