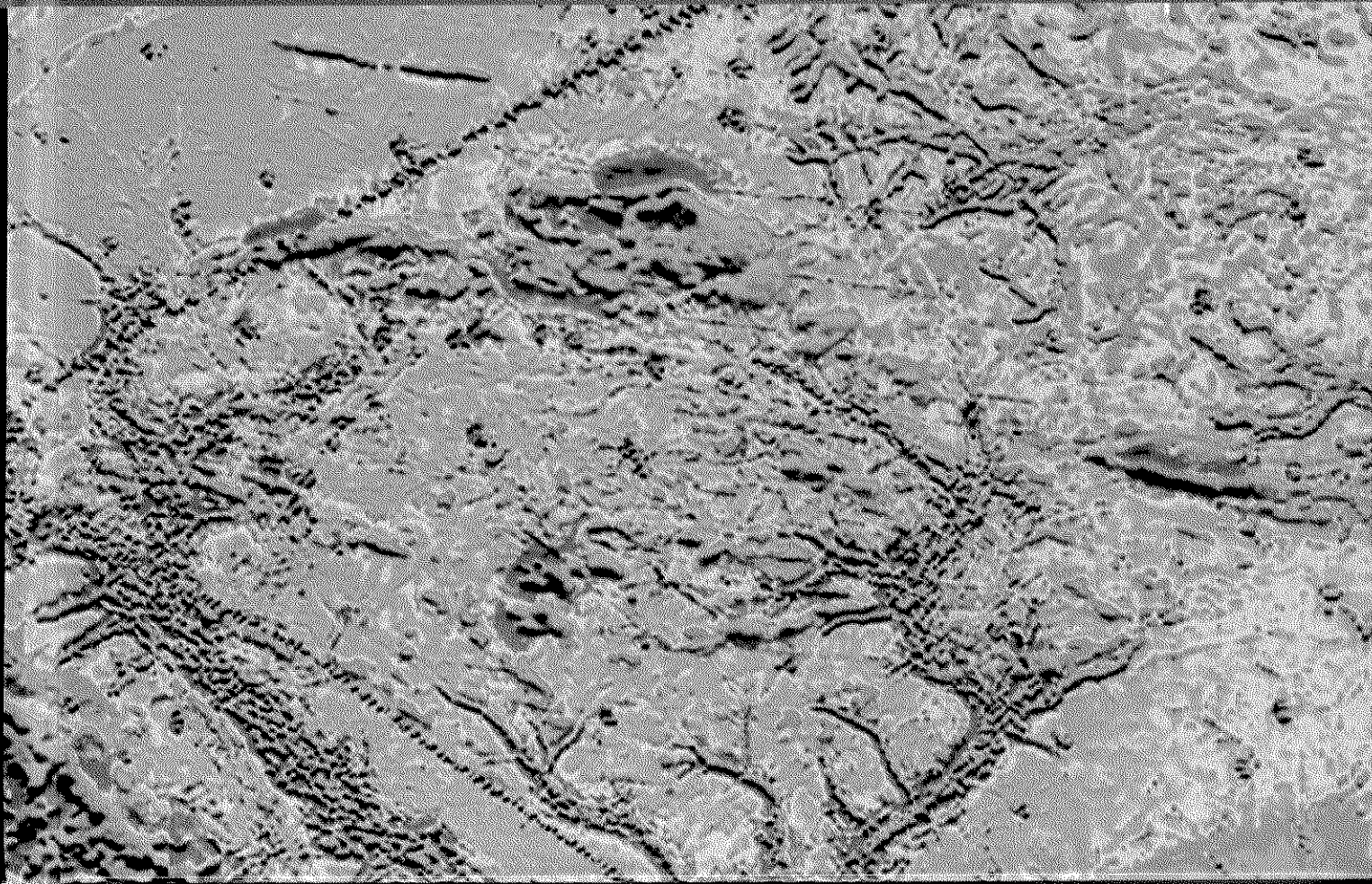


KEITH M SCOTT AND COLIN F PAIN

regolith SCIENCE



© CSIRO 2008

All rights reserved. Except under the conditions described in the Australian *Copyright Act 1968* and subsequent amendments, no part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, duplicating or otherwise, without the prior permission of the copyright owner. Contact CSIRO PUBLISHING for all permission requests.

National Library of Australia Cataloguing-in-Publication entry

Regolith science/editors, Keith M. Scott, Colin F. Pain.

9780643093966 (hbk.)

Includes index.

Bibliography.

Regolith.

Geomorphology.

Scott, Keith M.

Pain, C. F.

551.41

Published exclusively in Australia and New Zealand by:

CSIRO PUBLISHING

150 Oxford Street (PO Box 1139)

Collingwood VIC 3066

Australia

Telephone: +61 3 9662 7666

Local call: 1300 788 000 (Australia only)

Fax: +61 3 9662 7555

Email: publishing.sales@csiro.au

Web site: www.publish.csiro.au

Published exclusively throughout the world (excluding Australia and New Zealand) by Springer,
with ISBN 978 1 4020 8859 9

Springer

Van Godewijckstraat 30

3311 GX Dordrecht

The Netherlands

Tel: +31 78 657 60 00

Fax: +31 78 657 65 55

Web site: springer.com

Front cover: A pseudocoloured 1st vertical derivative magnetic image for the West Wyalong area in NSW, Australia.
Data supplied by Geoscience Australia.

Back cover (from left): A Ternary image of radiometrics (data supplied by Geoscience Australia); a pseudocoloured total magnetic intensity image (TMI) shaded by a 1st vertical derivative (data supplied by Geoscience Australia); a regolith landform map of Ebagooola, producing in a GIS environment.

Set in 10/13 Adobe Minion and ITC Stone Sans

Edited by Peter Storer

Cover and text design by James Kelly

Typeset by Desktop Concepts Pty Ltd, Melbourne

Index by Russell Brooks

Printed in Australia by Ligare

Contents

Preface	vii	9 Regolith geophysics	219
Acknowledgements	viii	<i>Tim Munday</i>	
Contributors	ix		
1 Introduction	1	10 Regolith and water	251
<i>Keith M Scott and Colin F Pain</i>		<i>Richard G Cresswell and Paul Shand</i>	
2 Regolith through time	7	11 Regolith description and mapping	281
<i>Brad Pillans</i>		<i>Colin F Pain</i>	
3 Landscape and regolith	31	12 Soils and natural resource management	307
<i>Graham Taylor</i>		<i>Robert W Fitzpatrick</i>	
4 Regolith mineralogy	45	13 Regolith sampling for geochemical exploration	341
<i>Richard A Eggleton</i>		<i>Charles R M Butt, Keith M Scott, Matthias Cornelius and Ian D M Robertson</i>	
5 Regolith geochemistry	73	14 Extraterrestrial regolith	377
<i>Kenneth G McQueen</i>		<i>Jonathan D A Clarke</i>	
6 Rock weathering and structure of the regolith	105	Appendix 1: Glossary of regolith terms	409
<i>Kenneth G McQueen and Keith M Scott</i>		<i>Richard A Eggleton, Colin F Pain and Keith M Scott</i>	
7 Geomicrobiology of the regolith	127	Appendix 2: Regolith geochemistry of elements	433
<i>Frank Reith, Mira Dürr, Susan Welch and Stephen L Rogers</i>		<i>Keith M Scott</i>	
Colour plates	159	Index	453
8 Regolith and biota	175		
<i>John Field and David Little</i>			

Contributors

Charles R M Butt

CRC LEME, CSIRO Exploration and Mining, PO Box 1130, Bentley, WA 6102.

Jonathan D A Clarke

CRC LEME, Geoscience Australia, PO Box 378, Canberra, ACT 2601.

Matthias Cornelius

Cullen Resources Ltd, 7 Hardy Street, South Perth, WA 6151.

Richard G Cresswell

CRC LEME, CSIRO Land and Water, 120 Meiers Road, Indooroopilly, QLD 4068.

Mira Dürr

CSIRO Land and Water, Private Bag 2, Glen Osmond, SA 5064.

Richard A Eggleton

CRC LEME, Research School of Earth Sciences, Australian National University, Canberra, ACT 0200.

John Field

CRC LEME, Fenner School of Environment and Society, Australian National University, Canberra, ACT 0200.

Robert W Fitzpatrick

CRC LEME, CSIRO Land and Water, Private Bag 2, Glen Osmond, SA 5064.

Kenneth G McQueen

CRC LEME, Research School of Earth Sciences, Australian National University, Canberra, ACT 0200; and Faculty of Applied Science, University of Canberra, ACT 2600.

Tim Munday

CRC LEME, CSIRO Exploration and Mining, PO Box 1130, Bentley, WA 6102.

David Little

Earth Tech, PO Box 5109, Townsville, Qld 4810.

Colin F Pain

CRC LEME, Geoscience Australia, PO Box 378, Canberra, ACT 2601.

Brad Pillans

CRC LEME, Research School of Earth Sciences, Australian National University, Canberra, ACT 0200.

Frank Reith

CRC LEME, CSIRO Exploration and Mining, PO Box 1130, Bentley, WA 6102.

Ian D M Robertson

CRC LEME, CSIRO Exploration and Mining, PO Box 1130, Bentley, WA 6102.

Stephen L Rogers

CRC LEME, CSIRO Exploration and Mining, PO Box 1130, Bentley, WA 6102.

Keith M Scott

CRC LEME, CSIRO Exploration and Mining, PO Box 136, North Ryde, NSW 1670, and Research School of Earth Sciences, Australian National University, Canberra, ACT 0200.

Paul Shand

CRC LEME, CSIRO Land and Water, Private Bag 2, Glen Osmond, SA 5064.

Graham Taylor

University of Canberra, Canberra, ACT 2601.

Susan Welch

School of Earth Sciences, Ohio State University, Columbus, Ohio 43210, USA.

8 Regolith and biota

John Field and David Little

8.1 INTRODUCTION

The effects of biota on the Earth's regolith occur at scales from 10^{-9} to 10^2 metres (Figure 8.1). Organisms – ranging from organic molecules and bacteria (Chapter 7), through those visible to the naked eye, to the largest living organisms (the giant trees) – all take part in the formation and distribution of the regolith (Field 2003). Although the importance of the biological component of the regolith was recognised hundreds of years ago (Chapter 1.5), re-emphasis has been given to it by the recognition that life depends on the environment provided by the 'critical zone' (Brantley *et al.* 2007).

At the small scale, initial weathering by organisms may be physical, such as when fungal hyphae and root hairs disrupt mineral grains but that physical disruption expedites the chemical breakdown of minerals by releasing CO_2 and, in a moist environment, vastly enhances the levels of carbonic acid above the abiotic concentrations at the weathering interface, while exuding low-molecular-weight organic acids (LMWOAs) (see also Chapter 7). At larger scales, material brought to the surface by burrowing animals has even led to the discovery of major mineralisation, such as malachite lumps in material excavated by wombats at Moonta, South Australia (Pryor 1962). Finally, at the regional scale, there is the general

protection and moistening effect of vegetation and litter, which encourage the ecosystem to colonise, exploit and grow, while maintaining moist conditions for mostly organic acids to attack the alumino-silicates and enhance weathering effects. This chapter considers the effects of biota on regolith materials at small to large scales (the effects of microorganisms having already been discussed in Chapter 7).

8.2 BIOTIC EFFECTS AND PROCESSES AT SMALL OR MICRO SCALES

8.2.1 Microorganisms and weathering – geomicrobial reactions

A huge variety of microorganisms is involved in the breakdown of rocks and primary minerals: bacteria and archaea (discussed in Chapter 7), algae, fungi, including mycorrhizae (Figures 8.2 and 8.3; Section 8.2.2), protozoans, and symbionts such as lichens (see Section 8.3.4). A few examples will be used here to demonstrate the widespread distribution and critical roles microorganisms play in weathering and regolith formation (see Banfield *et al.* (1999) for an excellent overall review).

The cycling of some elements is controlled by microbes: for example, the cycling of N (see also Section 7.3.2). Nitrogen is not available from

Metres	Particles	Minerals	Biota	Pores and Function	
10 ⁻¹⁰ (Å)	Atoms	S E C O N D A R Y M I N E R A L S	Organic molecules	MICROPORES	
10 ⁻⁹ (nm)	Molecules		Polysaccharides Humic and fulvic acids	Absorbed and inter-crystalline water	
10 ⁻⁸	Macromolecules		M I N E R A L S	MICRO-ORGANISMS Viruses Algae	MESOPORES
10 ⁻⁷	Colloids Sesquioxides Clay minerals			Bacteria Fungal hyphae	
10 ⁻⁶ (µm)	Silt			MICRO FAUNA MICRO FLORA Protozoa Nematoda Root hairs Microfungi, fungal hyphae	MACROPORES
10 ⁻⁵	Sand		Algal bodies, fungi, fruiting bodies Fine roots Mites, springtails Termites, ants	Aeration	
10 ⁻⁴			M I N E R A L S	MESO FAUNA Millipedes, centipedes, earthworms Rodents, fossorials	Fast drainage
10 ⁻³ (mm)	Gravel			COARSE ROOTS FLORA - herbs, forbs, grasses FAUNA - wombats, pigs, dogs	Root holes, burrows
10 ⁻² (cm)			Pebbles	MACRO FAUNA - buffaloes, elephants	Pipes and Tunneling
10 ⁻¹	Cobbles		M I N E R A L S	MACRO FLORA - trees	Gully head collapse
10 ⁰	Boulders	MACRO FAUNA - buffaloes, elephants		Underground flows, caves	
10 ¹		MACRO FLORA - trees		Aquifers	
10 ²					

JF001-08

Figure 8.1: Scales relevant to biota in the regolith: mineral and biological constituents of soils and the size and function of pores.

alumino-silicate weathering, but is fixed from atmospheric sources by microbes both in a symbiotic relationship with plants and as free standing organisms. The mineralisation and nitrification of N in the regolith are processes carried out almost exclusively by microorganisms, and the movement into plants that are not N fixers

is managed by the soil fungi. Nitrogen is moved out again during decomposition of plant remains by a suite of micro (and macro) organisms (such as the gut flora of all the invertebrates from woodlice to earthworms).

Algae have been shown to be involved in active weathering in local topographic lows – even in arid

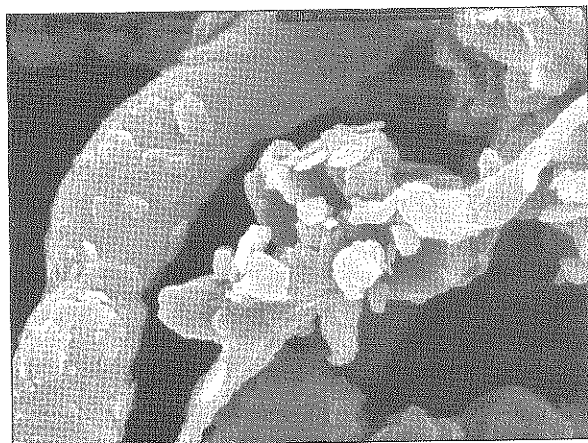


Figure 8.2: Root hair and mycorrhizal fungal hyphae (scale bar = 5 μm).

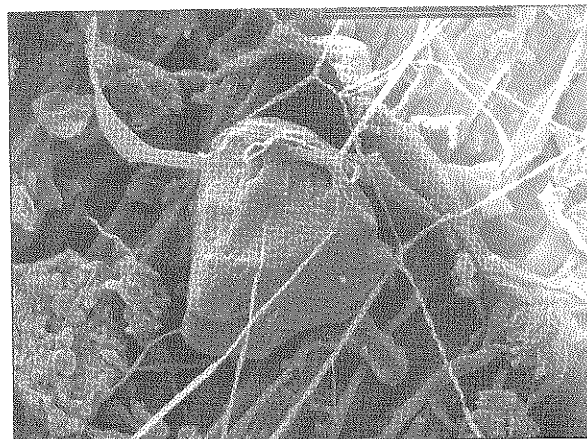


Figure 8.3: Fungal hyphae physically etch mineral grains (scale bar = 50 μm).

environments (Smith *et al.* 2000), where endolithic and epilithic algae are responsible for algal boring and plucking and etching of limestones (see also Section 8.3.5).

Soil fungi, and especially soil mycorrhizae, are an extremely important component of the regolith and have been studied extensively because they are critical to plant growth, and thereby all forms of agriculture and forestry. Fungi are implicated in all the myriad processes in the rhizosphere and are generally studied in conjunction with a host plant. However, they can be shown to take part in weathering reactions even when isolated from all plants. For example, Yuan *et al.* (2004) demonstrated that several isolates of mycorrhizal fungi were capable of replacing interlayer K with protons and effused oxalate – leading to further weathering of both phlogopite and vermiculite.

The minerals (soil and primary), organic matter (living and dead) and microorganisms are three critical components of regolith that control weathering (Huang 2000) and none of these can be considered in isolation. The regolith ecosystem has to be considered as a whole and understood at the atomic, molecular and microscopic level to make sense of weathering changes. The most important location for these changes is the rhizosphere, where the kinds and combinations of biomolecules are at a maximum (enhanced biological activity) and are also often different to the bulk soil (Theng and Orchard 1995).

8.2.2 The rhizosphere, rhizoplane, rhizodeposition and root exudates

The rhizosphere – the narrow zone of soils surrounding plant roots and directly impacted on by their activity (Allaby 1998; Eggleton 2001) – and rhizoplane (the surface of the root or root hair in contact with the organisms, organic matter and aluminosilicates in the rhizosphere) are of particular interest because this is one of the most biologically active zones in soils and regolith (for example, Bolan *et al.* 1997; Jones *et al.* 2003) (Figure 8.4). Root exudates and the rhizosphere microbial community are likely to prove particularly important in soil weathering because the exudates are likely to increase mineral weathering through their acidity and complexing ability, and also provide nutrition for microbial communities that mine metal nutrients from soil minerals – thereby indirectly increasing chemical weathering rates (for example, Chorover and Amistadi 2001; Martino *et al.* 2003). However, there is still considerable controversy regarding specific pedogenic implications of many rhizosphere processes (Drever and Stillings 1997; Jones *et al.* 2003).

8.2.3 Soil mineral–organic acid–microorganism interactions

There is a diverse set of organic acids involved in the biochemical reactions taking place in the regolith. These include ascorbic, aspartic, citric, fulvic and humic (individual acids and acid groups), hydroxybenzoic, malic, oxalic and tannic acids. These are

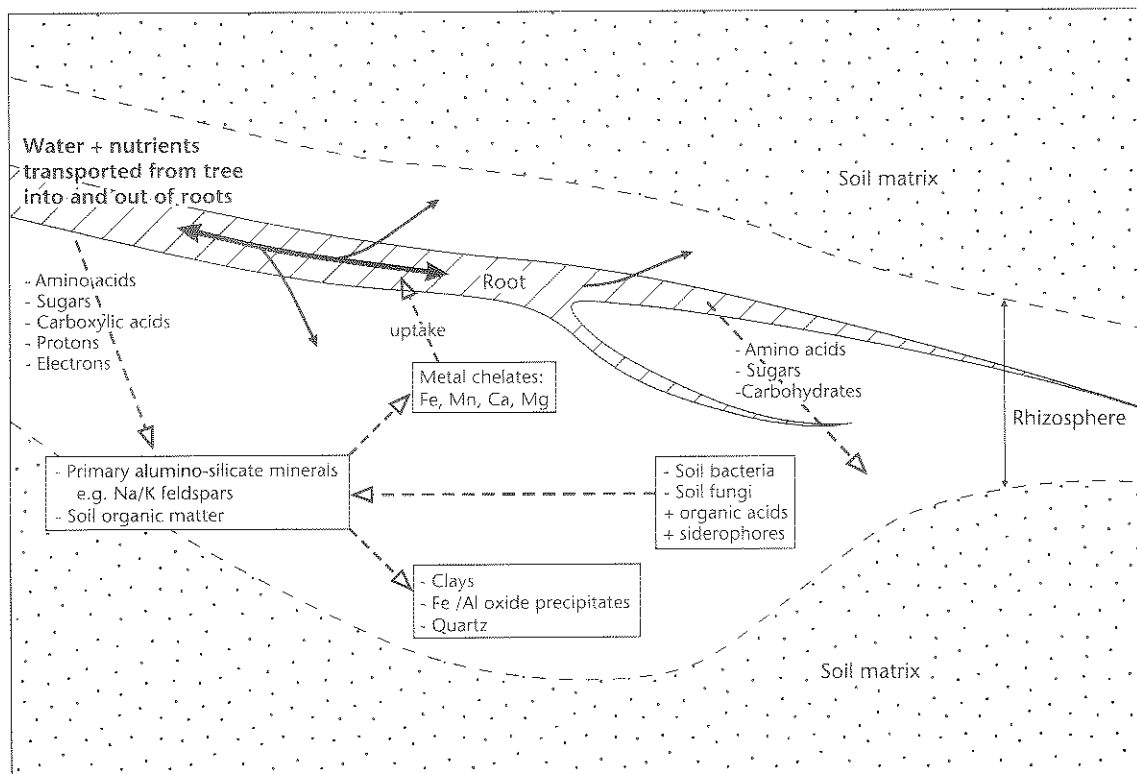


Figure 8.4: The rhizosphere

commonly grouped as the carboxylic acids, or the LMWOAs (the term used in this chapter; see also Appendix 1). In general, organic acids form (and are often called) ligands by accepting an electron, and they can react with ions (particularly metal and metalloid cations and anions) to form (organic) complexes. This group of biochemical reactions are at the core of aluminosilicate mineral weathering – with rates markedly increasing in the presence of virtually all organic acids (Chapter 7.4.3).

There are multiple sources of these organic acids, but one is from root exudates. Little (2007) found that Al was accumulated as either clay minerals or Al oxides in the rhizoplane, and for up to 100 μm beyond, with Fe and Ca showing slight accumulation in the outer parts of the root (Figure 8.5, page 159). Little *et al.* (2005a) showed that concentrations of elements such as Al, and Fe were up to 10 times higher, while Si was 2–5 times greater in solutions containing the dicarboxylic LMWOAs (oxalic, malic and citric acids) when compared with control solutions such as NaCl.

However, these acids cannot be considered in isolation because each particular acid, and its concentration and distribution, is, in turn, controlled by the microorganisms, the location in the regolith as related to the surrounding rhizosphere(s) and the aluminosilicate mineral context.

