THE EFFECTS OF BIOTA ON THE FORMATION OF REGOLITH: WHERE ARE WE UP TO, AND WHERE TO FROM HERE.

John B. Field

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

INTRODUCTION

The definition of regolith has evolved to encompass all materials between hard rock and fresh air and therefore must be argued to include all biota, living and dead. Today there is increasingly a broad acceptance by earth and environmental scientists that the biota are an important factor determining landscape processes both at the regolith and soil scale as well as landforms. However, until recently weathering has nearly always been described in terms of inorganic chemical pathways, mineral stability diagrams and simplistic chemical equations. Chemical reactions, which include carbonic acid and / or hydrogen ions from the disassociation of water (as the active agents driving weathering), occur in almost every geological, geochemical, regolith, soils or geomorphology textbook. There have been good reasons for ignoring the biochemistry and organic chemistry of biotic weathering. The reality of chemical weathering includes a multitude of organic acids, enzymes and other organic complexes such as chelates. The equations that describe these chemical reactions very rapidly become so complex that to understand the processes becomes the sole realm of an organic chemist.

Biota also affect regolith formation and preservation in many other ways such as the physical breakdown of materials, regolith erosion enhancement or protection and active and passive bioturbation, to mention just a few. Biota are important right across geographical scales from the continental scale of Zonal soils (read regolith) models of Jenny (1980 and updated radically by Mackenzie *et al.* (2004) for Australia) to the microscopic scale of the rhizosphere (Little *et al.* 2005). Biota also radically affect regolith formation across time scales from the millennia as plants began to alter the atmosphere thousands of millions of years ago; through the stabilisation of Central Australian sand dunes by vegetation during the last millennia (Rhodes *et al.* 2005); to the microseconds in which aluminosilicates are altered as enzymes and acids remove cations from colloids in the gut of an earthworm. There is an increasing interest in these processes and a number of researchers have been carrying out projects within CRC LEME and in other institutions during the past decade.

WHERE ARE WE UP TO?

An increasing number of research projects have been carried out internationally, but this review will concentrate on Australian research and will be divided into four sections from the broad scale, through regional and local to the micro scale with a brief mention of palaeoforms.

Broad scale

Biota has a fundamental role in controlling erosion across most environments where vegetation, in all its forms, can grow (including for instance, cryptogrammic crusts, lichen, liverworts and higher plants). There is a fundamental interaction between climate and biota at the continental scale (e.g. the Universal Soil Loss Equation used to predict erosion; Charman & Murphy, 1991). Climatic change not only affects regolith formation directly by controlling the quantities and chemistry of water available for reactions, it also controls the distribution of vegetation and therefore the cycles of weathering and erosion. Increasing aridity leads to the loss of vegetation and increasing transfers of regolith such as parna (Greene *et al.* 2002; Green *et al.* 2005).

Weathering depth and intensity is affected by vegetation biomass, such as the comparison between tropical and cool temperate environments; and by vegetation type, for instance in northern hemisphere forests the comparison between coniferous and deciduous forests. Forests produce very different microclimatic and weathering environments to savannah and grasslands, for instance the dominant group of organic acids under forests (whether northern hemisphere coniferous or deciduous, Australian dry or wet sclerophyll) are all described in general as "fulvic" acids when compared to grasslands (again from almost all environments) which are generally dominated by the less mobile "humic" acids. The problem is that this is the big picture and these "organic acids" are only described in these general terms and not as the multitudinous individual organic acids that occur in a huge variety and combinations. The truth of the matter is that there are often 5, 10 or even 20 discernible acids in the rhizosphere of just one root, on one tree, in one environment (Little *et*

al. 2005); and if another tree only 10 metres away is examined, at the very least the dominant acid or acids will change, if not the top 5 or 10, not to mention the fact that entirely new acids may be the most important.

Nutrient cycles are likewise described in general for every element known to be important for plant growth but each tree requires different elements in different balances, at different pH and Eh conditions (Hamilton, 1972). Nutrient cycles under different trees in a single eucalypt association on just one site are different to any other association (eucalypts are extremely well differentiated between niches) so Hamilton's (1972) research only began to show the broad effects of vegetation types, and more recent research is only just beginning to understand the effects such cycling might have on the processes of weathering (Leonard & Field, 2003).

