THE NATURAL DEVELOPMENT OF NUTRIENTS IN SOILS

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Abstract

The sustainability of vegetative systems depends on obtaining new nutrients to replace those that are lost. Mineral fertilisers are used in agriculture but in natural systems the replacement nutrients arise through micro-organisms. The paper addresses the interaction between micro-organisms and plants in the provision of new nutrients from soil minerals, and the sustainability of agricultural systems that attempt to directly replace lost nutrients rather than develop the biological health of soils.

Introduction

Plants are unable to extract all essential nutrients from minerals, and in natural systems the nutrients are largely obtained via symbiotic relationships with micro-organisms. Micro-organisms extract nutrients from the atmosphere and mineral soil and provide them in a form and relative abundance appropriate for plants. They also recycle nutrients in organic matter, and by developing organic matter resistant to breakdown help prevent the loss of nutrients through leaching and volatilisation.

Current broadscale farming systems seek to eliminate the need for micro-organisms by providing nutrients in an elemental form readily available to plants. This reduces the provision of benefits provided by microbes additional to nutrients, such as the protection of plants from pathogens, and the development of soil organic matter that improves soil aeration and the retention of water and nutrients. It also reduces the provision of micro-nutrients.

Most early agricultural schemes increased nutrient availability to crops by disturbing the soil and burning the prior vegetation. This necessitated a shifting agriculture due to the inevitable depletion of nutrients and development of pathogens with cropping. Better evolved schemes, as with the Mayan, involved offsite harvesting of nutrients using plants and applying these to the fields.

The Mayan system was sustainable given a sufficient population on the land to maintain the management system. Modern agriculture attempts to achieve the same outcomes as the Mayan system but through application of mineral fertiliser, herbicides and insecticides. Chemicals have been used to greatly reduce the number of people on the land involved in producing food.

The applied mineral fertilisers do not provide all essential nutrients and some of the applied elements, such as phosphorus, can become unavailable to plants by being bound. Soil micro-organisms are still needed to maintain a supply of essential elements to plants. However, the microbial balance is greatly upset by soil disturbance and application of high concentrations of chemicals including fertilisers, herbicides and pesticides. The current reliance on applying chemicals produces a cycle of increasing dependence on chemical applications.

Application of an ever increasing range and amount of chemicals represents symptomatic treatment that in the long term must fail. Symptomatic treatments provide immediate relief but cannot provide sustainable long term solutions. Moreover, their application locks users into a reliance on applying the symptomatic treatments. Many become addicted to the short term highs from immediate cash profits but the highs decline over time as costs increase and returns decrease. The highs can evolve into psychological withdrawal and depression, particularly during droughts. Management that involves increasing inputs to redress adverse impacts of prior inputs is not sustainable.

The addressing of symptoms as they arise is entrenched in current agricultural practices. Most economic models promote the addressing of limiting factors as profitability is usually greatest when only the most limiting factors are addressed. The issue is seen as being soil fertility with a focus on treating identified deficiencies rather than developing soil health. Indeed, those that focus on fertility often have no appreciation of what constitutes soil health. The situation is equivalent to medicine where those that focus on disease usually have little cognisance of what constitutes good health.

The piecemeal approach of sequentially addressing individual deficiencies as they are identified does not address long term system performance. For example, super phosphate applied to redress a nutrient deficiency produces acid soils where the acidity reduces nutrient availability. The acidity is addressed by applying lime. In the meantime the associated loss of soil organic matter and microbial activity produce compacted soils. This reduces water availability to plants by increasing surface runoff and it promotes the development of dryland salinity (Tunstall & Gourlay, 2006). The solutions advocated for salinity address the symptom of saline groundwater rather than the cause in soil degradation.

The basic axioms are that prevention is better than cure, and symptomatic treatments do not provide a cure. For agriculture it is generally too late for prevention hence a cure can only be obtained by addressing the cause. It is time to go back to the grass roots and provide plants with an appropriate biological, physical and chemical soil environment.

Minimal tillage illustrates the benefits that can be obtained by eliminating practices that cause adverse impacts. The tillage previously considered beneficial is now known to reduce crop yields through adverse impacts to soils while additionally representing a considerable cost in fuel. Zero tillage is now seen as being most desirable in allowing the soil to develop and function somewhat normally.