8.2.4 The rhizosphere as an ecosystem and the effects on regolith

The soil microbial community is heterogenous – varying between vegetation and soil type, soil horizons, between rhizosphere and non-rhizosphere soil compartments, and at even finer scales (Marilley and Aragno 1999; Marschner *et al.* 2005). What is clear, however, is the extent of influence. Root length and distribution – as well as fungal hyphae and other organisms associated with roots – are so extensive that virtually all the active soil (A and B horizons) is involved. Thus, up to 1.6 m of soil is involved for grasses and much greater depths for large trees (Figures 8.6 and 8.7). There are a number of ‘guilds’ of

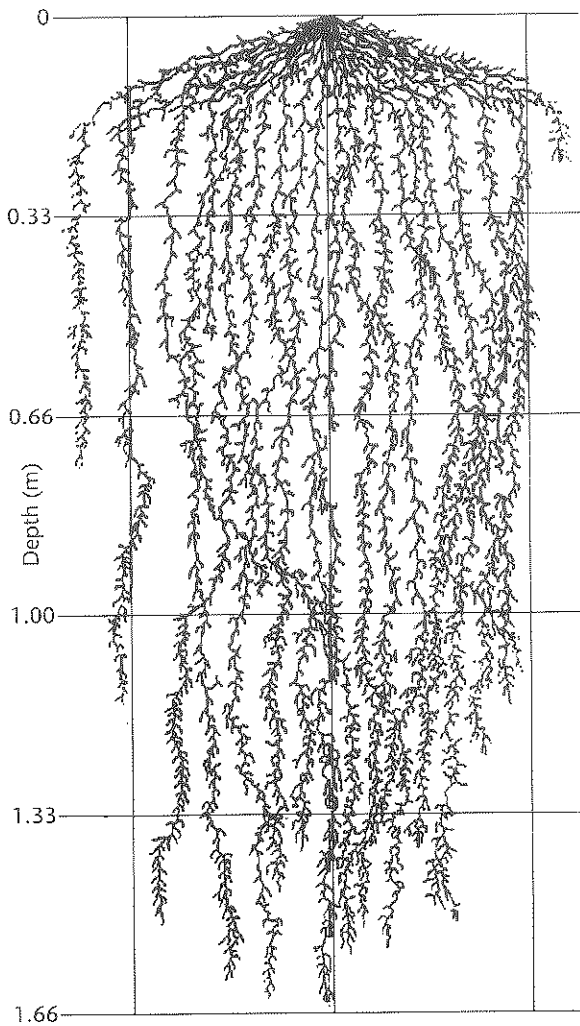


Figure 8.6: The root system of rye (a grass) grown in dry sandy soil showing only primary and secondary roots (from Gilkes 1998).

soil microorganisms – bacterial and fungal – responsible for biogeochemical processes of metal elements in soils. Saprotrophic fungi are responsible for much of the litter decomposition in forest soils: liberating elements from dead plant and animal materials back into the surface soil environment (Cairney and Meharg 2002; Smith 1982). Two important components of these recycling processes are dissolved CO_2 (a weak acid) and LMWOAs, which are able to change soil solution pH, provide vital nutrition for other microorganisms or directly react with soil minerals (Jones *et al.* 2003; Marschner and Kalbitz 2003). In an

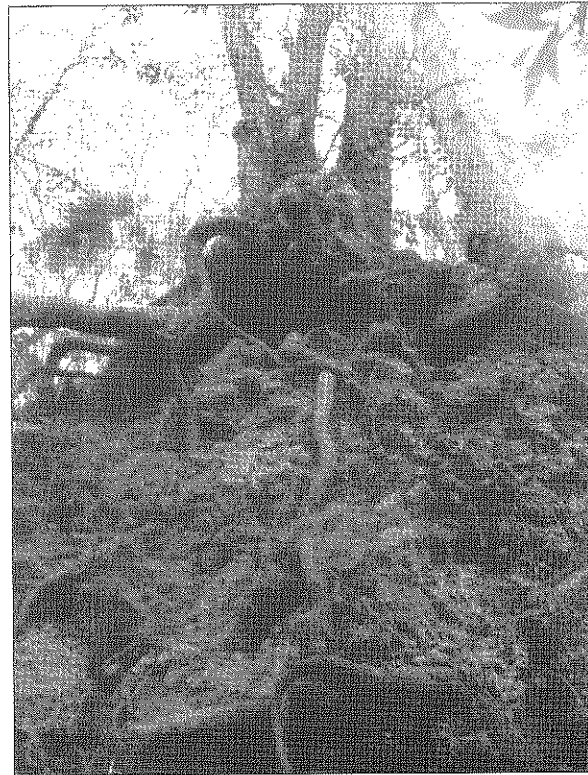


Figure 8.7: Extensive tree roots (2.5 m of soil in photo) allow greater infiltration of water and provide organic matter throughout the regolith – driving weathering.

ideal forest, the mobilised elements would then be readily available for uptake by tree roots, although this is not necessarily the case due to the inability of the trees to take up all forms of dissolved metal nutrients. It is nevertheless possible to observe mutual relationships between saprotrophic and mycorrhizal fungi, which overcome this barrier – at least in part (Cairney and Meharg 2002; Stone 1997).

One aspect of the rhizosphere that has received considerable attention in recent years is the formation of mycorrhizal symbioses, which have evolved as an improved nutrient uptake pathway for most terrestrial plant species (Brundett 2002). Mutualistic or symbiotic relationships are observed between plant roots and microorganisms that are able to extract elements such as N and P from the regolith, transform the elements into forms that can be taken up by, or transfer the element directly to, the plant roots (Curl and Truelove 1986; Hagerberg *et al.* 2003). These

relationships are strongly developed in many Australian ecosystems, where complex nutrient conservation and recycling mechanisms have evolved in nutrient-limiting landscapes (for example, Marschner *et al.* 2005). Mycorrhizal fungi are especially important agents for uptake of P and K (Fomina *et al.* 2005).

The abundance and diversity of microorganisms is strongly influenced by the roots of many plant species and, in most cases, the populations in the rhizosphere are much larger and more diverse than in adjacent non-rhizosphere soils (Gomes *et al.* 2003; Marschner *et al.* 2005). In addition, there are many studies that demonstrate the ability of mycorrhizal fungi and symbiotic bacteria to enhance metal nutrient uptake (such as Fe and K) in plants – as well as to accumulate trace metals, such as Cd, Cu, Pb and Zn, thus reducing their toxic effects (Cromack *et al.* 1979; Hulme and Hill 2003; van Hees *et al.* 2004; Raapana and Field 2006). There are three major groups of micro symbionts associated with tree roots in Australian ecosystems that show varying degrees of host specificity. The *Frankia* spp., mycorrhiza and some *Rhizobium* spp. are particularly important for nutrient uptake in plants of the Casuarinaceae, Myrtaceae and Mimosaceae families, respectively (Reddell *et al.* 1997; Brundett 2002). These micro symbionts expand the surface area of infected tree roots, make otherwise unavailable nutrients available for uptake and extend the effective rhizosphere into parts of the regolith that tree roots cannot reach (Hoffland *et al.* 2003; Paris *et al.* 1995) – thus having a potentially profound influence on chemical weathering in soils.

Recent technological advances have improved the investigation of root growth, as well as *in situ* sampling of rhizosphere soil water (Vogt *et al.* 1998; Arocena *et al.* 2004). Rhizotrons fitted with small digital cameras and micro suction cups allow detailed, non-destructive examination of root growth – as well as nutrient and water uptake and exudates from plant roots (Pan *et al.* 1998; Arocena *et al.* 2004). These rhizotrons can be installed beneath mature field-grown trees or agricultural lands – or scaled down versions (such as root study containers or rhizoboxes) can be used as controlled environments in nursery-scale microcosm and mesocosm investigations of rhizosphere biogeochemistry (for example, Arocena *et al.* 2004; Sandnes *et al.* 2005). Rapidly developing methodologies are also

being applied in order to understand a wide range of molecular-scaled microbe-to-mineral interactions that occur in soils (Vancura and Kunc 1987; Welch and Banfield 2002), and might be particularly useful in helping to distinguish between rhizosphere communities – where root exudates are major sources of microbial nutrition – from adjacent non-rhizosphere communities. It can be argued that deoxy ribonuclease (DNA) extraction followed by polymerase chain reaction (PCR) and Biolog sole C source utilisation experiments – when used in combination – are particularly effective tools for examining microbial community structural and functional diversity in samples from a range environments (Zak *et al.* 1994; Hernesmaa *et al.* 2005; Little *et al.* 2005b). Investigation of organic acid–soil mineral interactions in the rhizosphere is becoming more common as the importance of root and microbial metabolites in soil biogeochemical processes is increasingly recognised (Qin *et al.* 2004; Little *et al.* 2005a). In addition, there have been growing numbers of studies examining bioturbation (Holt *et al.* 1980; Field and Anderson 2003), and the effects of bacterial and fungal communities and organic acid anions on dissolution from pure mineral separates (Barker *et al.* 1998; Welch and Banfield 2002; Welch *et al.* 2002). The remainder of this section covers the application of a range of analytical techniques adapted for, and used in, fine-scale investigations of some of the different aspects of rhizosphere biogeochemistry.

Since the rhizosphere is such a complex micro-environment, it is difficult to develop analytical techniques that are specifically targeted at the biotic and abiotic components and the interactions between them. In most cases standard techniques for examination of bulk soil samples can be modified for use in the rhizosphere (for example, Kirk *et al.* 2004; Seguin *et al.* 2004). These techniques are often very expensive – and can be time consuming – as well as being limited in their application due to small sample sizes, difficulties associated with sampling live roots from field grown plants, and changed conditions when examining the rhizosphere in nursery and/or microcosm experiments (Haag and Matschonat 2001; Singh *et al.* 2004). It is therefore imperative to understand the biogeochemical processes that are likely to be important in the selected environment in order to target the

specific biogeochemical processes under investigation. In addition, it is often difficult to replicate all soil habitat factors without introducing artefacts to the experiment (Haag and Matschonat 2001). Nevertheless recent advances in geochemical sampling techniques – and the application of molecular biology and genomic studies to soil ecosystems – now allow soil ecologists to begin elucidating nano- to micro-scale biogeochemical pathways in soils and regolith. To date, few investigations use truly multidisciplinary approaches to examine the organic acid–microbe–mineral interactions occurring in the rhizosphere (Little *et al.* 2005a, b), which is surprising given that the complex root–microbe–mineral interactions, and their importance in soil formation, were first eluded to in 1904 (Hiltner 1904), which was nearly 40 years before Jenny restated soil formation as a function of interactions between climate, geology, topography and biology – all acting over time (Jenny 1941).

Understanding soil biogeochemistry in the rhizosphere of forest soils is particularly challenging due to the fine scales of investigation and the myriad of root–microbe–soil interactions occurring there. A particularly important consideration is which combination of molecular and culture-based approaches are most suitable for examining the resident soil microbial communities. Culture-based techniques, such as Biolog, give an indication of different microbial characteristics to those measured using restricted length fragment polymerisation (RLFP), fatty acid methyl esters (FAME) or polymerase chain reaction denaturing gradient gel electrophoresis (PCR DGGE) techniques (Buyer and Drinkwater 1997; Ramsey *et al.* 2006). However, while these techniques are all capable of identifying potential shifts in microbial community structure and function, the differences identified by one method may not necessarily be reflected by the results of other techniques. For example, when using FAME profiling in combination with PCR DGGE, Kozdroj and van Elsas (2000) found that a greater response to artificial root exudates were observed in the culturable fraction of the soil microbial community. In another study by (Widmer *et al.* 2001), it was demonstrated that DNA extraction with RLFP, phospholipid fatty acid and Biolog techniques identified a number of similarities and differences between microbial communities from

different sites – showing also that differences in community structure identified by one technique may not necessarily be reflected by similar differentiation using another, because each takes advantage of different aspects of the microbial community. Thus, the complementary use of two or more techniques can give a more comprehensive view of specific aspects of the potential structural and functional diversity of soil microbial communities.

8.2.5 Biotic paleoforms in regolith

Rhizomorphs, root channels and pore casts have been recognised in paleosols by a variety of workers (for example, Anand and Paine 2002). Their interpretation can lead to paleoclimate analysis and recognition of the processes acting at the time that the paleosol formed. Paleosols between basalt flows have been shown to contain ‘fossilised’ root traces among a suite of other characteristics, such as horizonation, ped structure, fossil plants and gastropods, and weathering indices consistent with pedogenesis, such as high K in paleosurface horizons (Sheldon 2003). In the sandstones of McMurdo Dry Valleys, Antarctica, Wierzchos *et al.* (2006) have demonstrated that endolithic microorganisms have their structures, such as cell walls, mineralised after death – along with allochthonous clay minerals and sulfate-rich salts filling the sandstone pores.

8.3 BIOTIC EFFECTS AND PROCESSES AT LOCAL OR MESO SCALES

As seen in Section 7.4, there is a complex interaction between the biotic and abiotic components of the regolith. Organisms are highly dependent on the soils in which they grow and, in turn, the physical structure and chemical and mineralogical composition of the regolith depend on the actions of these same organisms (Corbet 1935; Vancura and Kunc 1987). Locally active soil fauna and flora are important in maintaining soil stability and soil turnover – as well as organic matter addition and turnover (Burgess 1958; Nannipieri *et al.* 2003), which all have important consequences for pedogenic and regolith evolution.

At the local scale, individual organisms such as large trees may become ecosystems in their own right.

Other organisms such as termites or ants may be organised into groups or colonies.

8.3.1 Biochemical uptake and redistribution of regolith materials by plants

Plants include the largest sedentary organisms – trees – and, as a result, their effects can be seen at the local and meso scale and on a timescale allowing direct observation by humans. However, and despite the obvious feedback between organisms and the soils they depend upon, there has been little research on how organisms affect regolith characteristics – particularly the biochemistry and geochemistry – and especially in Australian landscapes (Hamilton 1972; Leonard and Field 2003, 2004). Rather, most studies aim to understand plant physiological processes, such as nutrient uptake, where essential and metal elements are either in deficit or in excess (Gadd 2004; Fomina *et al.* 2005), or where they are only biologically available (bioavailable) in specific forms. For example, most plants require Fe^{3+} for their nutritional requirements rather than Fe^{2+} , but Fe^{3+} is relatively insoluble in soils (Figure 5.7).

Some groups of metals can be regarded as both biologically important and derived from weathering (K, P, Ca, Mg, Zn, Cu, Ni, Co, Fe, Mn and Si) and these appear to vary less across organisms and space – particularly when compared with the non-nutrients (such as Al, Na, As, Ag, Au, Pb and U). The important elements range from highly deficient levels, where they are individually or collectively so low as to be limiting factors, to levels so high that they are toxic. In addition, plants of different genera take up a variety of elements at quite different rates and in different ionic and chelated forms (Leonard and Field 2004). For example plants, and plant parts, that are highest in Fe may or may not be the highest in Mn. Plants can be divided into accumulators (and hypo accumulators), passive plants and excluders (Baker 1981).

Biogeochemical cycling, geobotany, bioprospecting and biointrusion

Of particular interest to this study is how trees alter soil mineralogy and geochemistry as a result of biogeochemical cycling processes, such as rainfall modification through stem flow and canopy drip,

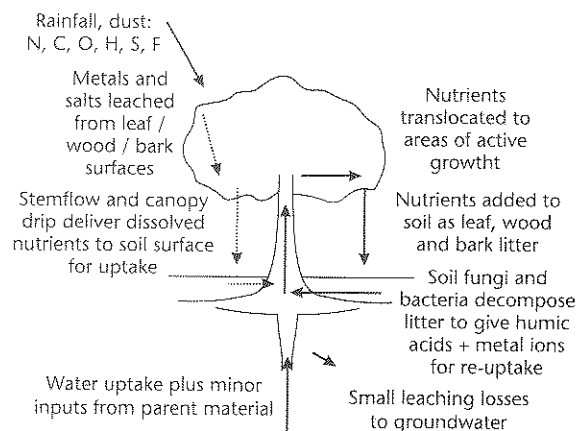


Figure 8.8: A simplified biogeochemical cycle based on a single tree.

litter fall and its decomposition (Figure 8.8), and the alteration of the underlying soil by uptake of metal nutrients (Figure 8.9) (Field 1983; Gilkes 1998; Gobran *et al.* 2001). However, from a geochemical-exploration point of view (Section 13.8), very little is known about the processes of uptake, distribution, redistribution and loss from plants in Australia.

Plant biochemistry reflects the chemistry of the materials in which plants grow. Hence, geobotany, bioprospecting, biomining and biointrusion are all fields of active research. *Geobotany* can be defined as the study of the relationships between the geochemistry (and mineralogy) of the substrate lithology and overlying regolith and the biochemistry of the different organs of the plant. *Bioprospecting* is a process whereby plant organs are sampled within an area to search for signs of concealed mineralisation. Because plants draw on large quantities of regolith, soils and groundwater within the rooting zone, they act as integrators and concentrators. The use of accumulator plants can increase the likelihood of finding geochemical anomalies because the plants actively collect particular elements and concentrate them in specific organs (Section 13.8). Work by Hulme and Hill (2003) has begun to differentiate amalgamators (usually perennial plants that sample a wide area of regolith) from penetrators (plants with deep tap root-type accession in the regolith) and to establish geobotanical associations of widely dispersed plants that can be used in geobotanical mineral exploration. *Biomining* uses

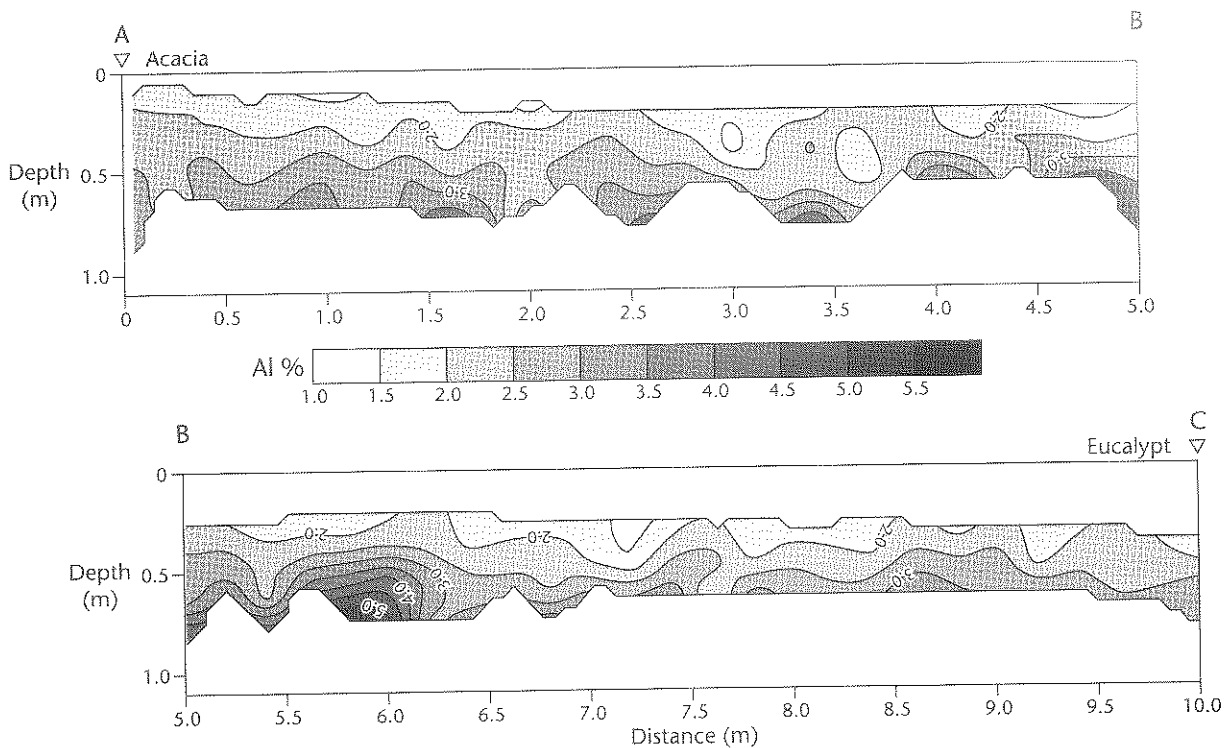


Figure 8.9: Distribution of Al (%) in the sidewall of a costean dug from the tree bole of an *Acacia falciformis* at A to an *Eucalyptus mannifera* at C. Areas of marked concentration or depletion generally coincided with the presence of larger roots (after Leonard and Field 2003).

plants to concentrate elements – usually metals from otherwise sub-economic ore deposits – into plant organs which are then harvested and ‘mined’ (commonly by ashing and then extraction). *Bioinvasion* is the study of the ways in which plant roots (and other organisms such as vertebrate and invertebrate bioturbators) access materials that have been buried or sealed off to prevent leakage or contamination of the environment by toxic material. The role and efficacy of clay seals on waste dumps and tailing dams can be radically affected by colonising the surface with different plants and their concomitant ecosystems.

Species-specific differentiation and internal redistribution

For some time, the different paths of elements into, within and through the biota have been recognised. These paths vary between even closely related organisms. The ability of many Australian species of plants to internally recycle elements is also well known,

whereby nutrients are redistributed within the leaves, twigs, branches, bole and roots in response to growth points, atrophy and abscission, so as to maintain critical elements within the organism for its advantage and ongoing growth (Banks 1989; Little *et al.* 2003; Leonard and Field 2004; Heinrich and Banks 2006). Additional adaptations include:

- very deep roots (for example *Eucalyptus camaldulensis* down to 10 m vertically: Davies 1953; Hulme and Hill 2003)
- very widespread rooting systems (out 20 m from the bole and well beyond the generally accepted distribution under the drip zone: Mylius 1992; Dexter 1967)
- extensive shallow root mats and fungal mat associations (Rao 2005).

However, the variety of elements and the ways in which they are transferred and stored is not well understood (Leonard and Field 2003; Raapana and Field

2006). The plants that accumulate high levels of particular elements that may be toxic in other plants (such as Ni) are being researched because these accumulator plants (amalgamators or penetrators) represent options for industry to mine biologically (biomine) by growing particular plants on sub-economic mineralisation or stock piles and subsequently harvest the plants and process them as 'ore' (Baker 1981).

The recent research of Leonard and Field (2003; 2004), Moerkerken (2005) and Raapana and Field (2006) demonstrated the differences in uptake and redistribution between species. In particular, whether or not a plant species fixes N_2 becomes a major factor in regolith bulk chemistry, as do root architecture, soil organic matter and the depth to which weathering is effective. Some organisms require more or less of each element and concentrations do not always reflect the generally accepted levels for macro or micro nutrients (and non-nutrients) – particularly when concentrations in individual organs are examined (Raapana and Field 2006; Leonard and Field 2004).