The differential distribution of cations in plants is a relatively new field of regolith research, and recently trees have been shown to exclude some metals while others are seeking to use plants to remove or concentrate metals from soil or water (Leonard & Field, 2003). Research has moved from plant nutrition to studying plants that behave as accumulators, indicators, or excluders, depending upon the relationship between availability in the soil and their nutrient requirement for the particular cation (Baker, 1981). Much of the research in this area has been done in laboratory situations but Lennard and Field (2003) examined the distribution of cations in old, established trees in a relatively undisturbed environment (Fig 1).
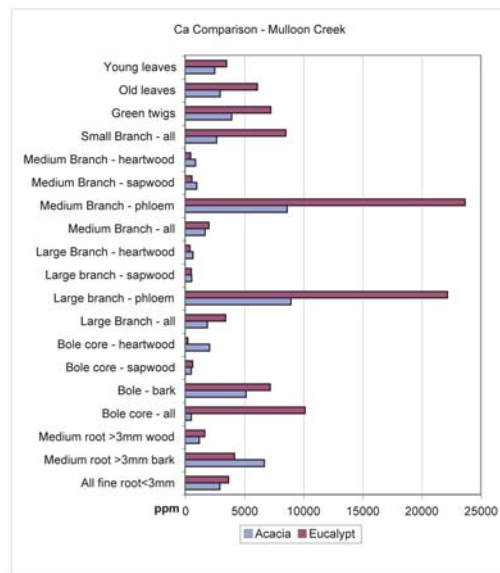

Fig 1. Calcium distribution in a mature Eucalypt (Lennard pers. comm. 2003)

Regional, and local scale processes

Effects of vegetation
Hamilton (1972; p360) observed that "litter types and …particular…soil properties are consistently associated with particular eucalypts". Individual trees affect sites within the timescale of a living tree, creating greater soil depth, moving the pH to an equilibrium best suited to themselves, adding a variety of organic matter (carbohydrates, cellulose, hemicellulose, lignin, chitin, etc.), increasing the Eh by drawing moisture out of the system in the processes of evapotranspiration, and altering a multitude of other soil characteristics (Leonard & Field, 2003; Moerkerken & Field, 2005). In so doing, the vegetation is in effect creating the soil profile. Thus regolith formation under a single tree becomes a study in itself, and to extrapolate to a stand, not to mention a forest, is a leap into the unknown at present. Treefall, the process when a tree is uprooted by wind or as a result of decline or old age, inverts the regolith and can result in erosion (Anderson, 2001). Uptake, use, storage and release of anions and cations by biota, affects the distribution of different elements in both the biota and the underlying regolith. The effects on the distribution of elements is of enormous importance for sampling for geobotanical surveys (Hulme & Hill, 2005).

Studies carried out recently considered the influence of two very different trees, not just a comparison between eucalypt species, and set out to measure differences in soil type, pH, electrical conductivity and cation distribution beneath the trees and along a costean between them, including a comparison of the actual distances from each trees' roots (Leonard & Field, 2003; Moerkerken & Field, 2005). A marked difference

in the soil type and other soil characteristics was expected when related to the trees influence in the middle of the transect. As one tree was an acacia, which has the ability to fix nitrogen from the atmosphere through a symbiotic relationship with micro organisms associated with its roots, pH was expected to be affected in this area. A 10 cm grid was used to accurately describe the exposed wall of the costean, showing soil horizons, root zones, roots, rocks and surface vegetation. The extent of each tree's canopy was also marked on the diagram (see for example Figure 2). Soils were sampled at 20 cm intervals both vertically and horizontally, from the soil surface to as deep as possible. These samples were then dried in the laboratory.

