BIOTA, REGOLITH AND LANDSCAPES: AT THE HILLSLOPE, PROFILE AND LESSER SCALES

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Regolith is defined by Eggleton (2001) as *"the entire unconsolidated or secondarily recemented cover that overlies more coherent bedrock, that has been formed by weathering, erosion, transportations and / or deposition of the older material. The regolith thus includes fractured and weathered basement rocks, saprolites, soils, organic accumulations, volcanic material, glacial deposits, colluvium, alluvium, evaporitic sediments, aeolian deposits and ground water."*

What this lengthy, and otherwise comprehensive definition does not include, is the biota. The biota must be included not only as the activators and those carrying out processes within the regolith, but also as an actual material constituent or component of the regolith. After all, all things from microbes through micro, meso and macro flora and fauna, in fact microbes to huge trees, are both a part of the processes, and constituents, components, or materials of the regolith. They cause and take part in the processes, and they are also a result, a regolith material.

There are many examples that support both these roles for biota: bioturbation and accumulation by biota; the actions of roots and accompanying microbes in the rhizosphere altering the soil and regolith environment; the removal from the other regolith materials into biotic stores for differing time periods; and, even the transfer and storage of material by biomass dependent processes such as fire. There has been much work done on nutrient cycling, the hydro–bio-geochemistry of catchment scale elemental cycles (Field 1983, Likens *et al.* 1977) but until recently, little was being done at hillslope, plot, profile and lesser scales (Gilkes 1998). On the other hand, almost no work has been done by regolith-oriented scientists on biomass stores of elements that are of interest to regolith scientists, pedologists, geomorphologists and those interested in landscape evolution. Virtually all the research on biomass accumulation has been carried out by biomass production scientists such as agronomists and foresters (Florence 1996).

BIOTURBATION OF REGOLITH MATERIALS BY MESO AND MACRO BIOTA

In the last three decades there has been a slowly increasing interest in Australia in bioturbation of regolith materials (Humphreys & Mitchell 1983, Humphreys 1985, Humphreys 1994, Humphreys & Field 1998). Almost every particle in the topsoil is transferred up, down, across, in or out of the A horizon of a soil in a time scale of hundreds or thousands of years. In the subsoil the same is true, except that the time scale is now probably of the order of tens or hundreds of thousands of years. Further down within the regolith, in the weathered material and saprolite, the transfers become smaller and the time scales longer, but transfer of components of the regolith does go on by leaching, solution, eluviation, illuviation and precipitation. Large biota take part in the form of roots transferring material physically and chemically by transfer of elements in the growth process. Gilkes (1998) reviewed much of this work and showed that environmental factors not only dominate abiotic weathering, but they exert very strong controls on the effects of biota, affecting not only process but the classes and numbers of individuals that are present at any site. There is still much to be done to broaden the work carried out in eastern Australia to cover tropical and sub-tropical, sub-alpine and semi-arid and arid environments. In terms of the sub-humid, temperate environments, Anderson (2001) reviewed meso- and macro-biota in the dry sclerophyll forests near Braidwood in NSW. He found that the meso- and macro-biota transferred material, at least at rates equal to regolith formation and/or erosion. In many cases bioturbation exceeded the rates of all other processes combined.

CHEMICAL, BIOCHEMICAL AND GEOCHEMICAL ALTERATION OF REGOLITH BY BIOTA

The idea that vegetation affects soil formation is one of the oldest ideas in soil science, going back to the writings of Dokuchaev in Russia two centuries ago (Dokuchaev lived 1846 to 1903, but his written work was not translated into English until the 1920s and 1930s). Jenny (1941) emphasised the organisms factor as one of the five soil-forming factors, and then Stephens gave it a more modern emphasis with his famous integration of climate, parent material, organisms, and relief, over time. However, the concept that biota are important to the formation of regolith at a very local scale has been slow to develop. In an early Australian study Hamilton (1972) demonstrated very small scale variations in factors such as pH, total dissolved solids, loss on ignition and bulk density in close vicinity to individual trees. He showed that soil pH can vary by up to two full units over a distance of 1, 2 or 3 meters when moving from the bole of one tree out into grassland or into the drip zone of another species of tree. This work was virtually ignored for 20 years until work by Hedenstroem (1993), Little (2001) and Miller (2002) demonstrated similar variations in soil and regolith characteristics from tree bole to tree bole or tree bole to grassland. In fact, this work showed that the effect of different vegetation types (and even individual species) left a characteristic and recognisable signature on the soil and regolith for time periods exceeding 100 years (Hedenstroem 1993). Noble & Randall (1998) have reviewed the general literature on the ways that trees affect soils *per se*, but they do not develop the argument at any length or in any detail on the processes of formation of regolith materials.