In terms of redistribution within a tree, Leonard and Field (2004) have shown that the individual tree species is very important (including root architecture, rooting depth, rooting volume and the distribution of roots versus the regolith horizons), but Hulme and Hill (2003) have shown that, in addition, season and proximity to rainfall events in the arid zone – and the regolith in which the tree is growing, including source lithology, groundwater chemistry, regolith geochemistry, and landform setting – can all contribute to plant uptake and distribution within the plant. Roach and Walker (2005) also demonstrated the importance of aspect and season for sampling vegetative organs.

All these characteristics also seem to contribute to the processes of redistribution within the plant, and also whether or not particular elements are macro or micro nutrients, whatever their relative abundances in the regolith on which the tree is drawing. Both Leonard and Field (2003) and Hulme and Hill (2003) showed that Zn (an important micro nutrient) does not seem to be differentially redistributed, and that other element concentrations can vary between sites even if only a single plant species is considered. On the other hand, Zn was shown by Reid *et al* (2005) to have higher concentrations in spinifex over mineralisation.

Hulme and Hill (2003) concluded that many elements were preferentially concentrated in particular organs of the River Red Gums. They also showed that concentrations of elements, such as As, can be used in addition to Au for Au prospecting. Leonard and Field (2004) demonstrated the different ways that trees deal with macro and micro nutrients. Thus, K is not withdrawn from *Acacia* leaves before abscission to anywhere near the extent that it is in a eucalypt; and the converse is true for Fe in the branch tissue, but not in the bole (Figure 8.10).

Although Hulme and Hill (2003) discuss a simple model of uptake that does not include microorganisms, it is clear that the effects on elemental, ionic and complex concentrations, the affinity of these to regolith particles, and bonding and synergistic and antagonistic reactions, are amplified if microorganisms are interposed at the interface between roots and regolith (Little and Field 2003; Little *et al* 2005b).

Of course, individual members of the biota and the regolith interact in a multi-dimensional space, with cause and effect becoming bidirectional; that is, a two-way feedback loop is created. The niche that an organism finds most favourable (has a competitive advantage in) becomes the niche that the organism inhabits and, in so doing, creates feedback mechanisms, whereby that organism enhances the very conditions that make it most competitive in its niche: is this a chicken or egg question?

Aluminium, iron, manganese and silica mobility in the presence of biota

Metal oxides are ubiquitous in the regolith and are very significant and reactive molecules, particularly in acidic to neutral environments. However, organic compounds exert very strong controls on the environment – and on the metal oxides, their formation, and surface properties (Kwong *et al.* 1977). For example, the microbial oxidation of Mn can produce Mn oxide coatings on soil particles up to 5–10 times faster than abiotic oxidation (Tebo *et al.* 1997). The metal oxides have important reactions with soil nutrients, such as P, and therefore have enormous influence on ecosystem functioning and biomass. The extraction of nutrients such as P from the bulk matrix often leads to the precipitation of metal oxides such as Mn, Fe and Al on the sheath of fungal

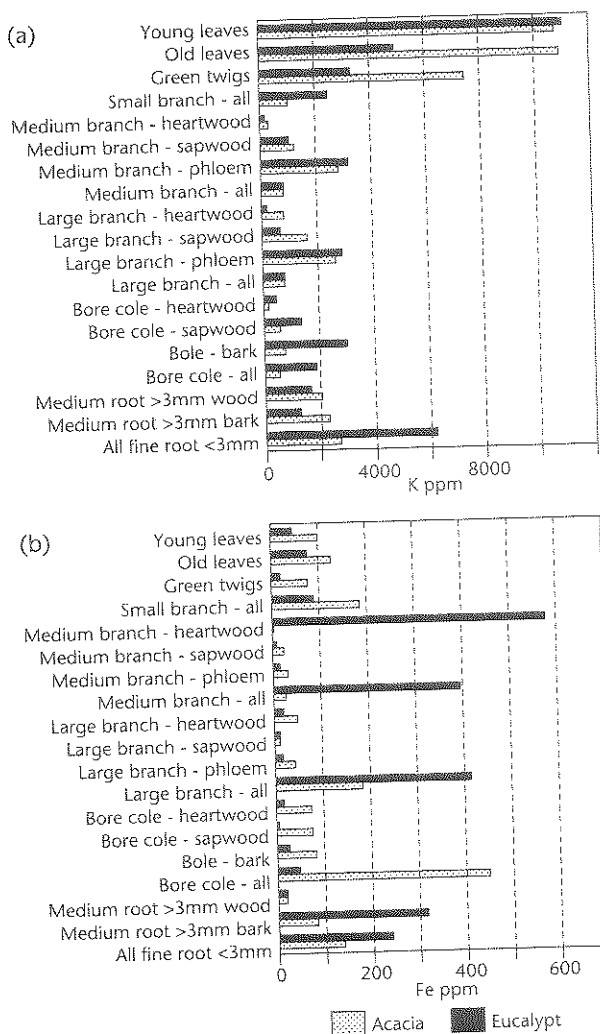


Figure 8.10: Distribution and redistribution of elements within the physiology of trees of two different species – *Acacia falciformis* and *Eucalypt mannifera* – for (a) the nutrient element K and (b) the micro nutrient Fe (after Leonard and Field 2004).

hyphae, and on the surface of root hairs – demonstrating the power of the biochemical processes fuelled by the biota (McLean *et al.* 2002). Recycling of elements, such as Si and Al, between the soil and trees has been documented by Gilkes 1988; Figure 8.11).

Phytoliths

Phytoliths (often, and literally, called a ‘plant stone’) are microscopic crystalline formations made up from a variety of elements and minerals (Hart 2001) that occur in various parts of many plants. The Si (or opal)

phytolith is most common – and varies in size, shape and ornamentation, depending on the plant part (stem, leaf and root) and taxa.

Generally, phytoliths have a similar distribution in regolith to organic matter (Alexandre *et al.* 1997), although specific patterns develop in different soil types (Hart and Humphreys 2003). In general, most biogenic Si is in the form of phytoliths, which seem to form two pools – those that are being recycled (about 90%) and those that remain in the soil as phytoliths for much longer periods of time (Alexandre *et al.* 1997). In systems that are high (or even saturated) in Si phytoliths appear to remain for longer and Si re-precipitation may take place close to the base of the active soil profile. In the case of an equatorial rainforest, the uptake by plants of Si increases the weathering and breakdown of aluminosilicate minerals, but does not increase the denudation rate because the Si is being cycled by the biota (Alexandre *et al.* 1997).

Phytoliths represent a direct impact on regolith biogeochemistry, with the control over aluminosilicate weathering by uptake of Si by plant roots (remove the products and move the reaction forward), the relocation of this Si onto, and then into, the soil horizons, and then its redistribution back down through the regolith.

8.3.2 Redistribution of regolith materials by plants and animals

Plants redistribute regolith materials in a number of obvious ways, but, in general, some of the processes responsible for the greatest quantities transferred are far less obvious. The chemical transfer of materials in solution by nutrient cycling, the uptake and storage of regolith materials in solution and storage in organic solids, and the control of biotransfers (even in the absence of vegetation such as following a conflagration) probably amount to the transfer of exponentially greater volumes of material, than the more obvious physical transfer. The latter also has many processes of redistribution, including root growth, that proceed very slowly making them less obvious, although the lifting of paths and general bulging upwards of the soil surface close to the boles of trees are easily measured once identified.

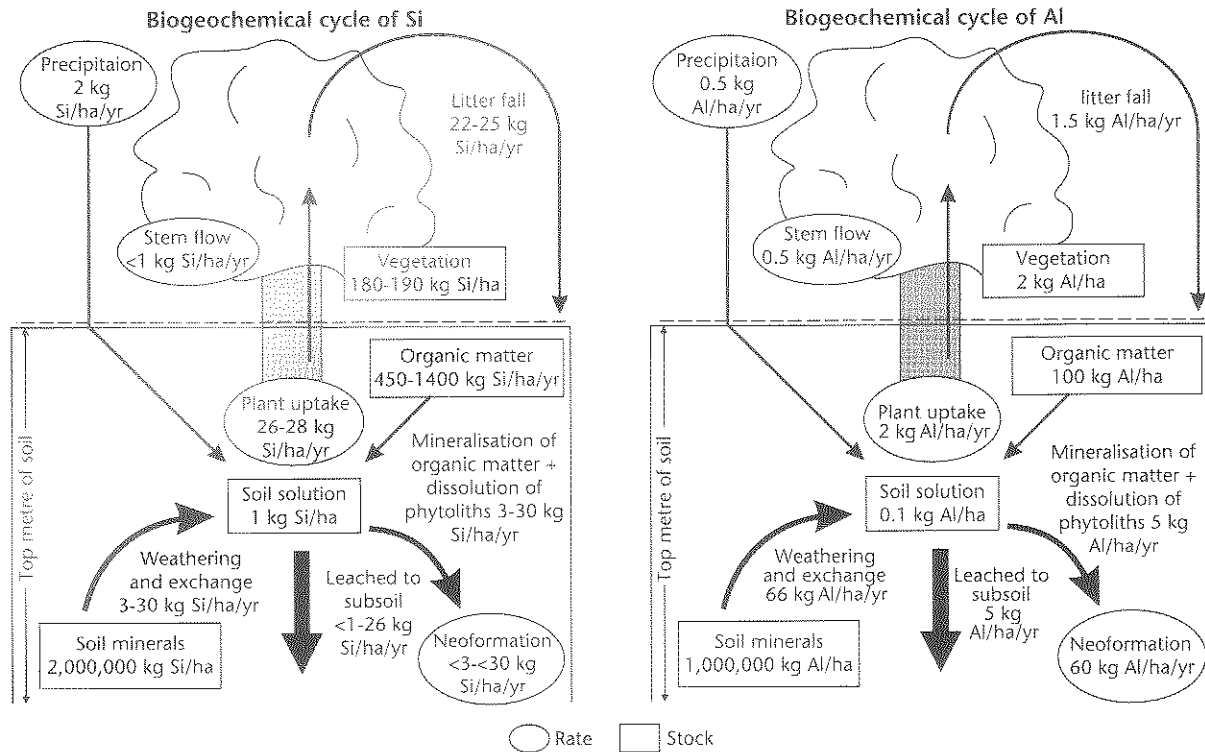


Figure 8.11: An approximate biogeochemical cycle for (a) Si and (b) Al in the solum and vegetation of temperate deciduous forests (after Gilkes 1998).

Root growth

Root growth and expansion occurs as a result of rapidly proliferating cells, and their subsequent expansion, at the tip (apical meristem), immediately behind the root cap and, to a lesser extent, along the sides (lateral meristem) of the roots and root hairs causes the regolith material to be moved upwards and to the sides with considerable force (1.45 MPa axially and 0.91 MPa radially; Bennie 1991) (Figure 8.12). Material usually doesn't return to its initial location at any time in the future on even slightly sloping land (Figure 8.13 and Section 8.3.5).

Tree fall

Tree fall creates a micro topography of pit and mound on slopes, and Norman *et al.* (1995) showed that the steeper the slope the greater the down-slope (and not back into the pit) movement of regolith material, while pits also became more elongate than round on steeper slopes (greater than 45 degrees).

Tree fall breaks up, and brings to the surface, bedrock, saprolite and sub soil (B horizons), increases

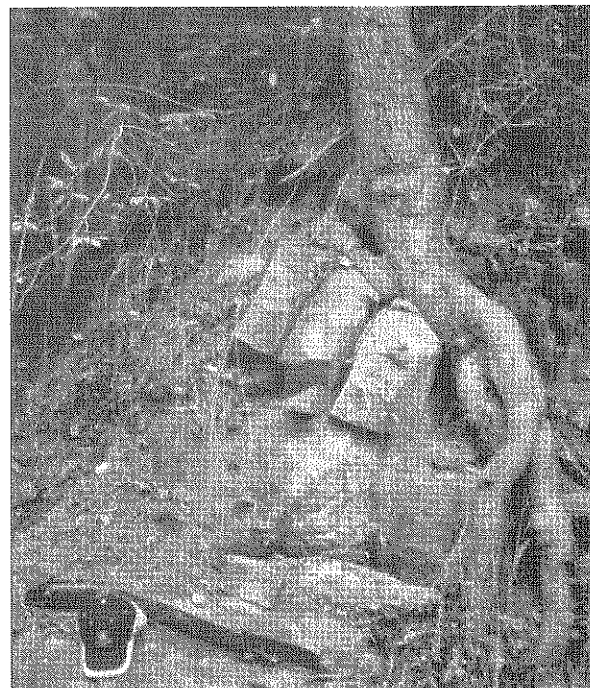


Figure 8.12: Wedging apart of rocks in regolith by large roots and tree boles.

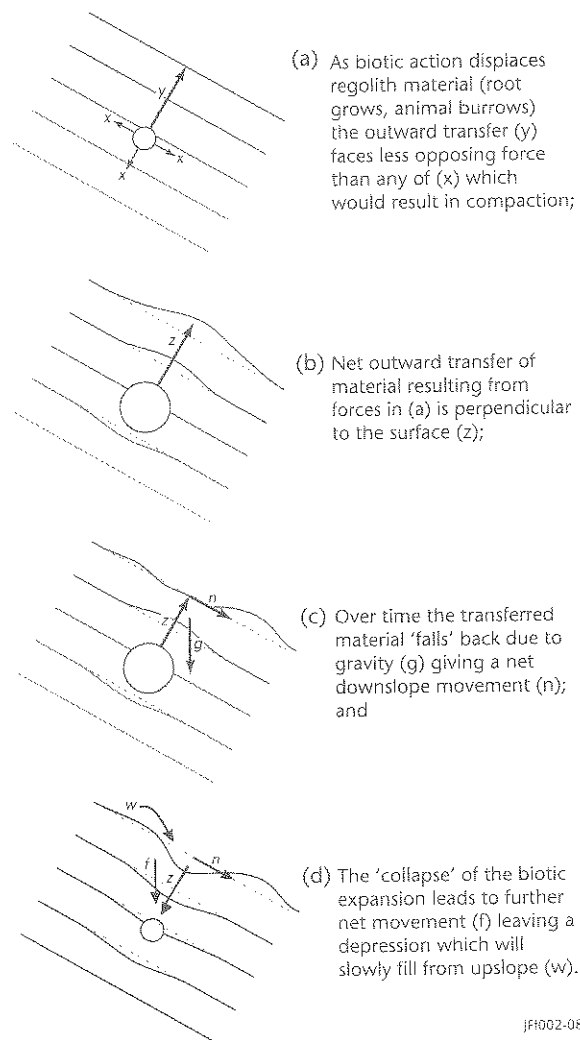


Figure 8.13: Down-slope transfer of regolith material by the growth and death of roots.

the heterogeneity of almost all soil characteristics and soil processes, such as metabolic and respiration rates, and may destroy (or sometimes enhance) soil horization. The pit and mound topography may have a micro relief of up to 0.5 m above and below soil level with mounds and pits being round to elliptical in shape and up to 5 m in diameter on average (Figure 8.14). Coverage seems to range widely, with northern hemisphere forests having up to 40% of the landscape covered by this micro topography (Denny and Goodlett 1956), while less than 1% is reported under tropical conditions (Putz 1983). The pits appear to fill more rapidly than the mounds flatten (Denny and Goodlett

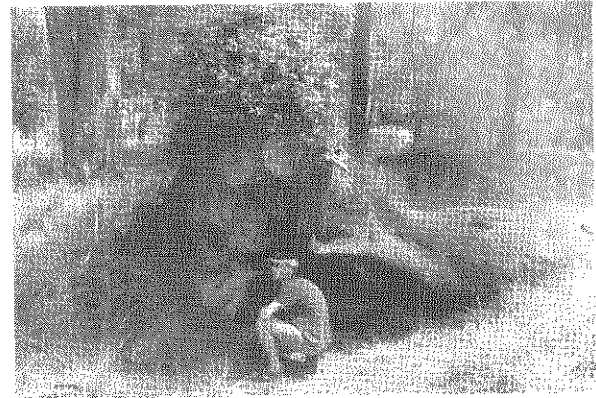


Figure 8.14: An example of the root plate from a large fallen eucalypt.

1956; Putz 1983), but the process seems to take several thousand years (Gabet *et al.* 2003). In fact, Osterkamp *et al.* (2005) have shown that partial rock veneers from tree fall (or root throw) can stabilise slopes in a sub-alpine setting over periods of several hundred years. Thus vegetation may not only stabilise a landscape during its life, but also once toppled and decomposing.

Litter fall and litter dams

Litter fall is an integral part of nutrient cycling, but is a much less obvious part of the effects of vegetation on the formation of regolith (Section 8.4.4). Its impacts include the redistribution of regolith components from depth to the surface (nutrients, non-nutrients, water, alumino-silicates, and so on.) brought up within the vegetation from shallow and deep roots.

Litter dams have been described in recent decades by workers such as Mitchell and Humphreys (1987), Eddy *et al.* (1999) and Howell *et al.* (2006). Once flow is impeded by litter, there is a pervious dam or weir against which more litter is deposited, along with alumino-silicates and living and dead organisms. As a result a micro- through to meso-patterned ground develops, with varying areas of bare ground or fresh sediment. Litter dams represent an important surface storage for both moisture and organic and alumino-silicate materials and can substantially reduce the movement of all materials to drainage lines.

8.3.3 Bioturbation and biotransfer

Bioturbation is the physical rearrangement (moving, sorting, mixing, churning, compacting, ingesting and

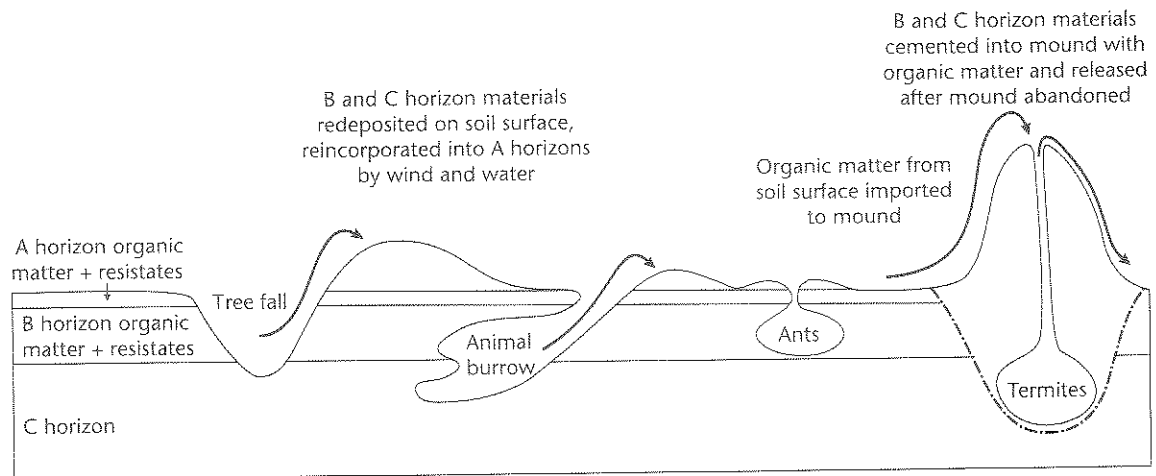


Figure 8.15: A schematic diagram of common forms of bioturbation and the soil horizons affected.

digesting) of regolith and soil by the biota – both from within and acting externally. In common usage, the term is applied to animate activity, with the general exception of the inclusion of tree fall. Biota exploit the regolith for nutrition, for protection and shelter and, in the process, create a new bio-fabric. Bioturbation is most obvious when it results from macro (vertebrates) and meso fauna (invertebrates) (Figure 8.15). As a result of bioturbation, regolith particles are dislodged, dislocated, built up (aggregates), broken down, reworked biologically, biochemically, chemically and physically and relocated to become loose, or compacted and/or cemented and more or less resistant to erosion. Some authors (for example, Johnson *et al.* 2005) use terms such as ‘conveyor belt’ (ants, termites and worms), ‘mix master’ (mole rats and pocket gophers), ‘crater maker’ (wombats and rabbits), and ‘mound builder’ (prairie dogs and viscachas) to describe the activities of organisms. While these actions, and therefore the terms, may sometimes be apt and descriptive, they also somewhat misleading because most bioturbator species in fact carry out combinations of more than one of these processes (not to mention varying levels of biochemical alteration as well) and the terminology is not mutually exclusive, so the additional jargon will not be used here.

Compared with the rates of other regolith processes such as soil formation, bioturbation rates are significant: turning over an average of 30 m³/Ma (30 cm of topsoil in <10 000 yrs; Anderson 2001), which is

comparable to the corrected soil formation rate of from 9 to 27 m³/Ma (Heimsath *et al.* 2000; Wilkinson *et al.* 2004). Individual and local processes, such as tree fall (700 m³/Ma) and wombat burrowing/mounding (100 m³/Ma), have rates an order of magnitude higher (Figure 8.16). The rate of addition of material to the surface by all these processes far exceeds the rate of erosion by a factor of three or four (for example, Anderson 2001).

In addition to bioturbation *sensu stricto*, many biotic effects enhance or retard other less- or non-biotic processes. For example, the production of loose regolith materials from burrowing provides easily erodible material for slope-wash or gully erosion.

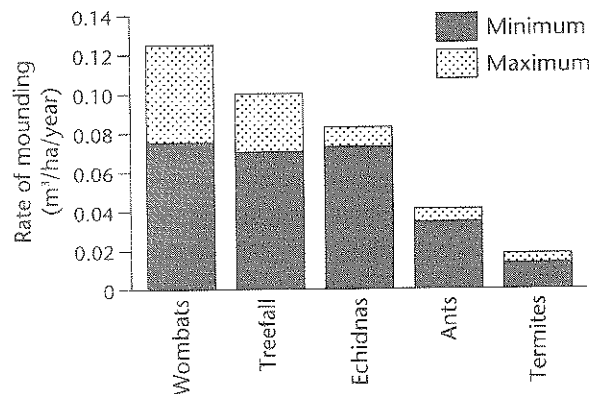


Figure 8.16: Rates of soil formation and bioturbation (volumes of material moved) in a dry sclerophyll forest, Southern Tablelands, NSW (Field and Anderson 2003).