The acacia has a much greater effect on pH to depth in soil than does the eucalypt with the lowest pH measured at a depth of 80 cm beneath the acacia, and the depth and extent of low pH (<5) extending for a far greater distance from the acacia (Leonard & Field, 2003). The pH is only a summary variable that is reflected in much more specific and important characteristics such as aluminium solubility and its distribution (Figure 2). The differences between the acacia and eucalypt could be due to the greater age of the acacia, and the fact that its decline, as evidenced by the damaged crown and large surface litter fragments has caused more roots to be shed and so increase organic matter in its root zone. This in turn would allow more biotic activity, providing more humic material to increase soil acidity. The sandy clay texture in the B2 horizon under the acacia (less clay than under the eucalypt) implies there is greater breakdown of saprolite in this area, which could be related to the levels of organic acids in the soil. This conclusion agrees with Baker (1981) who observed that root exudates may play a role in soil weathering and nutrient availability to the plant.
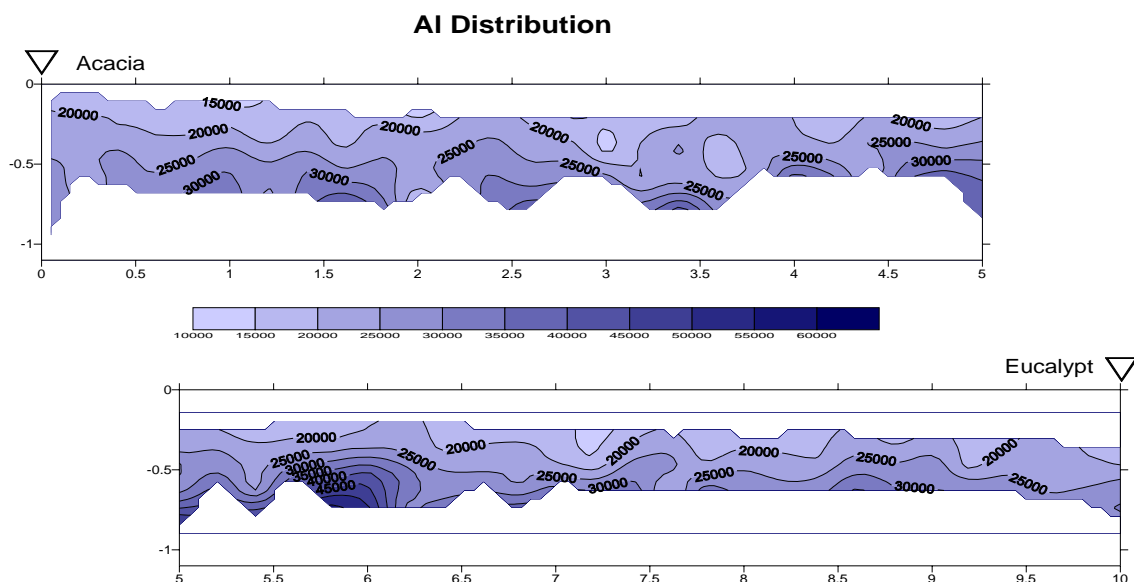

Figure 2. The distribution of Aluminium in soil between the boles of an *Acacia falciformis* and an *Eucalypt manifera*, Mulloon Creek, Southern Tablelands, NSW (Leonard pers. comm. 2003).

Bioturbation And The Upper Regolith / Soils
An understanding of the detachment and transfer of material by the biota – collectively called bioturbation, is another good example of the early stage of research at present. Through bioturbation, meso and macro biota cause changes in the physical and chemical composition of the regolith and soil. As a result of bioturbation, regolith particles are dislodged, built, broken down, reworked and deposited in a range of different forms from where they originated. They may pass from loose, uncompacted and friable to compact, cemented and erosion resistant materials, or vice versa. Australia has a number of large native bioturbators such as wombats, lyrebirds, mallee fowl, echidnas, kangaroos and wallabies, and reptiles plus the effects today of introduced species such as feral animals (rabbits, goats and deer) and domestic livestock. All these animals and a multitude more, are responsible for burrowing, making of animal tracks, compaction and channel side erosion, to mention only a few forms of material transport.

The amount of material moved and the relative importance of native animal bioturbation occurring in a dry sclerophyll forest ecosystem in Southeast Australia has only just begun to be assessed (Anderson, 2001; Field & Anderson, 2003). In Anderson's (2001) work, the bioturbation resulting from the activity of ants, mound building termites, earthworms, echidnas, tree uprooting and wombats was investigated in a dry sclerophyll forest at Mulloon Creek on the Southern Tablelands of NSW, Australia. In comparison to other soil and regolith forming and moving processes, bioturbation is significant. Soil material in the top 30 cm of the