The requirement is for a systems or ‘whole of life’ approach to agriculture that looks past immediate benefits and examines the long term viability of practices. For nutrition this does not necessarily preclude the need for application of minerals as most Australian soils have low nutrient availability. There is usually a need to supplement limiting elements. However, to be sustainable the applications must develop the functionality of the soil by building its biological populations rather than attempting to directly redress a plant imbalance.

Nutrient Provision

Basic biology text books chart the development of vegetation from the colonisation of bare rock to forests with the initial colonisers being bacteria followed by blue-green algae. Fungi require protection from the atmosphere and so first appear in a symbiotic relationship with algae as lichens. The first plants are usually mosses and these are eventually followed by higher plant life forms. The early successional sequence of biological development on newly exposed rock tends to mirror the early evolutionary development of terrestrial life forms.

The major functional difference between mosses and the earlier colonisers is the accumulation of nutrients in organic stores external to the organism. An organic mat develops through the moss roots entrapping dead organic material. Soil develops through the build up of this organic material and weathered materials derived from the rock. Soil development depends on microorganisms accelerating the weathering of rock and plants binding the released nutrients on and within organic matter.

The provision of nutrients from rock is separate from their accumulation and storage. Nutrient extraction is mainly by micro-organisms and storage is mainly through plants. However, recycling nutrients from the organic store is similar to their extraction from rock in depending on micro-organisms. The provision of nutrients in forms available to higher plants largely depends on micro-organisms, be it through the extraction of nutrients from minerals or the recycling of nutrients in organic matter.

Micro-organisms fix atmospheric nitrogen and supply around 98% of the nitrogen in plants. However, they also increase the availability of other nutrients such that their role in supplying nutrients to higher plants is comprehensive for all except carbon and oxygen which plants obtain directly from the atmosphere. It is therefore hardly surprising that plants have developed symbiotic relationships with micro-organisms that include bacteria, blue-green algae and fungi. The relationships range from specialised structures in roots and leaves to exogenous systems where the survival of the soil micro-organisms intimately depends on the association with plant roots just as much as with endogenous associations.

The occurrence of symbiotic bacteria is critical with legumes and extensive research has examined the conditions that promote the relationship. By comparison the role of fungi is poorly understood. It is generally accepted that the functionality of soils for plants improves with transition from bacterial to fungal dominated systems but the conditions needed to promote this transition are largely unknown. Benefits can be appreciable, as with grape vines where the transition to a fungal dominated system after around 15 years greatly improves the quality of the wine.

The focus with developing microbial associations has to date been largely on particular plant species because of the ease of measurement and the ability to link the treatment with benefits. The formation of mychorrhiza with legumes is an example. However, the principle being applied to individual species applies generally to soils. The performance of plants is intimately tied to the performance of soil microorganisms. The practical issues relate to how to achieve and measure desirable situations.

Developments have been limited by knowledge of what should be measured and how. There is an extensive literature on soil biology but the complexity usually results in a focus on a particular mechanism, such as nitrogen mineralisation, or the grouping of micro-organisms into generalised categories. These categorisations facilitate descriptive representations of the system but are of limited predictive value.

Given the limited knowledge of what is desirable, knowing what not to do can provide benefits. Direct application of N, P and K in a form available to plants negates the significance of the microbial populations for these nutrients. While the loss of microbes may not be significant for extracting other elements from soil minerals the loss generally degrades the soil structure by suppressing microbial activity that produces the long-lived organic compounds that improve the soil structure. Soil organic mater almost invariably declines with soil disturbance and this can be promoted by application of mineral fertilisers. The eventual result is soil structural decline that decreases the provision of nutrients from soil minerals. Addressing the need to supply the more than 50 elements used by plants in an available form is then problematical.

The provision of the full complement of elements required for plant growth is a critical issue with many Australian soils. Many surface rocks have derived from highly weathered sediments and so are nutrient poor. Also, the generally flat continent has not been subject to recent glaciations and hence has developed a deep mantle of weathered material. Many minerals have been leached from these weathered materials resulting in the widespread need for application of micro-nutrients such as molybdenum. Other elements have accumulated in the surface in adverse quantities, as with sodium and boron, where this limits the ability of plants to obtain essential nutrients.