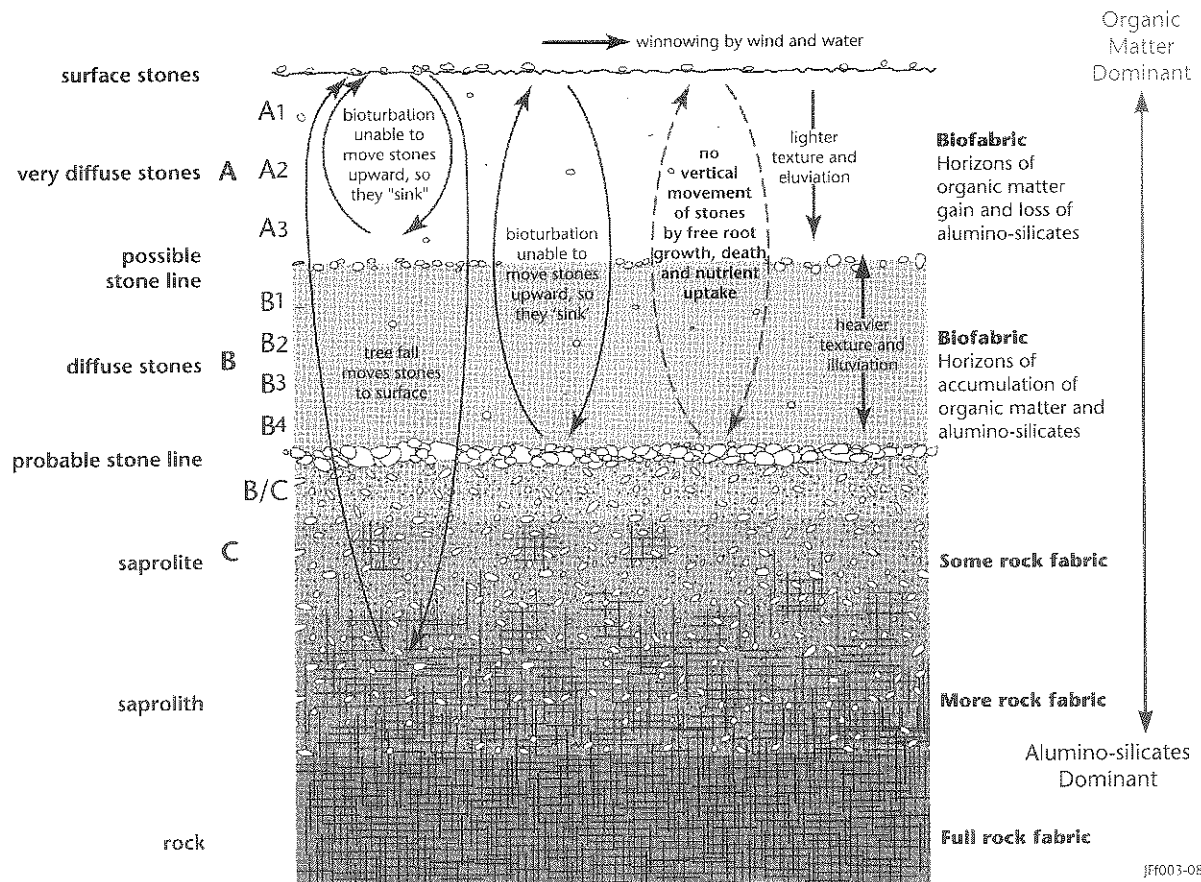


Figure 8.17: Regolith, soil and the concept of a biomantle.

Animals trample and compact regolith materials and concentrate flow along tracks, enhancing erosion; fauna add nutrients in faeces, urine and dead bodies altering nutrient cycles; and the combined biotic and abiotic processes may occur at the same time or sequentially (Carr *et al.* 2004).

Changes to the processes of biochemical alteration also occur as a result of bioturbation in all its forms. The exposure of soil that was previously at depth (even very shallow depths) allows erosion by raindrop impact and concomitant leaching and oxidation in a more oxic environment. Material brought to the surface by earthworms as casts has a new microorganism load – substantially altering organic content (weathered, decomposed, digested, gut mucous, altered microorganism load, and so on). The story for termites is similar, with the addition of intestinal flora via their faeces and saliva which they add to the mate-

rial they use to construct the mound. The latter is chemically and physically altered so that it is cemented, will resist erosion and will support the growth of some additional organic crusts, lichens and bryophytes. Mammals and marsupials not only dig and burrow, they defecate and urinate and these processes cause localised, but intense, changes to a whole range of biological populations and biochemical transfers, stores and processes. The result of bioturbation is the formation of a biomantle (Figure 8.17).

Nearly all forms of bioturbation lead to net down-slope transfer (however low the slope angle; Figure 8.13), or net transfer in the direction of the dominant processes of wind or water movement (Figure 8.17). Bioturbation also leads to the creation of microtopography, and large (and very large) pores and spaces of preferential permeability all lead to changes in the movement of fluids (air, water and solutions)

into, and through, the regolith. Air, containing CO₂ and O, and soil water and dissolved ions all gain preferential access to larger volumes of regolith – increasing all forms of chemical (biochemical) weathering and other regolith processes.

In this discussion, bioturbation will not include strictly physical processes (such as frost heave, frost shattering, wetting and drying, and shrink–swell) although there are many situations where these processes may be retarded (such as insulating organic matter and freeze–thaw processes) or augmented (addition of organic colloids and cations to the shrink–swell process). ‘Bombturbation’ (Hupy and Schaetzl 2006: the effects of armament explosion) and other human induced changes, such as ploughing, ripping, mounding, creating temporary or permanent beds, clearing of vegetation and the effects of domestic livestock, will also not be considered in this chapter.

Bioturbation by vertebrate fauna

Practically all vertebrates cause bioturbation. A brief list of the macro fauna in an international context (vertebrates, including warm and cold blooded) implicated (from a brief review of the literature) in bioturbation shows the diversity: aardvarks, anteaters, armadillos, badgers, beavers, canids (coyotes, dingoes, dogs, foxes, jackals, wolves), chinchillas, elephants, felines, fossorial animals such as moles, mole rats, and gophers (pocket and other sorts), ground squirrels, kangaroo rats, lizards, skinks and monitors, marmots, megapodes (mound building – incubator birds), prairie dogs, rodents of various sorts (mice, rats, and so on), snakes, susliks (a type of ground squirrel), tortoises, tuco-tucos (a type of rodent or hamster), viscachas, and viverrids (civets, genets, mongoose). While in Australia an even more eclectic collection includes bandicoots (of various types) bettongs (various), bower birds, brush turkeys, dingoes, echidnas, goannas, lizards and skinks, lyrebirds, macropods (kangaroos, potoroos, wallabies, and so on), mallee fowl, (the possibility of) marsupial moles, numbats, platypus, snakes, stick-nest rats and wombats. In fact, the numbers and varieties of fauna actively taking part in bioturbation are enormous: for example, 15% or so of all the Australian birds (White 2003) bioturbate soils or regolith:

‘... ten species extensively probe the soil during feeding; 11 rake the forest litter; 26 nest in soil burrows; 44 nest in shallow scrapes in the ground, often in colonies; 3 build incubating mounds; and 10 construct mud nests in trees and caves.’

Most recent investigations of bioturbation by meso and macro fauna were undertaken in Africa and the Americas (Ekundayo and Aghastise 1997; Whitford and Kay 1999; Aufreiter *et al.* 2001) and often outside the geosciences: for example, a substantial review of mammals by zoologists Reichman and Smith (1990). In Australia, studies have demonstrated the contributions of bioturbation to soil formation in the context of deep, old weathering profiles across the Australian continent: for example, Humphreys (1981, 1989, 1994), and Mitchell (1985, 1988) and their co-researchers (Cowan *et al.* 1985; Humphreys and Field 1998; Wilkinson *et al.* 2003) and, more recently, Field and co-workers (Field and Anderson 2003; Field 2003, 2004, 2006). Large bioturbators, such as wombats, rabbits, echidna, reptiles, lyrebirds and scrub turkeys all create obvious regolith changes in human timescales and hence they have been the focus of this research.

Many vertebrates have a distribution that relates to particular regolith and soil characteristics and/or types: for example, regolith moisture conditions (and landscape position; wombat burrow versus floodplain distribution; Anderson 2001), texture, depth or stoniness, or the distribution of resources on which to feed such as particular invertebrates in well-drained soils.

Animals can also create the circumstances that cause other geomorphic processes to change the regolith: for example, beavers construct dams that cause sedimentation, avulsion and the creation of new channels; and various animals burrow into stream banks, leading to bank collapse and stream changes, both within and alongside the drainage lines.

Vertebrate bioturbation is broken down into three broad classes:

1. the refugia - burrows, dens, warrens, nests and mounds (Box 8.1) – essentially long-term and fairly stable structures
2. foraging structures, such as tunnels, diggings, scrapes and scratchings (Box 8.2), which are an

Box 8.1 Refugia – burrows, dens, warrens, nests and mounds

Animals seeking shelter and protection make use of available hollows, small caves, ready-made depressions, and so on, or can construct or augment places to shelter, to raise young and stay safe from predators. Some animals may have one or more tunnels or nests (for example, male wombats have two or three dens or burrows, with a female inhabiting each) or different types of tunnels (for example, aardvarks dig some tunnels for food and other burrows for temporary or permanent nests; Smithers 1983). There is a continuum through two or more tunnels and/or openings, with animals such as suricates and mongooses, to those animals that either singly or in pairs, or as communities, build much more elaborate multi-tunnel, multi-entrance burrow systems. Material removed from tunnels and burrows becomes mounds.

Some of the most elaborate burrow systems are dug by rabbits and rodents, which have the highest bioturbation rates on a body weight basis. These warrens and burrow systems can have multiple entrances, complex interconnections below ground, and several nests and be inhabited by families or small communities of related animals. These complex systems can have a series of characteristics such as slopes, interconnectedness, arrangement of nest sites, shape and orientation of openings that are quite specific to the animals constructing them. They can also be built over time by the same individual or by groups as the family expands (such as prairie dog systems; Longhurst 1944; and evolving suslik burrows in Russia; Ognev and Tomilin 1947).

North American kangaroo rats create mounds (30 cm high and up to 4 m in diameter) that take

around 2 years to construct and begin to break down after a year or more of non-habitation of the burrow (Schooley and Wiens 2001). The mounds are spaced at from 2.5 to 10/ha and markedly alter the spatial patterning of soils and regolith and, in so doing, the distribution of vegetation and other fauna. The pattern of distribution of mounds is, in turn, affected by localised topographic conditions (such as regolith and soil texture and drainage). Mounding can reach extremes, such as the Mima mounds of the Western USA (up to 2 m high by 25–50 m in diameter), which are made of soil and other regolith materials by gophers.

Bioturbation varies from animals that produce long-lived and often complex networks of burrows and chambers to those that have relatively simple and short-lived excavations for refugia, such as most moles. Slightly more complex, but still only linear, burrows are constructed by some animals such as the Australian platypus, which digs a convex upwards burrow with the entry under water in a pool in a creek or river, and with a dry nest above the tunnel entry height. Many other animals, such as Australian wombats, dig tunnels from the surface sloping down into the regolith and with a simple larger cavity at the deepest point. Wombat burrows can range in length from 1 metre to more than 13 metres, and in diameter from 50 centimetres to almost a metre.

The construction of nests and nesting behaviour is usually limited to birds; this can range from simple nest construction on the surface to the mound nests produced by megapodes (1 m high, 2–3 m wide and 4–5 m long).

almost continuous process as animals seek food and other resources throughout their lives

3. the surficial effects of grazing animals (Box 8.3).

Each of these forms of bioturbation has the potential to initiate or enhance other geomorphic and regolith processes, such as the interaction of overland flow with litter dams, and rill formation, but larger scale processes, such as piping and gully initiation, often result from tunnels and burrows, and bank collapse along drainage lines.

Bioturbation by invertebrate fauna

Soil and other regolith material provide an environmentally stable, nutrient-rich, moist habitat for invertebrates. As a result, there are anywhere from a few tens to tens of millions of individuals beneath a square metre of surface litter (Viles 1988; Gabet *et al.* 2003) and 10–15 000 kg/ha (Coleman and Hendrix 2000). The quantities moved or bioturbated by invertebrates are considerable, and frequently compare favourably with rates of regolith and soil production and erosion. The macro invertebrates, such as soil-living bees, beetle

Box 8.2 Foraging – tunnels, diggings, scrapes and scratchings

Many animals forage for food on and within the surface horizons of the regolith, and others may dig for water adjacent to springs or in drainage channels. Some animals will also create dust or mud baths and coat their skin by rolling or wallowing (such as hippopotamuses and water buffalo), fluffing (poultry and many birds), blasting (elephants using their trunks), or throwing material onto their skin (bison, cattle) to protect themselves from parasites or sunburn. Tunnels and burrows are dug in order to move through the regolith, to find and recover food, and to avoid obstacles. Many animals dig among the organic materials in the litter and A1 horizons, such as ground-dwelling birds, while others, such as dogs and cats, create shallow excavations to bury food, and even their own excreta.

Surface and sub-surface bioturbators have multiple effects on regolith processes, including predation of invertebrates, eating of fungi (such as native truffles) and microorganisms, habitat alteration, and damage to living organisms, such as plants, mosses, and lichen, and impacts on parts of the regolith, such as surface crusts. In so doing, bioturbators can have marked effects on soil leaf litter decomposition, the structure of the surface soils and the larger scale processes such as infiltration.

larvae (such as scarabs), cicadas, crayfish, crickets, dung beetles, earthworms, mites, nematodes, spiders (trapdoors and funnel webs in particular), springtails and, particularly, ants and termites move through the regolith, pushing materials aside, creating tunnels, chambers, mounds and nests – some of which are obvious, but these organisms have many effects that are not seen without measurement. These effects include changes to permeability, destroying and creating regolith horizons and layers, and causing biochemical weathering within their gut, as well as the effects of saliva, mucilage excretion and digestive excreta.

Invertebrates can bring large volumes of relatively unweathered materials (or subsoil) to the soil surface, which can then be redistributed across the landscape

Box 8.3 Animal tracks and terracettes

The movement of fauna across slopes transfers litter and topsoil, compacts surface soil and leads to the creation of tracks, litter dams and terracettes. The effects of native herbivores and, to a greater extent, domestic livestock, compact surface soil and change bulk density and other soil characteristics, although these changes are less conspicuous than mound building and foraging.

Surficial effects on the redistribution of organic materials by the biota provide an interesting example of how biotic processes in regolith formation can interact to give more than a sum of the parts. Kangaroo and wallaby tracks (many other animals use these tracks, but the nomenclature attributes them to kangaroos and wallabies) move litter aside: exposing the surface aluminosilicate/organic matter horizon – the A1 soil horizon. This shallow depression forms a mini bank, bund or long, linear litter dam, and channels water across-slope at a near contour level until it overflows and concentrates the water in a mini rill.

The impact of animals trampling and causing erosion is highest on the floodplains, along drainage lines and on stream banks. Active erosion and destabilisation, leading to additional erosion, occurs as animals access water and seek to cross streams. Banks are often steep – resulting from on-going fluvial processes of channel evolution – and animals clambering or climbing the banks cause substantial sediment production. Animal excreta, and even the bodies of dead animals, have an effect on the regolith in and around the stream banks.

via the actions of water and gravity. For example, earthworms, ants and termites may be responsible for from 0.5–10, 0.004–1.8 and 0.013–0.4 m³/m²/ka, respectively (Mitchell 1988; Whitford 2000). Obviously, conditions do not favour all three organisms at the same time (termites dominate dry-seasonal environments, whereas earthworms dominate under humid conditions) so these rates are not additive (see Boxes 8.4 and 8.5).

Many invertebrate animals move within the soil by forcing themselves into interstices and pushing

Box 8.4 Nests and mounds: ants and termites

Miklos (1999) estimates that ants and termites together can bring 20–30 cm of soil to the surface each 1000 years. This exposed material is made more susceptible to chemical weathering (for example, Field and Anderson 2003). Ants and termites can concentrate organic matter in tunnels and mounds deep in the soils and regolith at the expense of inorganic minerals that they transport to the mound exterior. This generates complex fine-scale networks of nutrient sinks and sources across the landscape, and transports relatively unweathered regolith materials to the soil surface. Ants and termites are particularly active in tropical, semi-arid and arid ecosystems (for example, Holt *et al.* 1980; Cammeraat *et al.* 2002). While the ant or termite mound is maintained, these materials are essentially retained – with soil organic matter and mineral nutrients being released only slowly back in to the landscape. This release becomes more rapid after the mound has been abandoned and begins to disintegrate (Holt *et al.* 1980; Cammeraat *et al.* 2002).

The role of termites in mixing and fractionating both aluminosilicates and organic materials is extremely important in arid and semi-arid through to seasonally dry environments. Their role in decomposing otherwise inedible organic materials, such as cellulose and lignin, is critical to nutrient cycling and soil organic C in these drier environments. Termites can exponentially accelerate the breakdown of otherwise resistant materials, including resinous, high-

wax and high-lignin timbers, such as those of the Australian eucalypts, into rapidly weathering organic materials. Termites are among the few organisms that can decompose eucalypt stumps and provide the basis for further fungal attacks on dead and dying timber because they can also function as a vector by transferring spores.

Termite nests have a considerable effect on regolith hydrology: creating deep macropores and many minor interconnecting pores and chambers that allow exponentially higher quantities of water, air and gases, such as CO₂, to move through the regolith and soil. Termites can reinforce horizonation when combined with other processes, such as erosion and winnowing, while breaking it down in other cases, such as duplex soils where termites essentially bring the B horizon – and in some regions the saprolite – up to form their mounds, which subsequently erode and wash and winnow out across the topsoil. Because termites can bring subsoil and saprolitic materials to the surface, and may even concentrate particular grain sizes and/or mineralogies, they can be used to sample the regolith in bioprospecting (Petts 2006).

As with termites, there are arguments suggesting that ants destroy horizonation, whereas ants may be responsible for promoting, if not causing, texture contrast soils. It seems to depend upon the substrate regolith material and the environmental conditions, as well as species and community organisation.

particles and aggregates apart, while others excavate by eating or digging and can move quite large quantities of material from the voids they are producing to form mounds or nests. At a landscape scale, the mixing or slow stirring of the regolith and soil causes displacement outwards towards lower densities and pressures (and may leave a void) – usually perpendicular to the surface. On a slope, the subsequent ‘fall’ back to the surface (or into a void) is likely to be vertical under gravity. The result is a slow creep of material down-slope, which is analogous to particle diffusion (Figure 8.13). Heimsath *et al.* (2002) showed that grains keep being exposed at the surface, only to be buried again and so a net down-slope trajectory is

produced, despite a Monte Carlo pattern of movement in the first place.

Some invertebrates (such as earthworms: Box 8.5) actually ingest aluminosilicates while the majority only consume organic matter as they move through the soil (such as termites eating roots), but gut microorganisms affect weathering, both in the gut and, subsequently, in the soil – particularly in faecal material and castings. Dung beetles produce a nest filled with acquired dung formed into neat balls, which also contain dung beetle eggs (or an egg). The nest may be connected to the surface by a cylindrical tunnel back filled with dung by the adult on departure. Isolated egg-shaped cocoons containing dung beetle eggs

Box 8.5 Earthworms

Since the early work of Darwin (1837, 1881), it has been clear that earthworms can be said to create topsoil both biomechanically and biochemically. Earthworms can transfer considerable quantities of material from within the topsoil to the surface and even bury A and litter horizons in the process. In humid environments, earthworms may dominate the invertebrate fauna because of their relatively large size and their abundance in soils with relatively high organic matter and high levels of activity in temperate and warmer environments. Earthworms have a number of effects. First they create voids: excavating tunnels and ingesting soil materials in the process. The tunnels can be up to 5 mm in diameter for northern hemisphere species – and more for some large Australian native earthworms. These tunnels become macropores – allowing the preferential movement of water and gases – and so increasing aeration, infiltration and drainage.

Secondly, earthworms exude mucilaginous material that may help to stabilise the tunnel walls and support a range of microorganisms (Edwards and Shipitalo 1998). Thirdly, they process the ingested material through the gut – adding a vast array of microorganisms. In the process of consuming soil, the gut contents are subjected to both biochemical, biological and physical breakdown during digestion. The process also removes some nutrients, mixes plant and fungal fibres from the ingested soil along with secretions from the gut wall and com-

pacts the material – and additional microorganisms are added. Casts or faeces also contain intestinal mucus, which provides an additional substrate for all sorts of microorganisms while binding the material into very different, and more stable aggregates: all changes that will affect the biochemical reactions from then onwards. The resultant casts are bound together by all the secretions, derivatives and subsequent processes of microorganisms. A multitude of chemical reactions are promoted within and between organic materials, aluminosilicate minerals and living and dead microorganisms and can create organo-mineral bonds.

Some authors argue that earthworms restrict ongoing soil forming processes in the actual casts (Edwards and Shipitalo 1998), while others, such as Sharpley *et al.* (1979), have shown that casting can increase erosion. Pastures with good levels of earthworm activity had sediment run-off loads almost an order of magnitude higher than pastures without earthworms (Sharpley *et al.* 1979). On the other hand, the latter results also showed that higher earthworm numbers encouraged infiltration and reduced nutrient loss (specifically N and P) from paddocks.

Earthworms are generally described as being less important in Australia than Europe and North America due to lower latitudes, lower precipitation and general dryness of the continent – and very low levels of organic matter favouring bioturbation by other invertebrates such as termites and ants.

and/or larvae may also be located contiguously. Dung beetles are the best example of the incorporation of relatively fresh, inoculated organic materials into topsoils. Spiders produce burrows that are essentially vertical, widening upwards, which may, or may not, have a capping. Solitary ground-living bees construct flask-shaped chambers with a smooth internal wall, which are connected to the surface.

Less-obvious processes include use of saliva and gastrolith (Box 8.6).

8.3.4 Consequences of bioturbation within the regolith

Invertebrates that burrow and mound soil tend to produce a biomantle of topsoil, subsoil and overlying

saprolite and, as such, are primary agents producing horizonization. On the other hand, uprooted trees break up bedrock, transport soil up and onto the surface and increase the heterogeneity of soil, and disrupt soil horizonation. Biomantles form as single layers in fine-fraction parent materials, and two layers when formed on mixed fine-and-coarser materials (Figure 8.17).

Within the solum or biomantle, there is a complex interacting set of fast and slow, often countermanding translocations, taking place, as material is loosened and then transferred. The result can be several different forms of biostratification or horizon formation, or the destruction and homogenisation of layers. Bioturbation can, depending on the balance of organisms,

Box 8.6 Saliva, corpses, gastroliths, excreta and gut flora

There are many less-obvious interactions between biota and the regolith. For example, some birds construct nests out of mud and dung with or without saliva. The geochemical interactions between these chemically very active organic substances (enzymes, organic acids, chelates, inoculants containing complex and diverse microorganisms, and so on) and regolith are only postulated currently and require further research. The death of any organism and subsequent incorporation onto, and into, the regolith provides another example of incredibly rich organic material (both as organic substrates for more biota, plus inoculants, chemically aggressive and active substances, and so on) being added to the ongoing weathering of aluminosilicates.