profile is turned over by bioturbation in 6 to 10 k.y., which is much less than the time for the formation of soil calculated for a site east of the study (20 to 100 k.y.) (Heimsath *et al.* 2000). The total volume of material added to the surface through bioturbation of 0.03 to 0.04 mm yr^{-1} is greater than the calculated average rate of erosion on the Southern Tablelands (0.01 mm yr^{-1}) (O'Sullivan *et al.* 1996). Therefore, on average a majority of the regolith material is overturned by biota and remains at the site and contributes to soil production *in situ*. Thus through the turnover of material, disruption of particles, alteration of fabric and exposure of fresh material to further chemical, physical and biological processes, bioturbation makes a significant contribution to regolith evolution in dry sclerophyll forests. Some of these processes lead to greater horizonation in the solum and regolith (such as earthworms and echidnas), while others such as wombats, termites and tree uprooting tend to break down the differentiation into horizons.

Small and micro scale vegetation effects
The larger scale effects of organic matter addition on soil structure, infiltration and runoff are well described in the agricultural and forestry literature. Decomposition of organic matter and organic acid formation are also well described from the release of nutrients point of view. However the surface effects of litter fall on soil surface hydrophobicity and runoff (Liping Rao, 2005); the inhibition of infiltration and seed germination by fungal mats; the protective effects of cryptograms against wind and water erosion; and the effects of lichens on rock weathering (Hanrahan, 2005) are all research areas in the earliest stages of development for Australian environments. The effects of macro invertebrates such as termites, earthworms and ants are being considered in terms of the gross changes to regolith horizons and layers but little or no research has been carried out on the micro scale effects of ingestion, gut flora and fauna, digestion acids and enzymes, saliva and other exudates or excreta on aluminosilicate chemistry.

Reith (*et al.* 2005) worked on the microbial movement of a metal, gold that is generally thought to be relatively inert in inorganic chemistry, but rather obviously is much more mobile in organic rich environments such as topsoils; these authors have begun to demonstrate why. Plants can also dissolve and precipitate other relatively resistant elements such as silica. Humphreys and his students working at Macquarie University have demonstrated that soil distributions of phytoliths are related to vegetation and that they can be used as "tracers" of soil formation processes (Hart & Humphreys, 2005).

The very fine scale biogeochemical interface between roots or micro organisms and alumino silicates; the exudates and the extraordinary pH / Eh conditions at micro scales between biota and the soil and regolith; and the microbes in the rhizosphere, the micorrhyzae, and their biogeochemistry and interactions with organic particles and aluminosilicate minerals, are only just beginning to be researched (Little, 2005a, b).

The rhizosphere is a location where biological activity, in particular, the activity of plant roots, is a major factor in rock weathering and regolith forming processes. Plant roots take up nutrients from the regolith and secrete or exude organic compounds such as ligands, organic acids, sugars and starches, physically break down the regolith and also provide habitat for soil and regolith microbial populations Although less commonly observed, the regolith can also be physically altered by plant roots, which can exploit small cracks in the bedrock and as the roots grow, they expand the crack, eventually leading to the bedrock breaking further. Plant roots are responsible for binding and stabilising the regolith and slowing drainage and thereby increasing the residence time of water in the regolith. They can also create pores in the regolith and add organic matter, through root cell death and decomposition. Some of the more common means by which plant roots can directly affect chemical weathering processes are through nutrient uptake, cell respiration, release of organic matter in the form of sloughed off cells, exudates and secretions (Little, 2005a). These life processes can be particularly important in changing regolith properties like nutrient content, pH and redox potential, and drive forward chemical weathering reactions like oxidation, dissolution, hydrolysis and hydration (Little, 2005b). Some physical effects, like increases in water retention, as mentioned, can also less directly affect chemical weathering processes by increasing, or decreasing, the time available for chemical weathering reactions to occur. The rhizosphere is also an habitat for microbial populations that feed on mineral nutrients and organic materials in regolith. In many cases there are direct symbiotic relationships between plant roots and micro organisms - mycorrhiza, that enable more efficient uptake of nutrients that might otherwise be unavailable for plant growth, for example, phosphorus and potassium (Young & Young, 2001). In addition there are symbioses where elements and ions such as N, specifically as NO_3 and NH_4 are actively added to the regolith. The chemistry of the system must then include the action of these ions, for example, add H_2O to NO_3 and acidification of regolith results. So in addition to the direct physical and chemical effects of plant roots, there are many indirect associations between them and the regolith, especially by providing habitat for micro organisms in a multitude of ways (Little, 2005a).