Most of the fertile depositional soils used in agriculture have appreciable clay contents but clay minerals do not contain many of the elements essential for plant growth. The value of clay primarily arises from its ability to adsorb nutrients and water. Maintaining the fertility of clays with agriculture involves application of nutrients, either naturally through seasonal flooding or the application of fertilisers. The applications generally need to provide the full complement of nutrients rather than a small subset considered most limiting to plant growth.

The fertility of many natural systems is maintained through erosion depositing fertile material on the flats and exposing reasonably un-weathered material on the hills. The limitations of this process in Australia arise from the extensive flat terrain and the weathered status of many rocks.

Bacteria v Fungi

Bacteria can survive in hostile environments and are therefore the initial colonisers. Moreover, they have the ability to obtain nutrients from diverse sources, and their energy can derive from minerals as well as the sun. They represent the primary means of accumulating mineral elements into organisms. Blue-green algae (cyanobacteria) are similar to other bacteria except they must obtain energy through photosynthesis and hence are dependent on light.

Fungi also have a capability to obtain nutrients from diverse sources but their ability to survive hostile environments is much more limited than bacteria. Moreover, their energy source is typically organic matter, living and dead. Unlike bacteria and algae, the occurrence of fungi depends on the occurrence of other organisms.

Bacteria and fungi are typically viewed as decomposers as they obtain their energy from compounds in their environment. Photosynthetic bacteria excepted, most do not have the capacity to fix energy from solar radiation. However, they are also synthesizers as they use energy to transform acquired elements into new compounds. There is evidence that bacteria can even produce new elements by combining other elements (transmutation).

Bacteria and fungi can perform similar roles but their relative significance differs for decomposition and synthesis. Bacteria appear to be primarily involved in mineralisation which represents the breakdown of compounds. Even for the recycling of organic matter bacteria are essential, as with the nitrogen cycle. The release of elements in a form available to plants is intimately tied to bacteria.

The limitation of bacteria in supplying nutrients to plants relates to their dis-connectivity. Bacteria are small and unconnected, thus for plants to directly obtain nutrients the bacteria must be located within plant tissues. This occurs with symbiotic nitrogen fixing bacteria in the roots and leaves of some plants. However, this structural arrangement does not work for non-gaseous nutrient sources external to plant tissues. Bacteria release the minerals into their surrounding environment thereby necessitating the development of plant structures to exploit that environment.

Plant roots access nutrients in soil but they are physically large compared to bacteria. This creates a limiting situation in the expenditure of resource by plants to grow roots to acquire nutrients. The nutrients accessed must be considerably greater than expended in growing roots, and the wide distribution but localised occurrence of bacteria makes roots inefficient. This is countered to some extent by the movement of nutrients in solution but most cations are largely immobile through being bound onto soil colloids.

Fungal hyphae are similar in size to bacteria and, compared to plant roots, require little resource by way of nutrients and energy to exploit a large volume of soil. Also, as fungal hyphae are interconnected, they can translocate nutrients. An association between fungal hyphae and plant roots therefore provides a more efficient means for plants to obtain nutrients than by utilising roots alone. Many such associations exist, as with the arbuscular fungi having a direct association with the root. Their hyphae grow within as well as outside the plant roots.

Arbuscular fungi occur with a large number of plant species but their occurrence with plants is not universal. Brassicas for example, do not have arbuscular fungi. There can be many means of achieving the same end that have been developed through the evolution of species within complex communities.

Nutrient adsorption

The release of nutrients from bacteria into their general environment creates opportunities for loss through volatilisation and/or leaching, as occurs with de-nitrification. Such loss is limited by the adsorption of ions onto soil particles, particularly clay and organic colloids. The capacity for adsorption depends on the amounts of clay and organic matter, and their form.

The relative significance of clay and organic matter in retaining nutrients is addressed by Tunstall (2005a) with a focus on interactions with salinity. The relative adsorptive capacity of soil colloids is given by their cation exchange capacity (CEC) (Table 1). Different clay minerals have very different CECs but the CEC of organic matter is at least double that for the highest clay. Moreover, organic matter tends to buffer the soil pH around 7, and the CEC generally doubles with an increase in soil pH from 4 to 7. Small increases of organic matter can greatly increase the CEC and hence nutrient storage capacity of many soils (Tunstall 2006) and such changes can be influenced by management.