Gastroliths are stones swallowed by animals (usually aluminosilicates, but they can be formed in the stomach by precipitation – rather like human kidney stones), which were much more common in earlier geological periods – particularly in dinosaurs (aquatic dinosaurs may have used them for ballast) and large reptiles – but, even today, gastroliths may make up as much as 1% of the weight of crocodiles and alligators. They are also common today in seals and sea lions and almost all herbivorous birds: effectively providing the grinding medium (sand, grit, gravel, even cobbles, and shell grit, and so on) in the very muscular gizzard for physically reducing food material during digestion. Gastroliths may be highly polished (most of those recognised from the fossil record are) or may have little or no polish and be quite angular in modern birds. Gastroliths from dinosaurs can be several kilograms in weight, and modern ostriches can have stones up to 10 centimetres in length (Wings 2003). Gastroliths may or may not be found among the skeletons of dead animals, but are not often released from the gizzard of healthy, living animals.

either create horizonation or homogenise the biomantle (Figure 8.17).

Whether biota actually incorporate saprolite and rock into the biomantle depends on the processes involved. Tree fall on shallow regolith brings fresh

and weathering material to the surface, while it is doubtful whether gophers or rabbits actually bring even saprolite to the surface. However, the production of regolith and soil does not require the physical transfer of rock or saprolite upwards and onto the surface. Many authors are mistaken in their belief that biota, such as gophers, do not accelerate the production of regolith or produce soil, because they do not burrow among rocks or dig up the saprolite (for example, Gabet *et al.* 2003; cf. Heimsath *et al.* 2000). However, virtually all bioturbation processes increase the infiltration of water and the incorporation of organic material through increased porosity, reduced bulk density and the mixing of litter from both the surface and the root biomass. Also, the rate at which rock weathers nearly always increases with shallow to moderate burial, because moisture and temperature conditions within the regolith are more conducive than exposed conditions on the surface to all biotic chemical weathering processes, as well as even strictly abiotic geochemical weathering – if such a thing exists. The only exceptions to such a generalisation are predominantly abiotic physical processes such as freeze–thaw or frost shattering.

There is an argument that invertebrate bioturbators, such as ants, termites and earthworms, can turn finer material in the biomantle layer over to the exclusion of coarser particles (such as gravel and stones), and put in place a stone line or a texture contrast soil (coarser loams or loamy sands over clays or clay loams). A stone line is a non-geological, non-depositional (that is, non-stratigraphic) layer that can be considered to be an horizon in a pedological context.

Some larger bioturbators, such as rabbits, wombats and tree fall, can also act to destroy the texture contrast by inverting soil layers or remixing them. However, others – because their activities are limited to only one or two horizons or layers – will enhance horizonation, rather than destroy it (Figure 8.15).

There is a landscape zonation of specific bioturbators with particular environments. For example, wombats generally dig into softer floodplain and drainage line soils, rather than shallower, and more resistant soils with stronger texture contrast, and heavier textures in mid and upper slope positions (Field and Anderson 2003). Some authors go further: arguing that either climatic/microclimatic zones or

vegetation types can be used to predict levels of bioturbation. Carr *et al.* (2004) argue that bioturbation reaches a maximum under temperate humid Californian grassland (about four times the volume on average; around 100 cm³/m²) when compared with shrubland or forest. The dominance of burrowing rodents in these sites may explain the result, but the sample size is very small. On the other hand, Anderson (2001) and Field and Anderson (2003) clearly showed that in a similar environment (temperate humid NSW) – but on another continent with very different biota – tree fall moved the most materials, and in grasslands there are no other bioturbators to replace these processes (Figure 8.16).

Stone lines can be seen as a residue of bioturbation. As organisms cycle the materials they are capable of moving, some larger, denser particles or aggregates are left behind. If any sort of random walk process (not really random because most movement is at least partly upwards towards lower densities, aeration and/or away from saturation) can move some materials but systematically leave others behind, eventually a horizon, or layer with just that residual material, concentrates near the base of the bioturbation and a stone line is created (Figure 8.17). For example, North American gophers can produce a stone layer, just below the typical depth of burrows, from pebbles and cobbles that are too large for the animals to move during their burrowing and tunnelling activities (Johnson 1989).

In addition, if a particle that is too large to be moved by bioturbators lands on the surface (dropping stone, gastrolith, bone, shell, or man-made article, such as shards, points, ceramic fragments), it will slowly, but systematically, be lowered under gravity through the biomantle (almost literally, as material is moved up and piled out on top of it) until it reaches the stone line. If erosion on the surface due to wind or water exceeds the rate at which material is being bioturbated onto the surface, then not only will the artifacts be left at the surface, but the surface is also likely to be armoured with larger, resistant objects but it is likely to be lowered in the process. Stone lines (Johnson 2002), or a stone layer (Paton *et al.* 1995), do not form where there are no resistant larger particles (Figure 8.17).

In a similar manner, and sometimes with the assistance of winnowing by wind and water, texture contrast soils are formed.

8.3.5 Biotic processes on regolith surfaces

The regolith surface is the main interface between air and water – where a truly diverse biota has a dominant role. On fresh rock surfaces, the endolithic bacteria carry out forms of biogenic weathering – as do lichens. The following all alter the run-off or infiltration, while enhancing or retarding weathering:

- the surface effects of litter fall – the mulch effect of keeping the surface moist
- the biochemicals in litter that lead to hydrophobicity and run-off, or to aggregation and infiltration
- the fungal mats from symbiotic partnerships between the higher plants and microorganisms
- the cryptogams constituted from algae and fungi or algae alone.

The following manage erosion and sedimentation, while enhancing weathering:

- litter dams
- root holes
- bioturbation pores
- lichens
- liverworts, and other bryophytes.

Biotic surface processes are critical to the functioning of most landscapes.

Biogenic weathering, biofilms, biotic crusts, biomineralisation and endolithic microorganisms

Biogenic weathering is where 'life processes' dominate the formation and evolution of regolith. A biofilm is a complex aggregation of microorganisms, which is marked by the excretion of a protective and adhesive matrix and characterised by surface attachment, structural heterogeneity, genetic diversity, complex community interactions and an extracellular matrix of polymeric substances. Some, such as desert varnish, impede further weathering when they form; others, such as lichens, lead to enhanced weathering. Biotic crusts result from the growth effects of biota and reorganise the alumino-silicates in, and on, the surface of the regolith – often positively altering its stability, and changing the chemical composition and physical characteristics. Biomineralisation is a simple combination of the biota causing changes to alumino-silicate materials to produce new or secondary minerals.

Endolithic means living within, or penetrating deeply into, stony substances. An endolith is a (micro) organism (usually an archaeon, bacterium, or fungus) that lives, at least partly (fungi and lichens), within rock (coral, animal shells, or in the pores between mineral grains) and includes endolithic lichens.

The overlap between biogenic weathering and discussion in earlier sections (for example, Section 8.2) is complex. Specific examples will be given here under each named process and then, where relevant, these will be referred back to earlier subsections. Biogenic weathering occurs within one or two years of exposure of a fresh carbonate surface (Hoppert *et al.* 2004) in humid temperate environments. It also takes place when lithobiontic organisms, both epilithic (external to the alumino-silicate mineral surfaces) and endolithic (or cryptoendolithic) species colonise the surface, induce and accelerate weathering and actively penetrate the rock independently of pre-existing pores, fissure or other inhomogeneities in sandstones and volcanogenic rocks – even in environments as cold as the Antarctic (Johnston and Vestal 1991; Guglielmin *et al.* 2005). Initial colonisation takes place as algae and ascomycetes penetrate the rock and slowly – over several years – a more complex colonisation pattern by lichens develops. The rates of weathering are very much climate-dependent and also vary across lithologies. Biogenic weathering can also be demonstrated to occur in a laboratory setting (Cervini-Silva *et al.* 2005) using the same biogenic substances that are ubiquitous in soils (ligands such as oxalate, ascorbate, citrate and humic acids, and chelating agents) to weather P-bearing minerals, such as rhabdophane, to form more- or less-soluble organic complexes (ligand *plus* an ion) with both Ce and phosphate.

Surficial root mats, fungal mats, surface hydrophobicity, surface crusts, and cryptogamic crusts

These phenomena are special cases of concepts that have been discussed already in this chapter or covered later. However, they also represent more intense examples, more extreme processes and ever greater influence of biota over regolith evolution. Surficial root mats are generally described for rainforest environments, where high inputs of precipitation and high temperatures lead to very rapid leaching of very

quickly decomposing organic materials on, and in, the surface soils. The vegetation has evolved dense shallow root systems (plus deeper systems, including tap roots) to efficiently absorb the results of the very high turnover nutrient cycle. Rao (2005) demonstrated that fungal mats, and underlying root mats, redistribute low levels of both nutrients and water in the surface soils under dry sclerophyll forests and woodlands on the Southern Tablelands of NSW. The ecological system biases the distribution of both nutrients and water, so that the eucalypts get the lion's share and competitors are starved of both. Symbiotic fungi enhance the effects of the root mat. The fungal mat is hydrophobic – shaped into what resemble octagonal or hexagonal 'tiles' about 10–15 mm thick, lying immediately below the eucalypt litter and above the A1 horizon that contains the eucalypt root mat. The fungal mat appears to be an effective barrier to the germination of any plants – either simply by its aridity, but possibly also through allelopathic chemicals, including biphenols of various sorts. By so doing, this combination of regolith surface phenomena is used by the eucalypt overstorey to control competition for scarce resources.

Biological soil crusts are highly specialised communities of living cyanobacteria and tiny mosses and/or lichens that combine with their by-products and alumino-silicate minerals to form a crust millimetres in thickness bound together by organic materials. The crust can reach centimetres in thickness and vary in their makeup to include cyanobacteria plus or minus combinations of liverworts, mosses, lichens and a variety of free-standing fungi. They bind the surface and may cover all areas not growing higher plants and create a considerable micro topography with their filaments of cyanobacteria and green algae. The latter migrate outwards on wetting, creating additional sheath material that binds the soil further, holding it together on drying. The biotic crusts stabilise surfaces, markedly reducing both wind and water erosion, promoting soil moisture retention, fixing N for plants, conserving other nutrients, increasing infiltration and soil water retention and promoting seedling germination and plant growth. The growth of the filaments from the fungi in the symbiosis further adds to soil stability, when they exude polysaccharides – aiding in the cementing together of aggregates of soil (as distinct



Figure 8.18: Early stage succession, as higher plants colonise weathered material shed by surficial weathering of a granitic face.

from lichens and mosses that bind soil with additional rhizines or rhizoids). Non-filamentous soil crusts can actually reduce surface roughness, reduce soil infiltration and restrict the entry of air, germination of seedlings and seedling emergence. The very different effects of soil biotic crusts are crust specific, and vary across environments as well as surface soil materials.

Lichens and bryophytes

Although most bioturbation studies focus on 'large-scale' visible processes, vegetation establishment and growth also have important physical implications for mineral weathering and pedogenesis. Mosses and lichens – through their rhizines or rhizoids, as well as cryptogamic mats with rhizomes or filaments – are able to exploit minute flaws and cracks in mineral grains and relatively unweathered rock surfaces. As these root-like bodies grow, they expand tiny cracks and allow greater water penetration and add organic matter to the developing weathering rind. Increasingly complex grass and herb communities, followed by shrubs and, eventually, trees, then become established, with roots that grow deeper and expand the cracks in the weathering parent material further (Figure 8.18).

The lichen-based weathering model has been developed to a level where a number of authors now see it as a means to understanding biotic or biogenic mineral weathering in general (for example, Banfield *et al.* 1999). They state that microorganisms are known to increase rates and add additional processes to rock

weathering and regolith formation. They then expand using this explanation:

'Fixed C released by the photosynthetic symbiont stimulates growth of fungi and other microorganisms. These microorganisms directly or indirectly induce mineral disintegration, hydration, dissolution and secondary mineral formation. ... C sources ... can suppress or enhance rates of chemical weathering by up to three orders of magnitude, depending on the pH, mineral surface structure and composition, and organic functional groups. Mg, Mn, Fe, Al and Si are redistributed into clays that strongly absorb ions. Microbes contribute to dissolution of insoluble secondary phosphates, possibly by release of organic acids. Below fungi-mineral interfaces, mineral surfaces are exposed to dissolved metabolic by-products. Through this indirect process, microorganisms can accelerate mineral dissolution, leading to enhanced porosity and permeability and colonisation by microbial communities.'

8.3.6 Biota and regolith physical characteristics

The incorporation of organic material changes regolith characteristics such as bulk density, horizonation, texture, structure, moisture content, porosity, permeability, sorptivity, and hydraulic conductivity. Exploitation of the weathered regolith by plant roots influences soil insulation, compaction and aeration – as well as soil water conditions and the microbial community. Organic matter virtually controls soil structure, which, in turn, controls infiltration and run-off. The biota have an overall controlling influence on regolith water content and transfer:

- right from the very minor effects of tiny root holes left after the death of rootlets and root hairs, up to the largest roots and root macro pores
- from the myriad burrowing invertebrates and the micro though to macropores they leave behind
- from the effects of soil organic matter on soil aggregation and bulk density to infiltration and bulk soil water storage

- from the minute processes of root cell exudation of water to hydraulic lift by huge trees.

Biotic surface conditions

As discussed above, biotic regolith surface processes can have seemingly opposite results: on the one hand, stabilising surfaces, increasing infiltration and thereby reducing run-off and erosion; and, on the other, reducing infiltration and increasing run-off. Living and dead biota insulate surfaces from heat and reduce evaporation, increase infiltration and enhance weathering. These controls are, in turn, affected by environmental controls (moisture and temperature, even if only at the micro scale) and the nature of the surface materials – producing a wide spectrum of likely scenarios, the complexities of which cannot be dealt with here.

Bulk density, soil structure and soil or regolith horizons

Organisms seeking to exploit the regolith (particularly the organic component) for food and shelter rearrange the structure and fabric during the process. In doing so, they create a biofabric and/or a biostratigraphy. Once the organism has passed (or the root dies), a void is created that will stay open, fill with material from the passing organism, or collapse. Whatever happens, a heterogeneity is created that is biomechanically (and often biochemically) different and more likely to be aerated, be more porous and/or permeable to water and solutions, and have different nutrient and biological characteristics from that of the surrounding regolith. The result is a reduced bulk density, enhanced soil structure (Figure 8.19) and horizonation. The types and effectiveness of the variety of bioturbation acting on any site varies by vegetation and/or ecosystem type, although there is little consensus as to whether particular systems, such as forests, have more or less than grasslands.

Permeability, porosity, infiltration and drainage – roots holes, tunnels and burrows

Burrowing animals and insects, and recently deceased plant root systems, create passageways for air and water movement and thus change soil morphology. The pas-

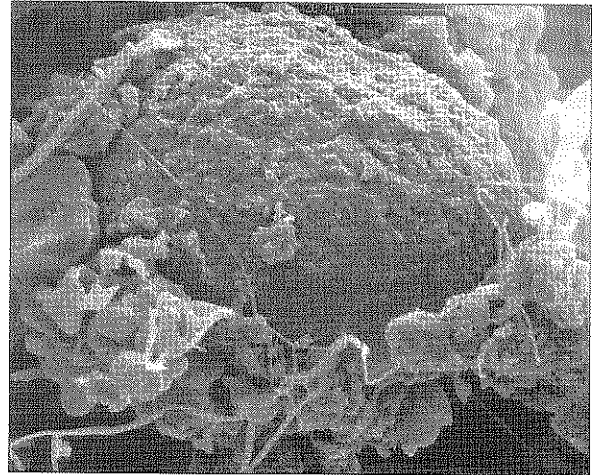


Figure 8.19: Fungal hyphae bind soil aggregates (scale bar = 20 μm).

sageways, or krotovinas, formed by these processes create loose material on the surface and also a vast network of micropores (root hairs, micro fauna), macropores (earthworms, and other invertebrates) and mega-pores (large root death, vertebrate tunnels, and so on) that become back filled once vacated by organisms moving (animals) or dying (roots). These krotovinas are filled with materials that are lower in bulk density, contain more organic matter, and are more porous and permeable. Krotovinas are likely to be narrow and elongated, with varying levels of connectivity. In addition, they were shown by Noguchi *et al.* (1999) to connect with many other features such as:

- other former root pores
- faunal burrows of all sizes (infilled or collapsed but still preferentially permeable pores and burrows)
- dehydration and shrink–swell cracks
- soil inter and intra aggregate spaces
- saprolite and rock fissures and preferential flow paths
- soil horizon boundaries.

Moles in temperate humid environments have been shown to double soil porosity (Mellanby 1971), increase soil moisture and invertebrate numbers, such as earthworms (an interesting interaction between predator and prey and resultant bioturbation), while decreasing bulk density. Rodents, with their extensive burrow

systems, create vast interconnected systems of open and back-filled macropores, which have huge impacts on air and water movement and, in turn, slope form and evolution. Earthworm tunnels generate macropores, which can increase soil porosity by 3–10 times (Edwards and Bohlen 1996). These macropores have high levels of connectivity within, and with the surface, and can increase infiltration (and reduce concomitant surface run-off) during rainfall while encouraging drainage and aeration once rain has ceased.

Because organic matter reduces bulk density, it increases both the hydraulic conductivity and sorptivity of soil and increases the heterogeneity of soil physical characteristics. In addition, because almost all forms of bioturbation create pores, organic matter increases infiltration rates up to three times (Williams and Vepraskas 1994). Devit and Smith (2002) showed that root canals from shrubs in the desert not only carried water more quickly into the regolith, but also more deeply, while fibrous roots, such as those under native tussock grasses in eastern Australia, can cause a full order of magnitude increase in both hydraulic conductivity and sorptivity (Rath 1993).

Hydraulic lift by vegetation

Hydraulic lift (or hydraulic redistribution) is a process whereby plants take water from depth and, using the xylem and capillary rise, bring water up through their roots into shallower layers where it may later exude from the roots and moisten the rhizosphere and beyond. Under Earth's gravity it is physically impossible to lift water more than 10 metres by suction. However, the very fine capillaries in plant xylem exert much greater localised forces, and plants can lift water an order of magnitude higher. During the day, lifting is driven by the evaporation of water out through the stomata, as well as consumption of the water as the H and O are split: H reacts with C from CO₂ to form carbohydrates during photosynthesis and oxygen is released as a by-product.

Capillary lift is undertaken by plants that have tap roots extending down into regolith layers for their own water supply and is more highly developed in plants that are adapted to dry environments and/or environments that are seasonally or periodically dry such as drought-prone areas. The xylem in roots is

very effective at preventing leakage, but it is not watertight, particularly in the smaller, younger roots. If there is a hydraulic gradient between roots in a dry soil and others in a moist or wet soil, then water will be moved along this gradient to reduce the potential. There is a need for the hydraulic gradient to be great enough to overcome the forces of gravity, and the resistance of the xylem in order to get a net mass transfer of water. Thus, there is a process of self-irrigation, whereby moisture continues to be brought up during non-sunlight hours and leaks into the rhizosphere to be taken up again once photosynthesis begins – and the in-plant store is consumed during the days. Thus, the plant (and its neighbours) has two reservoirs of water to use to drive photosynthesis when the stomata open. The effects are localised around each plant, with water close (< 2.5 m) to the tree in the shallow soil indistinguishable in isotopic signature to the groundwater, while 5 m from the tree in the same shallower soil horizon the isotopic signature returns to that of soil water from recent precipitation.

From the point of view of the formation and evolution of the regolith, there are the obvious effects of hydraulic lift that have already been mentioned in transferring water that will promote weathering by other forms of biota and in the non-biotic weathering spheres. There is also the possibility of the transfer of solutes (weathering products) in solution in the water in roots as water is drawn from considerable depth, encouraging chemical and biochemical reactions to go forward and the effects on the hydro-bio-geochemical cycling of elements. The support provided to the rhizosphere by extending the water supply into otherwise drying periods extends the time during which organisms can be active, and increases the metabolic rates throughout the root zone. Increased metabolism and increased time for chemical reactions means increased biotic weathering by all the organisms in the regolith.

Biota and slope processes, erosion and mass movement

The growth of roots, the construction of casts and mounds, chambers, galleries, tunnels, burrows, nests, tracks (which funnel water), and feeding scratches, scrapings, tunnelling, digging and sorting all transfer material, which, with the added effect of gravity, lead to

slope processes. Parallel changes to porosity and permeability, as already discussed, create preferential flow paths within the regolith, wherein water moves more easily and quickly and, in turn, aids the transfer of materials through the regolith and also enhances mass movement of materials down-slope. In extreme cases, krotovina lead to tunnelling, piping and gully-head collapse. Bioturbation of regolith can be broken down into four major effects on landscapes and slopes:

1. the augmentation of erosion or movement of surface material down-slope, commonly called biotransfer
2. the mixing versus homogenisation and/or horizontal or overturning of material, which leads to effect 3
3. enhanced weathering and regolith formation
4. enhancement of processes, such as infiltration, sub-surface transfer of water, solutes and solids.

If the relocation of material by bioturbation is considered in three dimensions on even low-angle slopes (Figure 8.13), it quickly becomes obvious that this transfer process moves material outwards (it can really only move upwards and perpendicular to the surface, unless compaction takes place) and laterally (with some compaction or 'flow'). When the space created by biota is vacated, it will be filled predominantly from up-slope and vertically above (by gravitational forces and usually to lower bulk density) and so leads to net downhill creep. As a result of root growth, Gabet *et al.* (2003) calculated the slope-dependent lateral rates of movement for northern hemisphere grass root growth down a slope of 10° at 10 m³/m/Ma, shrubs at 90 m³/m/Ma, and trees at 100 m³/m/Ma, (compare tree fall, which moved material at 1000 m³/m/Ma, and gophers at 5000 m³/m/Ma: Gabet *et al.* 2003).

The form of hillslopes can be controlled by biota causing, or enhancing, hillslope processes (surface erosion, sediment transport and deposition on hillslopes) by the release of uncompacted materials on to the surface by vertebrates and invertebrates when spoil-type mounds and constructed mounds are considered. Roering *et al.* (2002) showed that bioturbation under forests, on a loess-mantled hillslope on the South Island of New Zealand, increased sediment

erosion (Holocene conditions) and led to the development of broadly convex slopes, where, under earlier lower sediment flux rates in grassland-dominated landscapes (Pleistocene conditions), flatter locally incised slopes developed.