Palaeoforms from the effects of biota

Retallack (1990) compiled a compendium of palaeopedology and palaeo regolith characteristics and forms, but Anand and others (see for example Anand & Paine, 2002) have been instrumental in bringing forward a number of new palaeo biological regolith expressions to the attention of scientists of the regolith. The palaeo pupal cases described in the Weipa bauxite (Eggleton & Taylor, 2005) are another example and rhizomorphs, palaeo root channels, pore casts and zones are all yet to be researched in detail, not to mention entire palaeosols

WHERE TO FROM HERE

There is much still to be done. The work of each of the authors mentioned here came up with more questions than answers. These are only single sites with insufficient understanding of processes and factors to be able to extrapolate meaningfully or far. The opportunity exists to continue this type of study with different tree species in different climatic zones to see if the influence of trees on soils is consistent. Further study could concentrate on the same species of tree to determine if results can be repeated across environmental gradients, or continue to consider the influence of different trees to build a base of information with which to compare further studies.

Each of the species studied, each of the sites analysed, in each of the environments in which the sites were located are unique and extrapolation with little knowledge is fraught with problems. Do trees in tropical or arid systems behave in a similar way to those in humid temperate environments? Can we extrapolate across the monocalypts, across all the eucalypts, to all trees growing in Australia? We already know that one acacia behaves differently to one eucalypt, but is the difference between one tree and another of the same species, or of the same genera, greater or less than that between trees of different fundamental physiologies such as nitrogen fixing and non fixing species?

The area of research defined in this paper holds the greatest returns, and benefits over costs, for future understanding of regolith formation at the hillslope, regolith profile and smaller scales. There is so much that is barely understood and such intricacies and complexities in each new result. There is a need to collate, integrate and synthesise enormous volumes of work in allied fields of agronomy, horticulture, viticulture, forestry and plant science and industry, because what is known need not be repeated. However, like any research, these reviews will inevitably ask more questions than they answer, if only because trying to look in the mirror to reflect the research on the effects of regolith on biota, back onto the effects of biota on regolith, is not always possible.

The areas of most promise at the moment relate to plants, their roots, root microbes, nutrient and non nutrient uptake, element storage and their redistribution in both time and space. Concomitant research on the "free living" microbes in the regolith will need to be carried out to understand the context, one for the other. While there is a solid knowledge of some of the processes involved in biological weathering and regolith formation, little is known about the rate at which these process are occurring throughout the landscape. Many previous studies of soil – root interactions have simply focused on the processes involved in nutrient uptake by the plant root, under controlled conditions, without any thought about the implications for rock and mineral weathering or regolith development. Other studies, like Anderson (2001), have examined the physical turnover, or bioturbation, of regolith in dry sclerophyll forests, but as yet the amount of mineral nutrient turnover that occurs in regolith under eucalypt forests has not been quantified, nor do we understand the effects on weathering of compaction by livestock. Further, in almost all cases the complex relationships of micro organisms in the rhizosphere have had to be so simplified that we cannot extrapolate effectively. Therefore, while it is now increasingly being accepted that biota play an important role in regolith formation, a further, more detailed and widespread examination of the processes that enable biological activity, especially plant roots, to alter the regolith, is warranted.

REFERENCES

ANDERSON, G.R. 2001. The influence of macro and meso biota on regolith development and evolution in a dry sclerophyll forest. Unpub Hons thesis, SRES, ANU.

ANAND, R. R., & PAINE, M. 2002. Regolith Geology of the Yilgarn Craton, Western Australia: implications for exploration. *Aust J of Earth Sci.,* **49**, 3 – 162.

BAKER A.J.M. 1981. Accumulators and excluders – strategies in the response of plants to heavy metals. *Journal of Plant Nutrition* **3(1-4)**, 643-654.

CHARMAN, P. E. & MURPHY, R. W. (eds) 1991. Soils: their properties and management. Sydney University Press, Sydney.

EGGLETON, A.E. & TAYLOR, G.R. 2005. Bioturbation of the Weipa bauxite. In: Roach, I, C. ed. 2005 *Regolith 2005 – Ten Years of CRC LEME*. CRC LEME. 235-239.