Table 1. Characteristic cation exchange capacities of soils and soil components (meq/100g).

Material	CEC		Soil Texture	CEC
Kaolinite	3-15		Sand	1-5
Illite	15-40		Fine Sandy Loam	5-10
Montmorillonite	80-100		Loam	5-15
			Clay Loam	15-30
Organic Matter	200-400		Clay	>30

While the CEC identifies the capacity of soils to adsorb cations this alone does not identify the relative availability of ions to plants. The solubility of ions depends on pH, and the growth of roots and microorganisms depends on the availability of oxygen where that depends on the structure of the soil.

Organic matter improves aeration by improving the soil structure. It also improves water accession and retention. The improvement in soil structure improves the soil environment for micro-organisms and thereby improves the supply of nutrients. The improvement in soil structure also improves plant access to the nutrients by producing a favourable environment for root growth and function.

Table 2 identifies different forms of organic carbon often said to be associated with soils. However, litter is not part of the soil and nor are living organisms. Identifying soil micro-organisms as part of the soil is the same as identifying birds or plant leaves as being part of the atmosphere. The soil component most important for nutrient recycling is the 'carbohydrates +' as these represent the short lived component. They are the most important source of recycled nutrients because of their high turnover. The significance of the long lived components of soil organic matter mainly relates to their effects on soil structure, and the adsorption of nutrients and water.

The soil organic matter important for improving soil structure mainly derives through synthesis by micro-organisms, primarily fungi. Around two thirds of soil organic matter is identified as being composed of humic substances where the conversion factor from dead plant material to humic compounds is around 10%. However, the protein glomalin is estimated to comprise around 30% of soil organic matter where glomalin is produced by arbuscular fungi. The lack of mass balance in these figures reflects measurement procedures wherein few of the existing estimates of different soil organic fractions incorporate measurements of glomalin.

Table 2. Forms, longevities and relative levels of 'soil' organic matter.

Location	Form	Longevity	Level (% of above ground biomass)
Soil surface	Litter	days-years	1-10
Below Ground	Roots	days-decades	30-50
	Invertebrates	weeks-months	0.01-10
	Microbes	days-weeks	0.01-100
Soil Organic Matter	Carbohydrates +	days-weeks	0.01-30
	Glomalin	years-decades	0.01-100
	Fulvic acids	years-decades	0.01-100
	Humic acids	100-1000 years	0.01-100
	Humins	100->1000 years	0.01-100

'Carbohydrates +' A wide range of generally short lived organic compounds that includes carbohydrates, fats, waxes, alkanes, peptides, amino acids, proteins, lipids, and organic acids.

In anthropogenic terms the development of long lived organic compounds by micro-organisms represents a long term investment in infrastructure. Energy that could immediately be used for growth is invested in improving the environment for biological organisms generally, where that increases their supply of food as well as improving the physical conditions. The theoretically challenging aspect is that improvement to the overall system does not appear to solely depend on benefits to individual organisms. The system as a whole appears to optimise through complex interactions between a multitude of different micro-organisms and a diversity of higher plants. If so, the system is much more highly evolved than most biological systems.

Plant – Soil systems

The focus with the above is on the extraction and recycling of nutrients by soil micro-organisms. Plants have been mainly portrayed in a passive role as stores for nutrients and providers of organic matter for recycling. However, the symbiotic relationships between plants and microbes means that plants have an active role in nutrient acquisition arising from their capacity to place microbes in locations where they otherwise could not survive by providing them with food (energy). The locating of nitrogen fixing bacteria within leaves is an example. Plants similarly provide a favourable environment for microorganisms in soil through the organic matter providing food.

The significance of the symbiotic relationship for microbes is that their survival is not completely dependent on the physical soil environment. Benefits include the provision of energy as well as partial protection from the general soil environment. Vetiver grass (*Vetiveria zizaniodes*) provides an example as it has proven to be highly effective in rehabilitating mine sites and other areas with toxic materials. Vetiver grass has a large root mass with symbiotic arbuscular fungi. The fungus benefits the plant but the plant provides the means for the fungus to exist in inhospitable environments.