In areas where slopes are inhabited by gophers, it would be difficult not to see the tunnelling by gophers in pursuit of plant roots, and their resultant mounding, as the major source of sediment (Thorn 1978; 1982). Add to this the likely impacts on infiltration into the slope of water along the multitude of current and past open or infilled macropores, and the conclusion is that gopher activity is the dominant sediment-movement process (Black and Montgomery 1991). Gabet (2000) has developed a slope erosion model based on slope and gopher activity. Burrowing by wombats in the more easily dug, sometimes moist soils along floodplains and in drainage lines – often in less stable and usually sodic soils (Field and Anderson 2003) – can lead to up-slope piping from run-off and, eventually, to extensive gully systems (Field 2004; 2006). In Eastern Australia, these processes are widespread and have taken place in dispersible, sodic valley fill soils and have led to extensive gullying, channel incision, channel widening (lateral pipes and bank collapse) and lengthening.

An understanding of the effects of biota in moving materials around and down-slope has been around for a long time. Davis and Snyder (1898) saw soil creep as a result of animals burrowing and the growth and death of plant roots. Some authors (for example, Caine 1986) even attribute the form of hillslopes, hillslope erosion, sediment transport and deposition on hillslopes, and soil production rates primarily to bioturbation types, distribution and intensity (Viles 1988). These processes are now seen as comparable to the abiotic processes (biota still have effects on water content, insulation against temperature changes, clay formation, water table control, and so on) such as freeze-thaw and frost heave, shrink-swell of clays on wetting and drying, and other mass movement processes. Gabet *et al.* (2003) present a formula that can be used to calculate sediment fluxes resulting from root growth and decay of from around 8 m³/Ma in temperate grassland to around 32 m³/Ma under temperate forest on a slope of 10°. These values are an order of magnitude

less than the same authors suggest for tree fall and a further order for bioturbation by gophers.

Animals also directly impact on slopes by loading (combined animal weights) and resultant mass movement is also going to affect regolith formation and landscape evolution. Increased slope mass movement, as discussed above, when combined with loading by herds of animals such as reindeer, may be the trigger that initiates landslides.

8.4 BIOTIC EFFECTS AT BROAD SPATIAL AND LONG TIMESCALES: BIOGEOMORPHOLOGY AND ZOOGEOMORPHOLOGY

Biogeomorphology – a term coined by Viles (1988) and more recently the term zoogeomorphology, popularised by Butler (1995), are both used to describe the ways in which animals act as geomorphic agents. Clearly faunal bioturbation and biotransfers can be considered as examples of both bio- and zoogeomorphology. Bioturbation can be considered at scales from individual mineral grains, the scale of individual organisms, or collectively at scales of whole ecosystems or catchments and landscapes. These ecosystems can range in size from catchments of tens of thousands of square kilometres to forests of only a square kilometre or even tens of hectares. The most appropriate timescale to consider the formation of soils, regolith and landscapes across the Australian continent is a geological timescale – and that is most appropriately carried out at a continental, regional or broad spatial scale. Obviously, at a continental or regional scale, there is a very strong correlation of climate and biota and this is then reflected in the influence of biota on, for example, erosion.

As soon as long timescales are introduced, particularly in Australia, the effects of climatic change must be considered. Climate change and concomitant changes in the biota (plus or minus feedback into climate) lead to cycles of weathering and denudation, which are followed by more stable periods of more- or less-intense weathering. The cycles of weathering and erosion tend to swing between humid tropical conditions and the dominance of groups of plants such as rainforests, and more arid conditions leading to

vegetation retreat and the production of aeolian material. The effect of climate and vegetation on depth and intensity of weathering has been discussed many times in the literature of pedology and geomorphology, and can be summarised in the diagrams of Strahkov (1967) (Figure 8.20).

The effects of the blanket of living vegetation and litter on infiltration and evapotranspiration underlie these models for weathering. There are a multitude of effects: surface roughness reducing the speed of movement of both wind and water, reducing evaporation and transpiration, increasing storage and redistribution of water by standing vegetation, litter and well-structured regolith surficial layers; and then there are effects on other variables, such as temperature, and the mediation and habitat provision for other biota. If the regolith is maintained in a shaded and moist condition following enhanced accession and storage of water, then almost all the chemical reactions within it will be maximised and exceed the likely rates should the system dry out, or cool.

8.4.1 Erosion and weathering controls

Continent and larger scale comparisons of erosion and weathering are dominated by discussion of the effects vegetation cover, the evolution of soil mantles and the partitioning of water (for example, Douglas 1977). Vegetation shelters the regolith from sunlight and heating and cooling, from the erosive effects of wind while favouring deposition and from erosion by water, while storing and redistributing water and nutrients to produce more biomass and maintain the ecosystem.

After all, vegetation is the reason why arid environments do erode under wind and infrequent run-off at quite high rates while areas with much higher rainfall do not – even under most storm events. Vegetation is also a critical component in distribution of resources, such as water, and thereby erosion and deposition. Take for example banded vegetation in arid and semi-arid regions. Ecologists often discuss the bands in terms of redistribution of very limited resources – usually water (but also importantly, wind) – from across the whole landscape to concentrations within the bands, with bare and scalded areas simply regarded as extended and

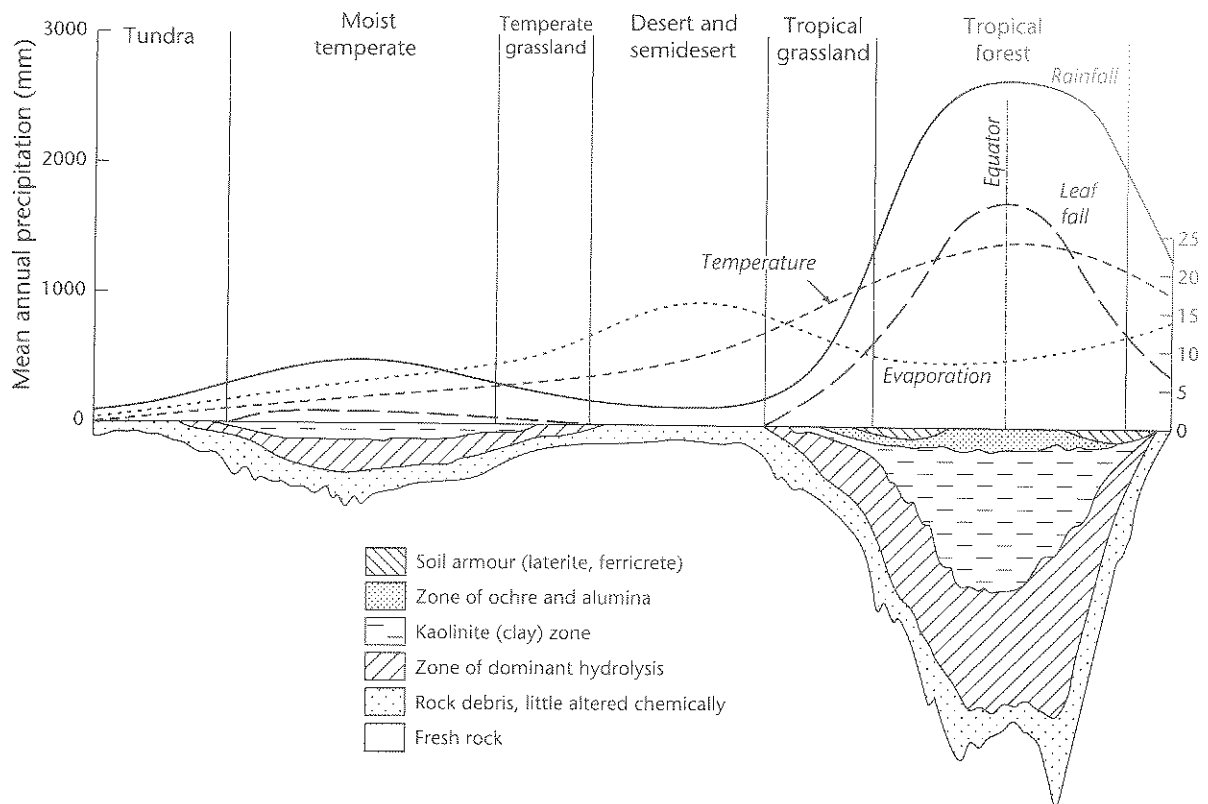


Figure 8.20: Weathering mantles, climate and biota (after Strahkov 1967).

contributing catchments for the vegetation bands. The effects on regolith formation, evolution and distribution from growing vegetation: the deposition and stabilisation of sediment and solutes in the band which were derived from the whole area, the uptake and cycling of nutrients, the enhanced weathering as a result of the plants and their concomitant soil organisms, the associated fauna and bioturbation, and the inputs and impacts of organic matter on the regolith characteristics are among the most obvious.

At more localised scales, vegetation changes are strongly correlated with regolith characteristics such as soil depth (average 66 cm depth under open forest/woodland and 28 cm under treeless heath and heathlands; Wilkinson *et al.* 2003, 2004). However, one must inevitably ask the question again – which came first: the vegetation type or the soil characteristic that gave a particular vegetation type a comparative advantage? The most productive way to see this argument is

to see the vegetation association and soil or regolith development as co-evolution (Field 2004, 2006).

Nevertheless Wilkinson *et al.* (2003, 2004) and others argue that weathering or soil production is inversely related to soil depth. However, maintaining a soil cover of any depth requires a stable vegetation cover.

Aspect is another example of the interaction between a landscape-scale variable and biota that provide a feedback loop, which, in turn, affects landscape form and thereby process. Selkirk *et al.* (2001) show that in the Blue Mountains west of Sydney, the valley physiography (working through aspect) affects fire regimes and the vegetation that, in turn, interact with moisture availability, temperature and sunlight. Moisture availability, temperature and incident sunlight, in turn, are components in regolith formation and erosion (soil depth) and the success of vegetation types. In the same environment, Wilkinson *et al.* (2003) demonstrated the relationship between spur

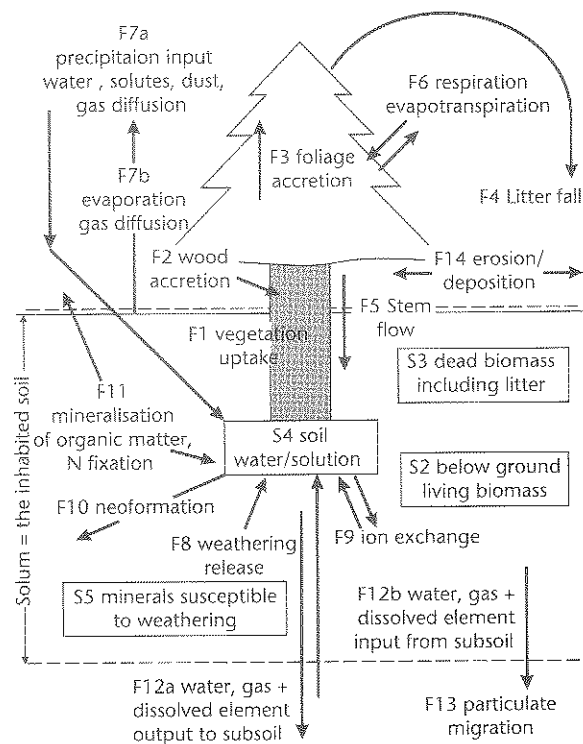
cross-sectional shape (that is, convexity) and soil depth and vegetation type.

8.4.2 Hydrobiogeochemical cycles

At the largest scale, ecosystems store and move large quantities of chemical elements around in geologic time frames – the hydrobiogeochemical cycle (Figure 8.21). For example, Gilkes (1998) calculates that typical vegetation growing on a substrate in a landscape for a million years at around 5 tonnes of biomass/ha/year – and containing a typical concentration of about 5 ppm Zn – will translocate from the weathering zone around 50 tonnes of Zn/ha up, and into, a cycle between the upper soil horizons, litter and living vegetation. In terms of constituents of biota, Zn is only a micronutrient.

The term ‘hydrobiogeochemical cycle’ is used when elements are followed from the underlying hard rock up through the regolith and soil and into standing biota, to seek out the sources, transfers and sinks for these within the overall system. During the last quarter of last century, work began to outline the paths in particular ecosystems. The most comprehensive and widely read of these studies are the Hubbard Brook experiments (for example, Likens *et al.* 1997) in north-eastern USA, followed by work at Plynlimon in the UK (for example, Kirby *et al.* 1991) and in Australia in New England, NSW (for example, Zakaria 1977; Lam 1979; Day 1980; Field 1983). All these studies detailed the hydrobiogeochemistry of nutrients and non-nutrients, cation and anions, through vastly different ecosystems, but they all proved the importance of the biota to the removal and cycling of elements out of, and back into, the regolith. The transfers are huge when considered on a regolith-formation timescale.

Several studies have used mass balances to calculate inputs from weathering and sought to balance them with outputs in streams (Markewitz and Richter 1998; Kearns *et al.* 2003; Alexandre *et al.* 1997). Groups of elements within these cycles have quite different paths: essential nutrients of C, H and O are not supplied from weathering, but are cycled within the regolith as organic matter; macro nutrients are sourced from a variety of sources – from the atmosphere for N, from the weathering of apatite, fluorapa-



[S] = Stock F = Flux

Stocks

- S1 Above ground biomass: leaves, wood, animals, fungi etc.
- S2 Below ground living biomass: roots, animals, fungi etc.
- S3 Dead biomass including litter
- S4 Soil water and dissolved elements
- S5 Minerals susceptible to weathering

Fluxes

- F1 Uptake by vegetation via root system
- F2 Accretion by wood
- F3 Accretion by foliage
- F4 Litter fall including leaves, wood, animals etc.
- F5 Stemflow of water and dissolved ions
- F6 Respiration (O_2 , CO_2), evapotranspiration (H_2O), fire (N, S, C)
- F7 Precipitation includes dust and dissolved elements, evaporation (H_2O), gas diffusion (e.g. CO_2) inputs/outputs
- F8 Weathering of minerals
- F9 Ion exchange from clay, sesquioxide and organic matter surfaces
- F10 Neoformation of minerals
- F11 Mineralisation of organic matter; N-fixation by legumes
- F12 Movement into/out of solum of water, gas and dissolved elements
- F13 Eluviation/illuviation of colloidal particles
- F14 Erosion/deposition of soil materials

Figure 8.21: A schematic hydrobiogeochemical cycle (after Gilkes 1998).

tite and other accessory minerals for P, and the K-spars and muscovite for K. Each element is then cycled through the regolith and is systematically transferred between organic components, labile compartments and living organisms (and also partitioned within the organisms), such as plants (Figure 8.22). The micro nutrients nearly all come from the weathering of minor and accessory minerals, and are subsequently cycled. The biota have a critical role in the release of nutrients from alumino-silicate weathering – and in the subsequent uptake storage and release again from organic materials, whether they are nutrients or not (for example, Si cycling; Alexandre *et al.* 1997).

In the case of P, the role of organic ligands produced by as-yet-unidentified microorganisms is fundamental to the breakdown of apatite, strengite and variscite and fluoroapatite with subsequent sequestering in secondary Fe, Al, and lanthanide minerals (Kearns *et al.* 2003). The lanthanide minerals can be very insoluble, but the role of soil fungi then becomes important in their cycling. The fluxes and stores vary according to species, genera and plant type (C3, C4, N fixer, phenotypes, and so on) as well as temporal and spatial dimensions. On a single site, for example, a succession of vegetation types will, over time, have an evolving set of fluxes and stores – as will periods of

drought or flood. Even in a period of a few days to weeks, stores and fluxes may change with soil moisture conditions, as a saturated soil first drains and then dries: a good example is the deficiency in B for sensitive species (to B concentrations), such as the *Pinus* genera. Additionally, across sites with different soils, regolith and/or lithologies, there will be very different hydrobiogeochemical cycles. Other landform characteristics (aspect, slope position and slope steepness) can also change the fluxes and stores across a landscape. Fluxes and stores change for different individual elements and groups of elements across the periodical table. The results can vary over several orders of magnitude in what appear to be as close to possible similar conditions for some elements (such as Fe) and as much as 10^6 times for others (Au). The non-essential elements can also be toxic – particularly in areas that are highly concentrated, such as over a weathering ore body.

One of the problems with research that relies on published values is the wide variation in these aspects of biomass uptake and storage when compared with regolith fluxes and stores. Not only do the values change with time and growth stages, even for only one species, but they also differ markedly across species and varieties.

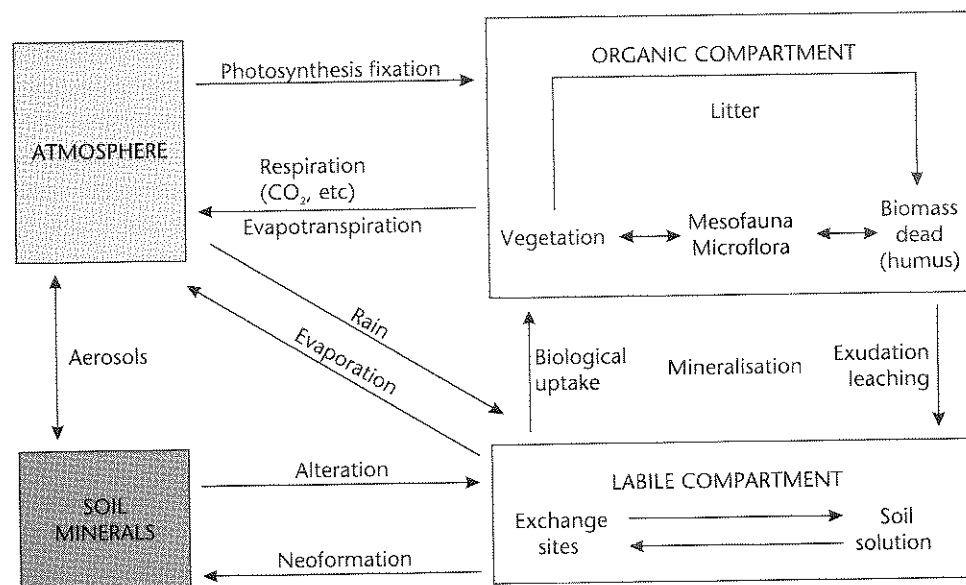


Figure 8.22: Processes, stores and fluxes within the living biota (flora, herbivores and carnivores), litter (detritivores and carnivores) and regolith (soil, saprolite and groundwater) compartments (after Gilkes 1998).

8.4.3 Vegetation bands, patterned ground, tiger striping, and resource distribution and concentration

When resources are limited to the point where ecosystems cannot function effectively over the whole landscape, but where redistribution of all the resources available to a smaller area can allow functioning, a mosaic or banding often occurs. Ecologists, geomorphologists and pedologists all argue for a parallel and causal evolution of climate and banded vegetation with landforms, regolith and soils. Some authors have argued that climatic deterioration can be a trigger for the evolution of this redistribution (Goodspeed and Winkworth 1978); others suggest grazing pressure may be the accelerant or underlying cause (Valentin *et al.* 1999), while, more recently, several have shown that simpler explanations, such as partitioning of water, can alone cause banding (Dunkerly 1997; Ursino 2007). Dunkerly and Brown (1995) suggest a system of germination and colonisation of litter dams being selected and scaled up through an unspecified process; some areas gain a competitive advantage at collecting and maintaining resources, to the detriment of surrounding areas – areas of vegetation and bare areas (Ursino 2007). Surface sealing, or crusting, across bare areas is a critical component of the processes of water redistribution (Greene 1992; Valentin *et al.* 1999).

The patterning can be approximately round (or spotted on roughly flat topography, but leading to a localised build-up of material under vegetation) (Dunkerly and Brown 1995; Valentin *et al.* 1999), through to long linear bands, such as those along contours on gently sloping land (Mabbutt and Fanning 1987). Linear vegetated bands can be expected to be perpendicular to the slope (0–2% slope) or dominant wind direction (Valentin *et al.* 1999). Valentin *et al.* found that slope gradient and mean annual rainfall are correlated with the distance (or wavelength) between the vegetated and bare areas. Wakelin-King (1999) ascribes banded vegetation to a widely distributed, but single, geomorphic unit – the sheet-flow plains, but others see it as much more widespread (Mabbutt and Fanning 1987).

Patterning, banding, banded mosaic, or (banded) tiger bush (striping or swirling like the pattern on tiger fur) are two or three phase sequences of alternat-

ing bare ground, or source areas, with bands of vegetation or sinks. Essentially resources such as water, nutrients and organic matter are harvested across the entire landscape and collect in the bands and are therefore able to support an enhanced biomass in a limited area. A strong feedback mechanism begins to develop whereby the density of plants (and all the other organisms in the ecosystem – such as termite mounds; Valentin *et al.* 1999) are strongly related to that systems ability to absorb (infiltrate and store) water, organic matter and nutrients, which, in turn, produces a greater density of plants and other biota. There is also a development of plant physiological mechanisms (either by single plant adaptation or by selection of fitter organisms) within the inter-grove and isolated vegetation (such as mulga and grasses) to be more water and nutrient efficient (Cook and Dawes-Gromadzki 2005), while those within groves seemed to consume greater resources and have enhanced biomass (including, incidentally, invertebrates such as termites, spiders and ants) (Cook and Dawes-Gromadzki 2005).

The bottom line is that the banding controls erosion, sedimentation and most other slope processes, and hence the biota, are intimately involved in the shape of the landscape and the formation and evolution of the regolith.

8.4.4 Fire and vegetation effects on regolith

The Australian regolith is particularly strongly affected by fire. The age and long weathering history of the Australian landscape (Chapter 2) has led to the very low productivity of Australian ecosystems. Fire may destroy vegetation and lead to very high levels of erosion if the right seasonal weather conditions follow (for example, Blake *et al.* 2005; Shakesby *et al.* 2003). Fire creates a mosaic of units within the landscape each bounded by a fire scar. These scars are more than vegetation boundaries because, as we have seen, vegetation affects the regolith from the surface down. Surficial mats affect hydrology and erosion, litter affects organic chemistry in the surface horizons and beyond, and roots mine the regolith for nutrient ions; therefore fire becomes a land-forming agent.

More localised effects of vegetation-fuelled fire are the ‘cooking’ of rocks, regolith and soils – not only

altering organic matter content, but also changing the overall structure (splitting and spalling of rocks), mineralogy and resistance to weathering and erosion. Any comminution affects the surface-to-volume ratio and therefore the rate of weathering, so spalling and splitting enhance the subsequent breakdown of primary mineral dominated rocks into weathering products.