FIELD, J.B. & ANDERSON, G.R. 2003 Biological agents in Regolith processes: case study on the Southern Tablelands, NSW. In Roach, I.C., 2003. *Advances in regolith. CRC LEME.*

GREEN, W., GREENE, R.S. & SCOTT, K.M. 2005. Indications of local sources of modern dust in NSW. In: Roach, I, C. ed. 2005 *Regolith 2005 – Ten Years of CRC LEME*. CRC LEME. 235-239.

GREENE, R.S., EGGLETON, R.A., NETTLETON, W.D., MASON, J.A. & GATEHOUSE, R. 2002. In Roach, I. *Regolith and Landscapes in eastern Australia. CRC LEME. WA.*

HAMILTON, C.D. 1972. The nature and causes of spatial variationin forest ecosystems. Unpub PhD. ANU, Canberra.

HANRAHAN, D. 2005. Lichen distribution and ecophysiological constraints. Unpub Independent Research Project. SRES, ANU.

HART, D.M. & HUMPHREYS, G.S. 2005 Phytolith depth functions in surface regolith materials. In: Roach, I, C. ed. 2005 *Regolith 2005 – Ten Years of CRC LEME*. CRC LEME. 235-239.

HEIMSATH, A.M., CHAPPELL, J., DIETRICH, W.E., NISHIIZUMI, K. & FINKEL, R.C. 2000. Soil production on a retreating escarpment in southeastern Australia. *Geology* **28** (9), 787-790.

HULME, K.A. & HILL, S.M. 2005. River red gum biogeochemistry associations with substrate: bedrock penetrators or stream sediment amalgamators. In: Roach, I, C. ed. 2005 *Regolith 2005 – Ten Years of CRC LEME*. CRC LEME. 235-239.

JENNY, H. 1980. *The Soil Resource*. Springer-Verlag, Inc. NY.

LEONARD, J. A. & FIELD, J.B. 2003. The effect of two very different trees on soil & regolith characteristics. In Roach, I.C., 2003. *Advances in regolith. CRC LEME.*

LIPING RAO. 2005. Spatial distribution of soil hydrophobicity under dry sclerophyll forests. Unpub MSc Major Research Essay. SRES ANU.

LITTLE, D.A., WELCH, S. A. & FIELD J. B. 2005a. Trace Elements in the Rhizosphere of *Acacia falciformis.* I. C. O. B. T. E., Melbourne

LITTLE, D.A., FIELD J. B. & WELCH, S. A. 2005b. Metal dissolution from rhizosphere and non-rhizospere soils using low molecular weight organic acids. In: Roach, I, C. ed. 2005 *Regolith 2005 – Ten Years of CRC LEME*. CRC LEME. 235-239.

MACKENZIE, N., JACQUIER, D., ISBELL, R., & BROWN, K. 2004. Australian Soils and Landscapes: an illustrated compendium. CSIRO. Melb.

MOERKERKEN, L. J. & FIELD. J. B. 2005. The distribution of precious metals in two dry sclerophyll forest trees: Early steps in research at Tomakin Park Gold Mine, New South Wales. In: Roach, I, C. ed. 2005 *Regolith 2005 – Ten Years of CRC LEME*. CRC LEME. 235-239.

O'SULLIVAN, P.B., FOSTER, D.A., KOHN, B.P. & GLEADOW, A.J. 1996. Multiple post-orogenic denudation events: an example from the eastern Lachlan fold belt. Australia. *Geology*, **24**, 563-566.

REITH, F., MCPHAIL, D. C. & CHRISTY, A. G. 2005. Bacillus cereus, gold and associated elements in soil and other regolith samples from Tomakin Park Gold Mine in southeastern New South Wales, Australia. *Journal of Geochemical Exploration*. **85,** 81-89.

RETALLACK, G.J. 1990. Soils of the past: An introduction to paleopedology. Harper Collins Academic. London.

RHODES, E., CHAPPELL, J.,FUJIOKA, T., FITSIMMONS, K., MAGEE, J., AUBERT, M &HEWITT, D. The History of aridity in Australia: Chronological developments. In: Roach, I, C. ed. 2005 *Regolith 2005 – Ten Years of CRC LEME*. CRC LEME. 235-239.