BIOTA IN THE RHYZOSPHERE OF THE REGOLITH

There are a myriad studies on the effects that the rhizosphere has on roots, root growth, plant growth and health and even plant death. However, there is a dearth of information on the effects roots and their ever present microbes have on the regolith (Banfield & Nealson 1997). The complexity of the interaction between bacteria and roots such as nitrogen fixing organisms, and fungi and roots (endo- and ecto-mycorrhizae in particular) are still poorly understood from the plant nutrition end. Almost nothing is known about the activities of these organisms from the point of view of their effect on the regolith. It is clear that extraordinary environmental conditions exist at the micron scale in proximity to roots, their bacteria and fungi. Extremes of pH and Eh conditions are beginning to be documented, but the transfer of elements through this zone, their removal from available sites on clays or organic colloids, or their removal from weathering fronts on primary and secondary minerals, is yet to be understood. An understanding of these processes, and those of microbes in regolith in general, is going to be the key to future studies of primary mineral weathering and the formation of secondary minerals within the regolith.

BIOTA AND BIOMASS ACCUMULATION OF REGOLITH MATERIALS

For many decades, agronomists, horticulturists, vignerons, foresters and others interested in biological production from regolith materials have examined biological materials to determine what elements are being accumulated in the biomass (e.g., Hingston *et al.* 1979). Their interest has not been in what effects such processes of accumulation had on the source materials, the regolith, but on what was needed by the biomass to maximise productivity.

All the elements in the periodical table can be broken down into: those that are essential to plant growth, C, H, and O; macro-nutrients, N, P, and K; meso-nutrients such as, but not exclusively, Ca, Mg and S; micro-nutrients such as Cu, B, Mo, Zn, Se, Fe, Mn and many others: and non-nutrients or associate elements such as Al, Na, Si and others which are not required by plants. The latter group can be further broken down into those that are toxic, even in small amounts, such as Al, and others which do not appear to harm the plant by their presence, no matter what the concentrations, such as Si. Plants take up elements from all of these groups. The uptake by plants themselves is slow in the absence of microbes, as can be shown by studies in sterile media, but there is evidence for active scavenging rather than passive diffusion. However, microbes such as fungi vastly increase the surface area over which transfers take place and appear to actively cause the uptake of a range of elements. Non-nutrient elements piggy-back on those being actively absorbed (charge, ionic size, valence state, etc., seem to confuse the process) and others appear to be absorbed, even though the plant can survive very successfully in their absence. In all cases, transfers of considerable quantities of regolith materials is taking place over some not inconsiderable distances. There is also a series of intermediate stores for a range of time periods, such as the range of living organisms, detritus, humus and organic residues.

In general, the literature on nutrient uptake can be used to estimate that in a dry sclerophyll forest environment for example, approximately one third of the total, in available form in the regolith, of important nutrient elements are held in the biomass at any one time (Florence 1996, Lambert *et al*. 1983, Raison *et al.* 1982, Turner & Lambert 1986). Conversely, if total (not available nutrient) budgets are considered, for biologically inactive elements (associate or non-nutrients), then probably less than 0.1% will be in the biomass at any one time.

Clearly this is an area of research crying out for further work with a regolith orientation, to be able to quantify the transfers of material in the regolith from the root zone up through the soil and out on to the surface as living biomass and then litter. These transfers, I hazard a guess, are more important than most others, whether they be due to leaching, capillary rise, bioturbation or any other remotely vertical transfer of materials

FIRE, BIOTA ACCUMULATION AND CYCLING OF REGOLITH CONSTITUENTS

Fire can be considered as a mineralising process whereby almost instantaneous oxidation releases all the elements previously stored in living, dead and decomposing biomass into the surface environment in stable oxides that are also reactive with water. If the quantities of materials described as being present in the biomass are suddenly freed from their organic complexes and the biomass by fire, then just such an event is truly catastrophic for the regolith, in dimensions if not in effect. Again there is much information and research into the effects of fire on soils (Raison *et al*. 1985), on the availability in the solum and other production oriented studies. However, very little has been done on the aspects to do with regolith formation and evolution processes. There are exceptions, such as research by Humphreys and coworkers (e.g., Humphreys & Craig 1981).

CONCLUSIONS

The area of research defined in this paper holds the greatest returns, 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.

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