The general patterns of water infiltration into the soil (Fig. 1) identify that most of the input of water seldom penetrates below the surface soil because of the water use by vegetation. The depth of penetration of rainfall is limited by plants drying the soil between rainfall events. Typically only around one third of the rainfall infiltrates through the A horizon into the B horizon. Loss of nutrients is limited as in much of Australia less than 2% of rainfall generally drains through the soil into some form of groundwater system.

A key issue with accessing new nutrients rather than recycling is that the development of soil profiles is associated with leaching of the surface soil (A horizon) and accumulation of ions in the subsoil (B horizon). The cycle of input by rainfall in the top and extraction of water from throughout the soil by plant roots produces a net downward flow of water in the soil illustrated by the relative volume of water recycling (Fig. 1). This cycle naturally leaches salts and clay from the surface soil into the subsoil.

The use of a triangle is indicative only but it is a realistic representation in identifying a continuous decline in water penetration with depth. The realised pattern depends on the temporal patterns of rainfall and potential evaporation, and the characteristics of the vegetation and soils.

Recycling inevitably involves nutrient losses, and over time high levels of microbial activity and leaching degrade the provision of nutrients from soil minerals in the A horizon. Systems that depend on nutrient recycling and the provision of nutrients from the surface soil will eventually inevitably decline because of the decline in nutrient availability. To produce a sustainable system nutrients must be obtained from other sources. Subsoils can potentially provide such nutrients due to lower leaching and accessions from the surface soil but their availability is limited by the distributions of micro-organisms and plant roots.

Subsoil environments vary greatly but, relative to the surface soil, have reduced water availability, low aeration, and little microbial activity. These factors combine to reduce the exploitation of subsoils by plant roots. However, given the leaching of surface soils there can be benefit in plants exploiting the subsoil environment. In some situations it can be essential for the maintenance of vegetation, as illustrated by the successional development of soils and vegetation on coastal sand dunes (Walker et al., 1981).

The development of vegetation in sand dunes having no accession of nutrients from elsewhere completely depends on micro-organisms extracting nutrients from the sand grains. Nutrients are gradually extracted from the sand and the temporal progression of vegetation succession from grassland to tall eucalypt forest reflects the accumulation of nutrients in forms available to plants. The soil profile develops from having a broad discoloured zone (aluminium and ion oxides) to having a distinct B horizon at around 1.5m cemented by the oxides and organic matter.

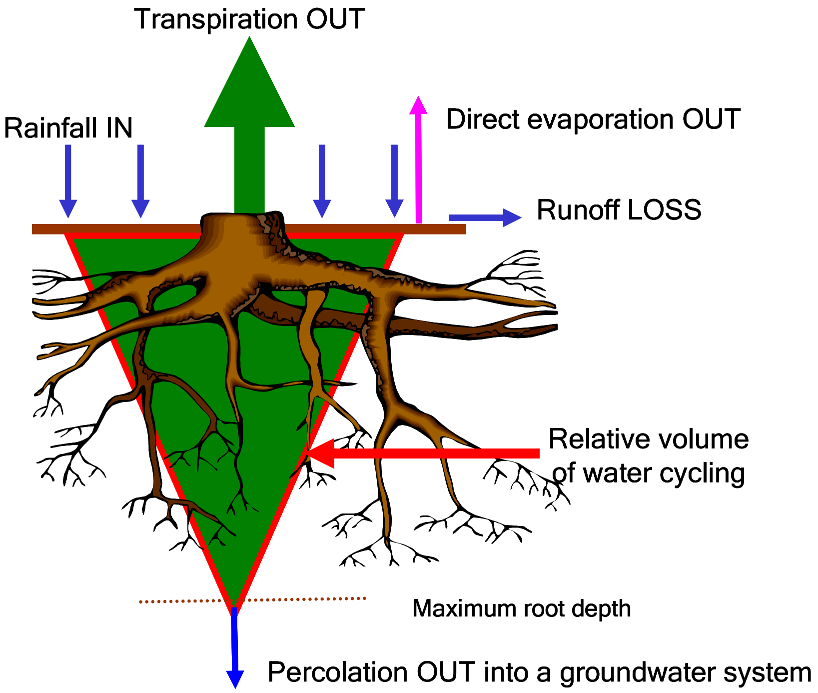

Fig. 1 Schematic representation of water accessions, losses and storage in soils. The relative volume of water recycling reflects the relative contribution to water storage of soil at different depths.