Fire can also 'create' new formations from elements that previously made up long-standing vegetation, such as 'wood-ash stone' (a calcite agglomeration), which is produced during the slow burning of a large standing tree bole (Humphreys *et al.* 1987). Heat from fires can cause seemingly opposite effects, with increasing strength or case hardening on the one hand and mechanical failure on the other, where responses from weathered samples mean that post-fire materials are comminuted and more readily break down (Allison and Bristow 1999). Many authors stress the widespread and major effects fire has on the landscape and regolith (for example, Allison and Bristow 1999) when temperatures commonly reach 400 or 500°C (Goudie *et al.* 1992) and sometimes as high as 1000°C (Allison and Bristow 1999). (The importance of maghemite formation in dating and indicating surface conditions is emphasised in Chapters 2 and 6.) The rapid rise in temperature, and subsequent cooling with nightfall or rain, imposes an extreme temperature gradient promoting rock disintegration and subsequent weathering susceptibility (Adamson *et al.* 1983). The opposing effect of case hardening appears to be related to rock thermal characteristics, material properties – such as dehydration of particular minerals in both the primary, and then the secondary mineralogy associated with weathering – and environmental constraints, such as diurnal temperature ranges and the prevalence of thermally induced storms (Pye 1982; Goldammer 1990). Allison and Bristow (1999) give the examples of dehydration of both free and locked water in serpentinite and wehrlite (in serpentinite) and actinolite (in gabbro, which dehydrates to chlorite and water) at 500°C, which reduces the modulus of elasticity and the physical strength of the rock. They show, on the other hand, that dolerite raised to 500°C has free water dehydration reactions, while locked water is retained within the mineral matrix – leading to a case-hardening effect and reduced weathering (until some other effect, such

as another fire at higher temperatures, causes breakdown).

We also know that anthropogenic effects stretching back through millennia have altered vegetation through the use of fire, with concomitant changes to the landscape. Anthropogenic vegetation changes are just the imposition of yet another layer of the effects of biota (and biota changes) on the Australian landscape and regolith – albeit an extremely intense series of changes that are taking place at the moment.

Each of the issues raised above illustrates the co-evolution of Australian landscapes and regolith with the Australian biota.

8.4.5 Water table control and dryland salinity

Biota – through evapotranspiration and root distribution – are a major control on surface and near-surface water tables. Vegetation layers (overstorey, understorey, herb and grasses and litter layers) act as sponges to incoming precipitation (they can even 'create' precipitation through fog drip): absorbing it and redirecting it, storing or evapotranspiring it. As a result, much less than 50% of incoming precipitation gets to the mineral soil surface in eucalypt forest and woodland, on average, on an annual cycle (Field 1983). This process of interception is slashed when vegetation is cleared. As a result, huge increases in regolith infiltration and run-off occur. Locally, this can cause rising water tables. Salinity in regolith and groundwater (including regolith and soil water tables) is controlled by a host of factors (for example, Bann and Field 2006a; Chapter 12). Because most Australian regolith and soil contains appreciable levels of Na salts and insufficient buffers of Ca, Mg and K (Stahl and Field 2003), the water becomes saline.

Processes such as capillary rise bring soil water to the surface. If evaporation takes place on a bare or sparsely vegetated site, even a low electrical conductivity (a measure of water impurities) in the soil water can lead to the concentration of a range of salts and inorganic and organic complexes on the soil surface. The result is dryland salinity (Bann and Field 2006b). The challenge is to understand how changing salinity levels affect regolith processes. Obviously, EC will have major effects on biochemical and chemical

equilibria, on hydration, and on osmosis, when the biota attempt to withdraw nutrients and water. There are also toxicity effects from the Na itself (not to mention Cl and other ions present). The net result is usually loss of some vegetation (but not necessarily other biota: Bann and Field, 2006a) with concomitant effects of changes to the surface hydrology (run-off, infiltration, and so on) through changes to the surface (crusting and sealing) and sub-surface (soil structure, permeability, porosity, sorptivity and hydraulic conductivity) characteristics of the regolith.

8.5 CONCLUSIONS

Biota are both a part of the landscape and a factor controlling the functioning of that landscape. The functioning of the biota is also critical to the management of landscapes across all timescales: from short-term human scales to geological timescales. Biota also function across virtually all spatial scales from the microbial to the continental. In fact, biota can be argued to make the Earth different from all the other planets. Individual organisms can dramatically accelerate the rate of weathering in their vicinity – a lichen or a simple vascular plant can accelerate the very beginnings of the weathering of a virtually bare volcanic flow when compared with adjacent fresh rock. This increased rate continues unabated through a succession to forest – and an individual tree has effects on its site occurring during its lifetime (Hamilton 1972; Leonard and Field 2003) – and affect regolith and soil characteristics such as depth, horizonation, pH, organic matter, Eh, texture (and differentiation, duplex profile) and soil-profile formation under a single tree. The soil in which vegetation grows can carry a 'signature' from that vegetation for considerable periods of time (Little 2001) and different species have different signatures. Soil along a transect between two species of trees, shows markedly different characteristics near each tree bole (Leonard and Field 2003), in the area affected by stem flow, under the drip zone and in the intervening area (Hamilton 1972). Many of these patterns in soil are strongly related to root growth, leaching and weathering as the result of the selective uptake of elements by the vegetation, the cycling and subsequent deposition in precipitation and litter fall. Trees take part in

more obvious bioturbation when uprooted – rotating the root ball and bringing subsoil up to the surface. Studies in forest science suggest that the quantities of material contained in the biota and turned over by vegetation are also of comparable time and spatial scales. Catastrophic events, such as fires, can then transfer very large quantities of materials within landscapes and become major land-forming events.

Meso and macro fauna transfer material at rates comparable to weathering and soil production and rates of erosion and deposition. Wombats, kangaroos, wallabies, lyrebirds and rabbits can move substantial quantities of material at particular places and times. Collectively, they are a major bioturbation factor. Smaller fauna such as earthworms, termites, ants and other insects are also important in bioturbation and, again, the dominance of one or more groups depends on the environment and timescale. Termites are very important in the seasonal tropics right through to the humid temperate, whereas earthworms are quite rare in some humid temperate forests such as the dry sclerophyll, and barely exist in the semi-arid and arid environments (although riparian and terminal drainage systems can locally support high numbers following major rains). The micro biota are also extremely important and, despite their very small size, sheer numerical dominance makes their weathering and bioturbation effects important in most landscapes.

There are clear opportunities for research in many aspects of the biota–regolith interface. While there is a large knowledge base relating to biota–regolith interactions, there still remains little understanding of how these interactions influence the regolith in real landscapes, especially in Australia. There are many avenues open to the study of biogeochemical interactions in the Australian soils and regolith, as there have been few pedogenic studies in the rhizosphere for most of the dominant Australian flora. This is surprising given the recognised harshness of Australian environments and the uniqueness of its flora. Although the rhizosphere is only a narrow interface between plant and soil, it is a zone of very high biogeochemical activity. This soil compartment is thus worthy of investigation to better understand how plants modify their soil environment, encourage mineral weathering processes and take up the potential pathfinder and target elements used during bioprospecting.

In summary, the biota are a critical component of all soils, regolith and landforms and the biota are also drivers and components of most of the important processes in the formation and ongoing evolution of the landscape.

8.6 REFERENCES

- Adamson D, Selkirk PM, Mitchell PB (1983). The role of fire and Lyre birds in the sandstone landscape of the Sydney Basin. In *Aspects of Australian Sandstone Landscapes*. (Eds RW Young and GC Nanson) pp. 81–93. University of Wollongong, NSW.
- Alexandre A, Meunier J-D, Colin F and Koud J-M (1997). Plant impact on the biogeochemical cycle of silicon and related weathering processes. *Geochimica et Cosmochimica Acta* **61**, 677–682.
- Allaby M (Ed.) (1998). *A Dictionary of Ecology*. Oxford University Press, Oxford.
- Allison RJ and Bristow GE (1999). The effects of fire on rock weathering: some further considerations of laboratory experimental simulation. *Earth Surface Processes and Landforms* **24**, 707–713.
- Anand RR and Paine M (2002). Regolith geology of the Yilgarn Craton, Western Australia: Implications for exploration. *Australian Journal of Earth Sciences* **49**, 3–162.
- Anderson GR (2001). The influence of macro and meso biota on regolith development and evolution. BSc (Hons) thesis. Australian National University, Canberra
- Arocena JM, Gottlein A and Raidl S (2004). Spatial changes of soil solution and mineral composition in the rhizosphere of Norway-spruce seedlings colonized by *Piloderma croceum*. *Journal of Plant Nutrition and Soil Science* **167**, 479–486.
- Aufreiter S, Mahaney WC, Milner MW, Huffmann MA, Hancock RGV, Wink M and Reich M (2001). Mineralogical and chemical interactions of soils eaten by chimpanzees of the Mahale Mountains and Gombe Stream National Parks, Tanzania. *Journal of Chemical Ecology* **27**, 285–311.
- Baker AJM (1981). Accumulators and excluders – strategies in the responses of plants to heavy metals. *Journal of Plant Nutrition* **3**, 643–654.
- Banfield JF, Barker WW, Welch SA and Taunton A (1999). Biological impact on mineral dissolution: application of the lichen model to understanding mineral weathering in the rhizosphere. *Proceedings of the National Academy of Science of the United States of America* **96**, 3404–3411. Colloquium Paper.
- Banks JCG (1989). A history of forest fire in the Australian Alps. In *The Scientific Significance of the Australian Alps. The Proceedings of the 1st Fenner Conference*. (Ed. R Good), pp. 265–280. Australian Alps National Parks Liaison Committee, Canberra.
- Bann GR and Field JB (2006a). Dryland salinity in south-east Australia: which scenario makes more sense? In *Proceedings Australian Earth Sciences Convention, Melbourne*. <www.earth2006.org.au>
- Bann GR and Field JB (2006b). Dryland salinity and agronomy in south-east Australia: groundwater processes or soil degradation associated with intensive grazing? In *13th Australian Society of Agronomy Conference, Perth. Ground Breaking Stuff*. <www.regional.org.au/au/asa/2006>
- Barker WW, Welch SA, Chu S and Banfield JF (1998). Experimental observations of the effects of bacteria on aluminosilicate weathering. *American Mineralogist* **83**, 1551–1563.
- Bennie AT (1991). Growth and mechanical impedance. In *Plant Roots: The Hidden Half*. (Eds Y Waisel, A Eshel and U Kafkafi) pp. 393–414. Marcek Dekker, New York.
- Blake WH, Wallbrink PJ, Doerr SH, Shakesby RA and Humphreys GS (2005). Magnetic enhancement in wildfire-affected soil and its potential for sediment-source ascription. *Earth Surface Processes and Landforms* **31**, 249–264.
- Black TA and Montgomery DR (1991). Sediment transport by burrowing animals, Marin County, California. *Earth Surface Processes and Landforms* **16**, 163–172.
- Bolan NS, Elliot J, Gregg PEH and Weil S (1997). Enhanced dissolution of phosphate rocks in the rhizosphere. *Biology and Fertility of Soils* **24**, 169–174.
- Brantley SL, Goldhaber MB and Ragnarsdottir KV (2007). Crossing disciplines and scales to understand the Critical Zone. *Elements* **3**, 307–314.
- Brundett MC (2002). Tansley review no. 134: Coevolution of roots and mycorrhizas of land plants. *New Phytologist* **154**, 275–304.

- Burges NA (1958). *Micro-organisms in the Soil*. Hutchinson University Library, London.
- Butler D (1995). *Zoogeomorphology. Animals as Geomorphic Agents*. Cambridge University Press, Cambridge, UK.
- Buyer JS and Drinkwater LE (1997). Comparison of substrate utilization assay and fatty acid analysis of soil microbial communities. *Journal of Microbiological Methods* **30**, 3–11.
- Caine N (1986). Sediment movement and storage on alpine slopes in the Colorado Rocky Mountains. In *Hillslope Processes*. Binghampton Symposium in Geomorphology: International Series No. 16. (Ed. AD Abrahams) pp. 115–137. Allen and Unwin, Boston, Massachusetts.
- Cairney JWG and Meharg AA (2002). Interactions between ectomycorrhizal fungi and soil saprotrophs: implications for decomposition of organic matter in soils and degradation of organic pollutants in the rhizosphere. *Canadian Journal of Botany* **80**, 803–809.
- Cammeratt LH, Willott SS, Compton SG and Incoll LD (2002). The effect of ants' nests on the physical, chemical and hydrological properties of a rangeland soil in semi-arid Spain. *Geoderma* **105**, 1–20.
- Carr J, Gould N and Sterling, J (2004). 'Does bioturbation activity vary with vegetation cover in the Santa Cruz Mountains, California'. Research Report Series No. 4. pp. 27–30. Department of Geography, University of Liverpool, UK.
- Cervini-Silva J, Fowele DA and Banfield J (2005). Biogenic dissolution of a ceri-phosphate mineral. *American Journal of Science* **305**, 711–726.
- Chorover J and Amistadi MK (2001). Reaction of forest floor organic matter at goethite, birnessite and smectite surfaces. *Geochemica et Cosmochimica Acta* **65**, 95–109.
- Coleman DC and Hendrix PF (Eds) (2000). *Invertebrates as Webmasters in Ecosystems*. CABI Publishing, Wallingford, UK.
- Cook GD and Dawes-Gromadzki T (2005). Stable isotope signatures and landscape functioning in banded vegetation in arid-central Australia. *Landscape Ecology* **12**, 216–224.
- Corbet AS (1935). *Biological Processes in Tropical Soils, with Special Reference to Malaysia*. W. Heffer and Sons, Cambridge, UK.
- Cowan JA, Humphreys, GS, Mitchell, PB and Murphy CL (1985). An assessment of pedoturbation by two species of mound-building ants, *Camponotus intrepidus* (Kirby) and *Iridomyrmex purpureus* (F. Smith). *Australian Journal of Soil Research* **22**, 95–107.
- Cromack K, Sollins P, Graustein WC, Speidel K, Todd AW, Spycher G, Li CY and Todd RL (1979). Calcium oxalate accumulation and soil weathering in mats of the hyphogeous fungus *Hysterangium crassum*. *Soil Biology and Biochemistry* **11**, 463–468.
- Curl EA and Truelove B (1986). *The Rhizosphere*. Springer-Verlag, Berlin, New York.
- Darwin C (1837). On the formation of mould. *Transactions of the Geological Society of London* **5**, 505.
- Darwin C (1881). On the formation of vegetable mould through the action of worms. J. Murray, London.
- Davies N (1953). 'Investigations on the soil and water relations of the river red gum forests'. Final Report Murray Management Survey. Report no. R 124. Forestry Commission of New South Wales, Resources Branch, Sydney.
- Davis WM and Snyder WH (1898). *Physical Geography*. Ginn and Co. Publishers, Boston and London.
- Day DG (1980). Drainage density changes during rainfall. *Earth Surfaces Processes* **1**, 63–70.
- Denny C S and Goodlett JC (1956). Microrelief resulting from fallen trees. In *Surficial Geology and Geomorphology of Potter County, Pennsylvania* (Ed. CS Denny) pp. 59–66. Professional Paper 288. United States Geological Survey, Reston, Virginia.
- Devit DA and Smith SD (2002). Root channel macropores enhance downward movement of water in a Mojave Desert ecosystem. *Journal of Arid Environments* **50**, 99–108.
- Dexter BD (1967). 'Flooding and regeneration of river red gum, *Eucalyptus camuldulensis* (Dehn)'. Bulletin Number 20, Forests Commission of Victoria, Melbourne.
- Douglas I (1977). *Humid Landforms*. ANU Press, Canberra.
- Drever JJ and Stillings LL (1997). The role of organic acids in mineral weathering. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **120**, 167–181.

- Dunkerly DL (1997). Banded vegetation: development under uniform rainfall from a simple cellular automaton model. *Plant Ecology* **29**, 103–111.
- Dunkerly DL and Brown KJ (1995). Runoff and runoff areas in a patterned chenopod shrubland, arid western New South Wales, Australia: characteristics and origin. *Journal of Arid Environments* **30**, 41–55.
- Eddy J, Humphreys GS, Hat DM, Mitchell PB and Fanning PC (1999). Vegetation arcs and litter dams: similarities and differences. *Catena* **37**, 57–73.
- Edwards CA and Bohlen PJ (1996). *Biology and Ecology of Earthworms*. Chapman and Hall, London.
- Edwards WM and Shipitalo MJ (1998). Consequences of earthworms in agricultural soils: aggregation and porosity. In *Earthworm Ecology*. (Ed. CA Edwards) pp. 147–161. CRC Press, Boca Raton, Florida.
- Eggleton RA (Ed.) (2001) *The Regolith Glossary: Surficial Geology, Soils and Landscapes*. CRC LEME, Canberra.
- Ekundayo EO and Aghastise VO (1997). Soil properties of termite mounds under different land use types in a typical paleudult of midwestern Nigeria. *Environmental Monitoring and Assessment* **45**, 1–7.
- Field JB (1983). The sources of solutes in, and chemical budgets for three small rural catchments, New England, N.S.W. PhD thesis, University of New England, Armidale, NSW.
- Field JB (2003). Biota, regolith and landscapes: At the hillslope, profile and lesser scales. In *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposia 2003*. (Ed. IC Roach) pp.115–118. CRC LEME, Perth.
- Field JB (2004). Geomorphology and the biota. In *Proceedings of the 11th Australia New Zealand Geomorphology Group Conference 2004*. (Ed. D Fabel) p. 24. Australia New Zealand Geomorphology Group, Melbourne.
- Field JB (2006.) The effects of biota on the formation of regolith: where we are up to, and whence from here. In *Regolith 2006 Consolidation and Dispersion of Ideas*. Hahndorf, South Australia (Eds RW Fitzpatrick and P Shand) pp.284–287. CRC LEME, Perth.
- Field JB and Anderson GR (2003). Biological agents in regolith processes: case study on the Southern Tablelands, NSW. In *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposia 2003*. (Ed. IC Roach) pp.119–121. CRC LEME, Perth.
- Fomina M, Alexander IJ, Colpaert JV and Gadd GM (2005). Solubilization of toxic metal minerals and metal tolerance of mycorrhizal fungi. *Soil Biology and Biochemistry* **37**, 851–866.
- Gabet EJ (2000). Gopher bioturbation; field evidence for nonlinear hillslope diffusion. *Earth Surface Processes and Landforms* **25**, 1419–1428.
- Gabet EJ, Reichmen OJ and Seabloom EW (2003). The effects of bioturbation on soil processes and hillslope evolution. *Annual Review of Earth and Planetary Sciences* **31**, 249–273.
- Gadd GM (2004). Microbial influence on metal mobility and application for bioremediation. *Geoderma* **122**, 109–119.
- Gilkes RJ (1998). Biology and the regolith: an overview. In *The State of the Regolith*. (Ed. RA Eggleton) pp.110–125. Special Publication No. 20. Geological Society of Australia, Sydney.
- Gobran GR, Wenzel WW and Lombi E (Eds) (2001). *Trace Elements in the Rhizosphere*. CRC Press. Boca Raton, Florida.
- Goldammer JG (Ed.) (1990). *Fire in the Tropical Biota*. Springer-Verlag, Berlin
- Gomes NCM, Fagbola O, Costa R, Rumjanek NG, Buchner A, Mendona-Hagler I and Smalla K (2003). Dynamics of fungal communities in bulk and maize rhizosphere soil in the tropics. *Applied and Environmental Microbiology* **69**, 3758–3766.
- Goodspeed MJ and Winkworth RE (1978). Fate and effect of runoff – with particular reference to arid and semi-arid plain lands. In *Studies of the Australian Arid Zone. III. Water in Rangelands*. Proceedings of the Symposium, Rangelands Research Unit, Alice Springs Field Centre, 15–18 October. (Ed. HMIW Howes). Division of Land Resources Management, CSIRO, Melbourne.
- Goudie AS, Rogers A and Viles HA (1992). *The Students Companion to Geography*. Blackwell, Oxford.
- Greene RSB (1992). Soil physical properties of three geomorphic ones in a semi-arid Mulga Woodland. *Australian Journal of Soil Research* **30**, 55–69.
- Guglielmin M, Cannone N, Strini A, Lewkowicz A. (2005). Biotic and abiotic processes on granite

- weathering landforms in a cryotic environment, Northern Victoria Land, Antarctica. *Permafrost and Periglacial Processes* **16**, 69–85.
- Haag D and Matschonat G (2001). Limitations of controlled experimental systems as models for natural systems: a conceptual assessment of experimental practices in biogeochemistry and soil science. *The Science of the Total Environment* **277**, 199–216.
- Hagerberg D, Thelin G and Wallander H (2003). The production of ectomycorrhizal mycelium in forests: Relation between forest nutrient status and local mineral sources. *Plant and Soil* **252**, 279–290.
- Hamilton C (1972). The nature and causes of spatial variation in forest ecosystems. PhD thesis. Australian National University, Canberra.
- Hart DM (2001). The elemental composition of phytoliths. In *Phytoliths: Application in Earth Sciences and Human History*. (Eds JD Meunier and F Colin) pp. 313–316. Balkena.
- Hart DM and Humphreys GS (2003). Phytolith depth functions in surface regolith materials. In *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposia 2003*. (Ed. IC Roach) pp. 159–163. CRC LEME, Perth.
- Heimsath AM, Chappell J, Dietrich WE, Nishiizumi K and Finkel RC (2000). Soil production on a retreating escarpment in southeastern Australia. *Geology* **28**, 787–790.
- Heimsath AM, Chappell J, Spooner NA and Ques-tiaux DG (2002). Creeping soil. *Geology* **30**, 111–114.
- Heinrich I and Banks JCG (2006). Variation of phenology, tree growth and wood anatomy of *Toona sinensis* and *Toona ciliata* in relation to different environmental conditions. *International Journal of Plant Science* **167**, 831–841.
- Hernesmaa A, Njorklof K, Kiikkila O, Fritze H, Haahtela K and Romantschuk M (2005). Structure and function of microbial communities in the rhizosphere of Scots pine after tree-felling. *Soil Biology and Biochemistry* **37**, 777–785.
- Hiltner L (1904). Über neuere Erfahrungen und Probleme auf dem Gebiete der Bodenbakteriologie unter besonderer Berücksichtigung der Grundung und Brache. *Arbeiten der Deutschen Landwirtschaftlichen Gesellschaft* **98**, 59–78.
- Hoffland E, Giesler R, Jongmans AG and van Bree-man N (2003). Feldspar tunneling by fungi along natural productivity gradients. *Ecosystems* **6**, 739–746.
- Holt JA, Coventry RJ and Sinclair DF (1980). Some aspects of the biology and pedological significance of mound-building termites in a red and yellow earth landscape near Charters Towers, North Queensland. *Australian Journal of Soil Research* **18**, 97–109.
- Hoppert M, Flies C, Pohl W, Günzl B and Schneider J (2004). Colonization strategies of lithobiontic microorganisms on carbonate rocks. *Environmental Geology* **46**, 421–428.
- Howell J, Humphreys GS and Mitchell PB (2006). Changes in soil water repellency and its distribution in relation to surface microtopographic units after a low severity fire in eucalypt woodland, Sydney, Australia. *Australian Journal of Soil Research* **44**, 205–217.
- Huang PM (2000). Abiotic catalysis. In *Handbook of Soil Science*. (Ed. ME Sumner). CRC Press, Boca Raton, Florida.
- Hulme KA and Hill SM (2003). River red gums as a biogeochemical sampling medium in mineral exploration and environmental chemistry programs in the Curnamona Craton and adjacent regions of NSW and SA. In *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposia 2003*. (Ed. IC Roach) pp. 205–210. CRC LEME, Perth.
- Humphreys GS (1981). The rate of ant mounding and earthworm casting near Sydney, New South Wales. *Search* **12**, 129–131.
- Humphreys GS (1989). Earthen structures built by nymphs of the cicada, *Cyclochila australasiae* (Donovan) (Homoptera, Cicadidae). *Australian Entomological Magazine* **16**, 99–108.
- Humphreys GS (1994). Bioturbation, biofabrics and the biomantle: an example from the Sydney Basin. In *Soil Micromorphology: Studies in Management and Genesis. Developments in Soil Science. Vol. 22*. (Eds AJ Ringrose-Voace and GS Humphreys) pp. 421–436. Elsevier, Amsterdam.
- Humphreys GS and Field RJ (1998). Mixing, mounding and other aspects of bioturbation: implications