The depth to the B horizon increases with time because plants cannot prevent solubilised nutrients from being leached during periods of high rainfall. The vegetation begins to decline where the nutrient losses exceed the gains because the surface soil can no longer provide sufficient new nutrients to replace the losses, and nutrient accession from the subsoil cannot be maintained when the B horizon is leached below the rooting depth. When the B horizon is at 10m (giant podzol) the vegetation has degraded to a very low sparse shrubland / sedgeland.

The insitu accession of new nutrients depends on exposing fresh mineral material, as occurs with erosion of the surface soil. However, this is counter productive to vegetation development in the short term due to the loss of nutrients contained in the eroded surface soil. It is, however, beneficial in areas where the eroded materials accumulate, as with deposition on plains. Erosion can also provide long term benefits insitu, as illustrated by soils in Europe and North America. The exposure of fresh, largely un-weathered rock through glaciations has resulted in the widespread development of soils which, by comparison with Australia, are highly fertile.

At time scales relevant to human life spans the issue is how to access new nutrients without loosing those already incorporated into the recycling. This is partially addressed through fertiliser application but the applications seldom provide all essential nutrients, and they increase the recycling losses. It is increasingly being addressed by applying rock dusts that have appropriate chemical compositions, and utilising nutrient extraction by microbes. In natural systems the accession of new nutrients is achieved by deep rooted plants obtaining nutrients from subsoils and this is the approach taken with permaculture.

While theoretical considerations identify that deep rooted plants are important in producing sustainable systems there is little evidence that can be used to quantify their importance. As plant roots preferentially occur in cracks and other structural unconformities their environment need not be the same as for the general subsoil. Also, the amounts of nutrients obtained from subsoils are low compared to those involved in recycling, and the measurement methods do not provide a reliable measure of the availabilities of even the major nutrients.

For nutrients the significance of the subsoil logically primarily relates to micronutrients. Deep roots are positioned to access new sources of limiting micronutrients which are then recycled through organic matter.

Mechanical devices

Erosion is the most common method by which plants gain access to new nutrients, and in many landscapes erosion is essential for plants to gain access to new nutrients from rock minerals. However, in erosional areas the increased access to nutrients is associated with a loss of previously acquired nutrients.

Normal root growth represents a mechanical device that allows plants to access nutrients in subsoils. The root growth preferentially follows cracks, old root channels, and other pathways of least resistance to water flows. The expansion of roots in cracks in rocks promotes their breakdown and hence weathering, and thereby increases the availability of new nutrients.

The expansion associated with soils freezing promotes weathering and hence the release of nutrients. Also, the associated heaving brings subsurface material to the surface. An analogous mechanism appears to arise with trees whereby subsoil is bought to the surface around tree boles. In 1973 Tunstall observed subsoil materials on the soil surface around the trunks of poplar box trees in SW Queensland, an effect that had previously been reported for an apple orchard. Eddie Pook, then in the Ecology Section of CSIRO Plant Industry, subsequently observed this mechanism while it was occurring in a forest in SE NSW.

Part of the process could be similar to frost heaving but with the swelling associated with wetting of dry soil creating the force rather than freezing. With homogeneous material the swelling would raise the level of the soil surface without there being any rearrangement of material. However, obstructions such as roots can cause an upward deflection of lateral forces thereby bringing subsurface material to the surface. A complementary effect could arise through the vibration of tree trunks by wind creating thixotrophic conditions around tree boles. The usual attribution of accumulation of subsoil material at the surface around tree boles to the expansion of tree roots is physically unsound where roots developed above the subsoil, as is normal with trees.

The thixotrophic mechanism provides an explanation for the development of gilgaied formation in coarse textured soils, as identified by Tunstall (2005b) for a paperbark woodland (mainly *Melaleuca viridiflora*). The sparse emergent blue gums (*Eucalyptus tereticornis*), which are very large compared to the paperbarks, occur on the largest / highest mounds. This upwelling of soil would also occur with the process described for the development of galgais in clay soils by Tunstall (2005b). Erosion from the mounds tends to deflate them but this is countered by subsoil under the mounds being uplifted due to pressures created by swelling. For the brigalow (Acacia harpophylla) system addressed the gilgaied formation prevents loss of nutrients through erosion while the upwelling of material under mounds improves microbial and hence plant access to new nutrients.