- for pedogenesis. In *Proceedings of the 16th World Congress of Soil Science*, Montpellier, France, 20–26 August. International Union of Soil Sciences, Wageningen, Netherlands.
- Humphreys GS, Hunt PA and Buchanan R (1987). Wood-ash stone near Sydney, NSW: a carbonate pedological feature in an acidic soil. *Australian Journal of Soil Research* **25**, 115–124.
- Hupy JP and Schaetzel RJ (2006). Introducing 'Bomb-turbation', a singular type of soil disturbance and mixing. *Soil Science* **171**, 823–836.
- Jenny H (1941). *Factors of Soil Formation: a System of Quantitative Pedology*. McGraw-Hill, New York.
- Johnson DL (1989). Subsurface stone lines, stone zones, artifact-manuport layers, and biomantles produced by bioturbation via Pocket Gophers (*Thomomys bottae*). *American Antiquity* **54**, 370–389.
- Johnson DL (2002). Darwin would be proud: bioturbation, dynamic denudation, and the power of theory in science. *Geoarchaeology: An International Journal* **17**, 7–40.
- Johnson DL, Domier JEJ and Johnson DN (2005). Reflections on the nature of soil and its biomantle. *Annals of the Association of American Geographers* **95**, 11–31.
- Johnston CG and Vestal JR (1991). Photosynthetic carbon incorporation and turnover in Antarctic cryptoendolithic microbial communities: Are they the slowest growing communities on Earth? *Applied Environmental Microbiology* **57**, 2308–2311.
- Jones DL, Dennis PG, Owen AG and van Hees PAW (2003). Organic acid behaviour in soils – misconceptions and knowledge gaps. *Plant and Soil* **248**, 31–41.
- Kearns JP, Cervini-Silva J, Fournelle J, Schloss P, Williamson L, Reuss R, Handlesman J and Banfield JF (2003). Mechanisms of Biogeochemical Influence on Phosphorus Bioavailability in Cold Terrestrial Ecosystems. *Eos Transactions American Geophysical Union* **84(46)** Fall Meeting Supplement, Abstract B21C-0720, American Geophysical Union, Washington DC.
- Kirby C, Neal C, Turner H, and Moorhouse P, (1991). A bibliography of hydrological, geomorphological, sedimentology, biological and hydrochemical references to the Institute of Hydrology experimental catchment studies in Plynlimon. *Hydrology and Earth Systems Science* **1**, 755–763.
- Kirk JL, Beaudette LA, Hart M, Moutoglis P, Kloromos JN, Lee H and Trevors JT (2004). Methods of studying soil microbial diversity. *Journal of Microbiological Methods* **58**, 169–188.
- Kozdroj JJ and van Elsas JD (2000). Response of the bacterial community to root exudates in soil polluted with heavy metals assessed by molecular and cultural approaches. *Soil Biology and Biochemistry* **32**, 1405–1417.
- Kwong NG, Kee KF and Huang PM (1977). Influence of citric acid on the hydrolytic reactions of aluminium. *Soil Science Society of America Journal* **41**, 692–697.
- Lam KC (1979). Production of runoff, solutes and sediments in a small catchment on the Northern Tablelands, New South Wales. PhD thesis. University of New England, Armidale, NSW.
- Leonard JA and Field JB (2003). The effect of two very different trees on soil and regolith characteristics. In *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposia 2003*. (Ed. IC Roach) pp. 263–266. CRC LEME, Perth.
- Leonard JA and Field JB (2004). Differential distributions of cations in the regolith and vegetation. In *Regolith 2004. Proceedings of the CRC LEME Regional Regolith Symposia 2004*. (Ed. IC Roach) pp. 215–219. CRC LEME, Perth.
- Likens GE, Tartowski SL, Berger TW, Richey DG, Driscoll CT, Frank HG and Klein A (1997). Transport and fate of trifluoroacetate in upland forest and wetland ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* **94**, 4499–4503.
- Little DA (2001). The subalpine inverted treeline: soil patterns and nutrient processes. BSc (Hons) thesis. Australian National University, Canberra.
- Little DA (2007). The rhizosphere: organic acid microbe mineral interactions. A multidisciplinary investigation of forest soil biogeochemistry in temperate Australian landscapes. PhD thesis. Australian National University, Canberra.
- Little DA and Field JB (2003). The rhizosphere, biology and the regolith. In *Advances in Regolith*.

- Proceedings of the CRC LEME Regional Regolith Symposia 2003.* (Ed. IC Roach) pp. 271–274. CRC LEME, Perth.
- Little DA, Field JB and Banks JCG (2003). Soil and regolith patterns and nutrient processes across an abrupt woodland-grassland ecotone. In *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposia 2003.* (Ed. IC Roach) pp. 275–277. CRC LEME, Perth.
- Little DA, Field JB, Welch SA and Rogers SL (2005a). Metal mobilisation from rhizosphere and non-rhizosphere soils using low molecular weight organic acids. In *Regolith 2005 – 10 years of CRC LEME. Proceedings of the CRC LEME Regional Regolith Symposia 2005.* (Ed. IC Roach) pp. 197–201. CRC LEME, Perth.
- Little DA, Welch SA, Macdonald LM and Rogers SL (2005b). Microbial community structural and functional diversity in the rhizosphere of co-occurring forest trees. In *Regolith 2005 – 10 years of CRC LEME. Proceedings of the CRC LEME Regional Regolith Symposia 2005.* (Ed. IC Roach) pp. 202–206. CRC LEME, Perth.
- Longhurst W (1944). Observations on the ecology of the Gunnison prairie dog in Colorado. *Journal of Mammalogy* **25**, 24–36.
- Mabbutt JA and Fanning PC (1987). Vegetation banding in arid Western Australia. *Journal of Arid Environments* **12**, 41–59.
- Marilley L and Aargno M (1999). Phylogenetic diversity of bacterial communities differing in degree of proximity of *Lolium perenne* and *Trifolium repens* roots. *Applied Soil Ecology* **13**, 127–136.
- Markewitz D and Richter DD (1998). The bio in aluminium and silicon geochemistry. *Biochemistry* **42**, 235–252.
- Marschner B and Kalbitz K (2003). Controls of bioavailability and biodegradability of dissolved organic matter in soils. *Geoderma* **113**, 211–235.
- Marschner P, Grierson PF and Rengel Z (2005). Microbial community composition and functioning in the rhizosphere of three *Banksia* species in native woodland in Western Australia. *Applied Soil Ecology* **28**, 191–201.
- Martino E, Perotto S, Parsons R and Gadd GM (2003). Solubilization of insoluble inorganic zinc compounds by ericoid mycorrhizal fungi derived from heavy metal polluted sites. *Soil Biology and Biochemistry* **35**, 133–141.
- McLean JS, Lee J-U and Beveridge TJ (2002). Interactions of bacteria and environmental metals, fine-grained mineral development and bioremediation strategies. In *Interactions between soil particles and microorganisms: impact on the terrestrial ecosystems.* IUPAC Series on Analytical and Physical Chemistry of Environmental Systems. (Eds PM Huang, J-M Bollag and N Senesi) pp. 227–262. John Wiley and Sons, Chichester, UK.
- Mellanby K (1971). *The Mole.* Williams Collins and Sons Ltd, Glasgow.
- Miklos AAW (1999). Stone-lines and oxic horizons: biogenetic organizations-soil fauna. In *Abstracts, Symposium: Slope Processes that Produce Stone-lines.* Regional conference on geomorphology, 17–22 July, Rio de Janeiro. p. 103. International Association of Geomorphologists (IAG).
- Mitchell PB (1985). Soil bioturbation. PhD thesis. Macquarie University, Sydney.
- Mitchell PB (1988). The influences of vegetation, animals and micro-organisms on soil processes. In *Biogeomorphology.* (Ed. HA Viles) pp. 43–83. Blackwell, Oxford.
- Mitchell PB and Humphreys GS (1987). Litter dams and microterraces formed on hillslopes subject to rainwash in the Sydney Basin, Australia. *Geoderma* **39**, 331–357.
- Moerkerken (2005). Distribution of precious metals in two dry sclerophyll forest trees: early steps in research at Tomakin Park Goldmine, New South Wales. In *Regolith 2005 – 10 years of CRC LEME. Proceedings of the CRC LEME Regional Regolith Symposia 2005.* (Ed. IC Roach) pp. 235–239. CRC LEME, Perth.
- Mylius SJ (1992). The Effects of Eucalypts on Soils of Southern New South Wales. BSc (Hons) thesis. Australian National University, Canberra.
- Nannipieri P, Ascher J, Ceccherini MT, Landi L, Pietramellara G and Renella G (2003). Microbial diversity and soil functions. *European Journal of Soil Science* **54**, 655–670.
- Noguchi S, Tsuboyama Y, Sidle RC and Hosoda I (1999). Morphological characteristics of macropo-

- res and the distribution of preferential flow pathways in a forested slope segment. *Journal of the Soil Science Society of America* **63**, 1413–1423.
- Norman SA, Schatzl RJ and Small TW (1995). Effects of slope angle on mass movement by tree uprooting. *Geomorphology* **14**, 19–27.
- Ognev SI and Tomilin AG (1947). *The Mammals of the USSR and Adjacent Countries*. Academy of Sciences Press, Moscow and Leningrad (Russian).
- Osterkamp WR, Toy TJ and Lenart MT (2005). Development of partial rock veneers by root throw in a subalpine setting. *Earth Surface Processes and Landforms* **31**, 1–14.
- Pan WL, Bolton RP, Lunquist EJ and Hiller LK (1998). Portable rhizotron and color scanner system for monitoring root development. *Plant and Soil* **200**, 107–112.
- Paris F, Bonnaud P, Ranger J, Robert M and Lapeyrie F (1995). Weathering of ammonium- or calcium-saturated 2:1 phyllosilicates by ectomycorrhizal fungi *in vitro*. *Soil Biology and Biochemistry* **22**, 1237–1244.
- Paton TR, Humphreys GS and Mitchell PB (1995). *Soils: A New Global View*. UCL Press Limited, London.
- Petts A (2006). From the Tanami to Tanzania: Termite Adventures. In *Regolith 2006 Consolidation and Dispersion of Ideas*. Hahndorf. (Eds RW Fitzpatrick and P Shand) pp. 270–273. CRC LEME, Perth.
- Pryor G (1962). *Australia's Little Cornwall*. Rigby Ltd, Adelaide.
- Putz FE (1983). Treefall pits and mounds, buried seeds, and the importance of soil disturbance to pioneer trees on Barro Colorado Island, Panama. *Ecology* **64**, 1069–1074.
- Pye K (1982). Morphological development of coastal dunes in a humid tropical environment, Cape Bedford and Cape Flattery, North Queensland. *Geografiska Annaler* **64**, 212–227.
- Qin F, Shan X-Q and Wei B (2004). Effects of low-molecular-weight organic acids and residence time on desorption of Cu, Cd and Pb from soils. *Chemosphere* **57**, 253–263.
- Raapana JAW and Field JB (2006). *Macrozamia communis* (L. Johnson) as a biochemical biogeochemical indicator of mineralisation on the South Coast of New South Wales. (Understanding regolith processes). In *Regolith 2006 Consolidation and Dispersion of Ideas*. Hahndorf. (Eds RW Fitzpatrick and P Shand) pp. 284–287. CRC LEME, Perth.
- Ramsey PW, Rillig MC, Feris KP, Holben WE and Gannon JE (2006). Choice of methods for soil microbial community analysis: PLFA maximizes power compared to CLPP and PCR-based approaches. *Pedobiologia* **50**, 275–280.
- Rath H (1993). An investigation of the physical and chemical properties of soils under regrowth dry sclerophyll forest on the Southern Tablelands of NSW. BSc (Hons) thesis. Australian National University, Canberra.
- Rao L (2005). Spatial distribution of soil hydrophobicity under dry sclerophyll forests. Masters thesis, Fenner School, Australian National University.
- Reddell P, Yun Y and Shipton WA (1997). Cluster roots and mycorrhizae in *Casuarina cunninghamiana*: their occurrence and formation in relation to phosphorus supply. *Australian Journal of Botany* **45**, 41–51.
- Reichman O and Smith SC (1990). Burrows and burrowing behaviour by mammals. *Current Mammalogy* **2**, 197–244.
- Reid N, Hill SM and Lewis DM (2005). Tanami geobotany and biogeochemistry: towards its characterisation, role in regolith evolution and implications for mineral exploration. In *Ten Years of CRC LEME. Proceedings of the CRC LEME Regional Regolith Symposia 2005*. (Ed. IC Roach) pp. 256–259. CRC LEME, Perth.
- Roach IC and Walker SD (2005) Biogeochemical expression of gold in native tree leaves at Wyoming and Tomingley, NSW. In *Regolith 2005 – Ten years of CRC LEME*. (Ed. IC Roach) pp. 277–282. CRC LEME, Perth.
- Roering JJ, Almond P, Tonkin P and McKean J (2002). Soil transport driven by biological processes over millennial time scales. *Geology* **30**, 1115–1118.
- Sandnes A, Eldhuset TD and Wollebaek G (2005). Organic acids in root exudates and soil solution of Norway spruce and silver birch. *Soil Biology and Biochemistry* **37**, 259–269.

- Schooley RL and Wiens JA (2001). Dispersion of kangaroo rat mounds at multiple scales in New Mexico, USA. *Landscape Ecology* **16**, 267–277.
- Seguin V, Gagnon C and Courchesne F (2004). Changes in water extractable metals, pH and organic carbon concentrations at the soil-root interface of forested soils. *Plant and Soil* **260**, 1–17.
- Selkirk PM, Adamson DA and Downing AJ (2001). Landform and vegetation change in the Greaves Creek Basin: an asymmetric hanging valley in the Blue Mountains, New South Wales. *Australian Geographer* **32**, 45–75.
- Shakesby RA, Chafer C, Doerr SH, Blake WH, Wallbrink P, Humphreys GS and Harrington BA (2003). Fire severity, water repellency characteristics and hydrogeomorphological changes following the Christmas 2001 Sydney forest fires. *Australian Geographer* **34**, 147–175.
- Sharpley AN, Syers JK and Springett JA (1979). Effect of surface-casting earthworms on the transport of phosphorus and nitrogen in surface runoff from pasture. *Soil Biology and Biochemistry* **11**, 459–462.
- Sheldon ND (2003). Pedogenesis and geochemical alteration of the Picture Gorge subgroup, Columbia River basalt, Oregon. *Geological Society of America Bulletin* **115**, 1377–1387.
- Singh BK, Millard P, Whiteley AS and Murrell JC (2004). Unravelling rhizosphere–microbial interactions: opportunities and limitations. *Trends in Microbiology* **12**, 386–393.
- Smith OL (1982). *Soil Microbiology: a Model of Decomposition and Nutrient Cycling*. CRC Press Inc, Boca Raton, Florida.
- Smith BJ, Warke PA and Moses CA (2000). Limestone weathering in contemporary arid environments: a case study from southern Tunisia. *Earth Surface Processes and Landforms* **25**, 1343–1354.
- Smithers R (1983). *The Mammals of the Southern African Subregion*. University of Pretoria, Pretoria, South Africa.
- Stahl N and Field JB (2003). Stream salinity in a coastal catchment, Bega, NSW: A conceptual model. In *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposia 2003*. (Ed. IC Roach) pp. 391–393. CRC LEME, Perth.
- Stone AT (1997). Reactions of extracellular organic ligands with dissolved metal ions and mineral surfaces. *Reviews in Mineralogy* **35**, 309–344.
- Strakhov NM (1967). *Principals of Lithogenesis*. Oliver and Boyd, Edinburgh.
- Tebo BM, Ghiorse WC, van Waasbergen LG, Siering PL and Caspi R (1997). Bacterially mediated mineral formation: insights into manganese (II) oxidation from molecular genetic and biochemical studies. *Reviews in Mineralogy* **35**, 225–266.
- Theng BKG and Orchard VA (1995). Interactions of clays with microorganisms and bacterial survival in soil: a physicochemical perspective. In *Environmental impact of soil component interactions. Vol II*. (Eds PM Huang, J Berthelin, J-M Bollag, WB McGill and AL Page) pp. 123–143. Lewis Publishers, CRC Press, Boca Raton, Florida.
- Thorn CE (1978). A preliminary assessment of the geomorphic role of pocket gophers in the alpine zone of the Colorado front range. *Geografiska Annaler* **60A**, 181–187.
- Thorn CE (1982). Gopher disturbance: its variability by Braun-Blanquet vegetation units in the Niwot Ridge alpine tundra zone, Colorado Front Range, USA. *Arctic and Alpine Research* **14**, 45–51.
- Ursino N (2007). Modeling banded vegetation patterns in semiarid regions: interdependence between biomass growth rate and relevant hydrological processes. *Water Resources Research* **43**, W04412.
- Valentin C, d’Herbes JM and Poesen J (1999). Soil and water components of banded vegetation patterns. *Catena* **37**, 1–24.
- van Hees PAW, Jones DL, Jentschke G and Godbold DL (2004). Mobilization of aluminium, iron and silicon by *Picea abies* and ectomycorrhizas in a forest soil. *European Journal of Soil Science* **55**, 101–111.
- Vancura V and Kunc F (1987). Interrelationships between microorganisms and plants in soil. In *Proceedings of International Symposium*. Liblice, Czechoslovakia, 22–27 June. Czechoslovak Academy of Sciences, Prague. (English version: Elsevier, Amsterdam; New York. 1989.)
- Viles HA (1988). *Biogeomorphology*. Blackwell, Oxford.
- Vogt KA, Vogt DJ and Bloomfield J (1998). Analysis of some direct and indirect methods for estimating

- root biomass and production of forests at an ecosystem level. *Plant and Soil* **200**, 71–89.
- Wakelin-King GA (1999). Banded mosaic ('tiger bush') and sheetflow plains: a regional mapping approach. *Australian Journal of Earth Sciences* **46**, 53–60.
- Welch SA and Banfield JF (2002). Modification of olivine surface morphology and reactivity by microbial activity during chemical weathering. *Geochimica et Cosmochimica Acta* **66**, 213–221.
- Welch SA, Taunton AE and Banfield JF (2002). Effects of microorganisms and microbial metabolites on apatite dissolution. *Geomicrobiology Journal* **19**, 343–367.
- White ME (2003). *Earth Alive: From Microbes to a Living Planet*. Rosenberg Publishing, Dural, NSW.
- Whitford WG (2000). Keystone arthropods as webmasters in desert ecosystems. In *Invertebrates as Webmasters in Ecosystems*. (Eds DC Coleman and PF Hendrix) pp. 25–41. CABI Publishing, New York.
- Whitford WG and Kay FR (1999). Bioturbation by mammals in deserts: a review. *Journal of Arid Environments* **41**, 203–230.
- Widmer F, Fleibach A, Laczko E, Schulze-Aurich J and Zeyer J (2001). Assessing soil biological characteristics: a comparison of bulk soil community DNA-, PLFA-, and BiologTM-analyses. *Soil Biology and Biochemistry* **33**, 1029–1036.
- Wierzos J, Ascaso C and McKay CP (2006). Endolithic cyanobacteria in halite rocks from the hyper-arid core of the Atacama Desert. *Astrobiology* **6**, 415–422.
- Wilkinson MT, Humphreys GS, Chappell J, Fifield K and Smith B (2003). Estimates of soil production in the Blue Mountains, Australia, using cosmogenic ¹⁰Be. In *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposium 2003*. (Ed. IC Roach) pp. 441–443. CRC LEME, Perth.
- Wilkinson MT, Humphreys GS, Chappell J, Fifield K, Smith BL and Hesse P (2004). Soil production, landscape evolution and vegetation dynamics in the Blue Mountains, Australia. In *American Geophysical Union, Fall Meeting 2004*, abstract #H51C-1147.
- Williams JP and Vepraskas MJ (1994). Solute movement through quartz-diorite saprolite containing quartz veins and biological macropores. *Journal of Environmental Quality* **23**, 810–815.
- Wings O (2003). Observations on the release of gastroliths from ostrich chick carcasses in terrestrial and aquatic environments. *Journal of Taphonomy* **1**, 97–103.
- Yuan L, Huang J, Li X and Christie P (2004). Biological mobilization of potassium from clay minerals by ectomycorrhizal fungi and eucalypt seedling roots. *Plant and Soil* **262**, 351–361.
- Zak JC, Willig MR, Moorhead DL and Wildman HG (1994). Functional diversity of microbial communities: a quantitative approach. *Soil Biology and Biochemistry* **26**, 1101–1108.
- Zakaria AS (1977). Controls upon the Mineral Outputs from three small catchments in New England. PhD thesis. University of New England, Armidale, NSW.

This comprehensive reference on the fundamentals of regolith geoscience describes how regolith is developed from parental rocks and emphasises the importance of chemical, physical, water and biological processes in regolith formation. It provides details for mapping regolith landforms, as well as objective information on applications in mineral exploration and natural resource management. *Regolith Science* also provides a concise history of weathering through time in Australia. It includes previously unpublished information on elemental abundances in regolith materials along with detailed information on soil degradation processes such as acid sulfate soils.

Written by experts in the field, *Regolith Science* summarises research carried out over a 13-year period within the Cooperative Research Centre for Landscape Environments and Mineral Exploration. This book will be a valuable resource for scientists and graduate/postgraduate students in geology, geography and soil science, professionals in the exploration industry and natural resources management.