Brigalow evidences how organisms can modify their environment to their benefit, both actively and passively. Water use by the plants promotes the development of gilgaied soils and hence prevents water loss through surface runoff. The gilgai development also promotes the provision of nutrients and restricts their loss. Additional to this passive development of soil of beneficial soil conditions, plants additionally use active mechanisms such as nitrogen fixation through mychorrhiza.

The organic – mineral balance

The desirable levels of soil organic matter are generally identified as being between 2 and 4%, but the upper threshold is closer to 8%. Many natural systems in Australia are outside these bounds, almost invariably low. Soil structure generally degrades when levels of organic matter are below 2% while high levels can reflect reduced turnover and hence reduced availability of nutrients.

The prime controls on the accumulation of soil organic matter are:

- The upper threshold of soil temperature for organic matter accumulation is around 25C as breakdown usually exceeds accumulation above this point. The soil organic matter increases 2-3 times for each 10^{o}C decrease in mean annual temperature below this threshold.
- Wet soils tend to accumulate more organic matter than comparable dry soils due to reduced aeration reducing breakdown. Arid soils generally have relatively low organic matter content because of high rates of decomposition as well as low inputs.
- Organic matter tends to be higher under grassland than forests. Roots of grasses provide higher levels of input than from trees, where organic matter from roots is more protected than surface litter. Moreover, grasses preferentially occur on finer textured soils.
- Fine textured soils (clays) tend to accumulate organic matter more than coarse textured soils due to deceased aeration and protection of the organic matter.

High levels of clay help protect organic matter from breakdown and so promote the accumulation of organic matter. Moreover, clay content is usually positively correlated with plant growth and the occurrence of grasses, and both increase the input of organic matter into the soil.

While the prime controls on the extraction of nutrients from soil minerals can be identified their relative importance is uncertain. This uncertainty partly arises because the significance of different factors can differ greatly between systems. However, it is also due to the limited observations and hence lack of information. The prime controls on the extraction of nutrients from soil minerals appear to be:

- Mineral composition of the material
- Degree of weathering of the material
- Accessibility to microorganisms
- Plant rooting depth

Placing rock dust with an appropriate mineral composition in association with active microbes typically improves root growth and promotes plant performance generally. The Keyline system (Yeomans, 2002) greatly increases the potential for extraction of nutrients from soil minerals by increasing the aeration, organic matter and microbial populations in subsoils

Conclusions

There is a widespread need to improve the levels of organic matter in Australian soils as more than 75% of farming soils have been identified as having organic carbon contents less than 1.75%. This involves increasing the level of soil nutrition to increase the amount of organic material being recycled but, to be sustainable, the nutrition should be increased by developing the natural processes rather than relying on extensive inputs. A reliance on mineral inputs does not redress all nutrient deficiencies and promotes imbalances. Moreover, the cost of many inputs is linked with oil hence high levels of input cannot be sustained into the future.

The requirement is to develop a functional soil rather than continue to treat it as a hydroponic medium that, apart from physically supporting plants, simply acts as a reservoir for applied water and nutrients. While means exist to rapidly improve the level of soil organic matter these must take account of the need to promote the accession of nutrients from soil minerals to be sustainable. A one to one relationship between applied and available nutrients is not sufficient. Applied materials should promote the natural soil functions and provide ten or hundred fold gains.

The existence of practical examples of such gains in the development of sustainable systems demonstrates that they can be achieved. However, while some components of the different management systems are generic others are site specific. Even with generic methods, gaining benefits depends on knowledge of the constraints. Knowledge of the applicability of methods is needed to reliably produce benefits as there is no ‘one size fits all’ solution that can be guaranteed to produce the desired benefits regardless of the constraints.

Improvements in technology and understanding provide possibilities for improving management methods. Also, changes in constraints, such as increases in amount of wastes and fuel prices, provide opportunities that previously did not exist or were impractical. Realising on these opportunities can redress a long standing issue critical to the survival of societies by way of the sustainable provision of nutritious food.

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