SOIL BIODIVERSITY

PRINCIPLES

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1. Soil Biodiversity and its Assessment

The soil biota constitutes a major fraction of global terrestrial biodiversity. The majority of the terrestrial phyla of invertebrates, protists, fungi and bacteria are represented in the soil community. Within each of these groups the species diversity may also be extremely high. The different groups require different methods for their extraction from soil, identification and quantification. The necessity for using a variety of methods, many of which are destructive of the soil habitat, means that there is no single case where a full inventory of the soil diversity has been achieved. For some groups the methods have significant limitations and the percentage of species identified often well below the number exisiting. This is particularly so for the micro-organisms. Traditional methods relied on the use of agar growth media to isolate fungi and bacteria but it is recognised that this is highly selective and results in only a small fraction of the diversity being recognised – perhaps less than 5% in the case of fungi (Hawksworth and Kalin-Arroyo in UNEP 1995). Molecular methods have given further insights to this issue. Torsvik et al (1996) demonstrated the existence of 13,000 genetically distinct bacterial types in a small sample of soil compared with only 66 isolated by the conventional plating techniques.

More efficient inventory is possible for the invertebrates, but levels of diversity are still very high. Over 1000 species of invertebrates were identified in 1m^2 of soil in temperate forests in Germany (Schaefer and Schauermann, 1990).

Because of the very demanding nature of soil biota inventories the practice of using 'Key Functional Groups' (FGs) has become more common (see Box). This approach economises on expertise, time and cost by obviating the necessity of attempting to assess all groups. It also offers the opportunity to utilise relatively standardised methods that enable comparisons to be made across sites and biomes. There is as yet no general agreement on the number of groups to be used or on their definition but three broad criteria can be applied. The first is that of distinct functional identity ie. that the different groups have distinct, and clearly definable functions within the ecosystem. Some of these functions are very specific, such as nitrogen fixation, whilst others are more general such as soil structure modification. The set of FGs should in any case represent a broad suite of ecosystem functions. Second the set should embrace a wide range of taxonomic groups. Third the characterisation of the group in terms of identity and abundance should be relatively easy. This may vary between groups, some such as the macrofauna being easy to define taxonomically down to species level, whilst bacteria may require molecular typing at a 'sub-specific' level in order to assess diversity.

Box 1 shows an example of a list of Key Functional Groups of the soil biota which fulfils these criteria.

Key Functional Groups of Soil Biota

1. Ecosystem Engineers (eg. macrofauna such as termites and earthworms): organisms which have major physical impact on soil through soil transport, building of aggregate structures and formation of pores – as well as influencing nutrient cycling.
2. Decomposers (eg. cellulose degrading fungi or bacteria): micro-organisms posessing the polymer degrading enzymes that are responsible for most of the energy flow in the decomposer food web.
3. Microregulators (eg. microfauna such as nematodes): animals which regulate nutrient cycles through grazing and other interactions with the decomposer micro-organisms.
4. Micro-symbionts (eg. mycorrhizal fungi, rhizobia): micro-organisms associated with roots that enhance nutrient uptake.
5. Soil-borne pests and diseases (eg. fungal pathogens, invertebrate pests): biological control species (eg. predators, parasitoids and hyper parasites of pests and diseases) can also be included.
6. Bacterial trasformers: bacteria performing specific transformations of carbon (eg. methanotrophy) or nutrient elements such as N, S or P (eg. nitrifying bacteria).

2. Soil Biota and Ecosystem Services

Within all terrestrial ecosystems most of the energy captured by the vegetation is used by the soil biota for a series of essential functions eg. driving nutrient cycles; regulating the dynamics of soil organic matter, soil carbon sequestration and greenhouse gas emission; modifying soil physical structure and water regimes; enhancing the amount and efficiency of nutrient acquisition by the vegetation through mycorrhiza and nitrogen fixing bacteria; and influencing plant health through the interaction of pathogens and pests with their natural predators and parasites. These services are not only essential to the functioning of natural ecosystems but constitute an important resource for the sustainable management of agricultural ecosystems (Daily et al 1997, Naeem et al 1999).

3. Impact of Land-Use change on Soil Biodiversity.

There are now well documented cases to show that conversion of natural vegetation to other land-uses, including agriculture, results in change in the diversity of the soil community. .Changes in the below-ground biodiversity are often thought to track those of plants, although there is evidence that the soil community may be more functionally resilient than the above-ground biota (Giller et al 1997). As land conversion and agricultural intensification occur, the ***planned*** biodiversity above-ground is reduced (up to the extreme of monocultures) with the intention of increasing the economic efficiency of the system. This impacts the ***associated*** biodiversity of the ecosystem – eg., micro-organisms and invertebrate animals both above and below ground - lowering the biological capacity of the ecosystem for self-regulation and thence leading to further need for substitution of biological functions with agrochemical and petro-energy inputs. The sustainability of these systems thus comes to depend on external and market-related factors rather than internal biological resources. The biodiversity of soil under natural vegetation may be taken as a baseline for monitoring changes under varying land-use.

The assumption is often made that the consequent reduction in the diversity of the soil community, including cases of species extinction, may cause catastrophic loss in function, reducing the ability of ecosystems to withstand periods of stress and leading to undesirable environmental effects. The detection of critical thresholds for functional change is however still a matter of debate. The high biodiversity within many functional groups of soil organisms has been interpreted as conveying a substantial degree of redundancy to the soil biota and led to suggestions of high resilience (Swift et al., 1996; Lavelle et al., 1997; Giller et al., 1997).

4. Intellectual Property Rights

A great variety of industrially valuable products have been obtained from soil micro-organisms. The most well known examples are antibiotics the majority of which have been isolated from soil fungi or actinomycetes. The advent of molecular techniques, which enable comprehensive sampling of the microbial genome from the soil in the form of DNA fragments, has very significantly increased the opportunity for identifying such products. The DNA can be inserted into culturable organisms, such as the bacterium ***Escherischia coli.*** Proteins and other metabolic products resulting from the expression of the foreign (soil) genome in the host bacterium can then be recovered from the culture and characterised. For instance one approach that has been used is to cut the extracted DNA into usable fragments and clone it into a vector such as the bacterial artificial chromosomes (BACs) that have been developed for transferring eukaryotic genome fragments into prokaryotes.

By these means a large range of novel chemicals are being discovered, some of which are of industrial value. This has led to the concept of 'microbial prospecting' in soil ie the process of using these molecular techniques to search the soil for products of the microbial genome that have industrial value. Microbial prospecting is a fast-growing component of the bio-genetic industries in northern countries and interest is quickly turning to prospecting in tropical soils.

The capacity for microbial prospecting raises a significant issue of intellectual property rights (IPR) concerning the ownership of organisms discovered in soil. The rights to the microbial genome, and the products that it may yield, for a given soil, are not well defined in the law of most countries. However both the country in question, as well as the specific land owner and/or user, might expect to benefit from this resource. Tropical countries may find themselves unable to fully benefit from these opportunities if appropriate controls are not in place.

BEST PRACTICES

1. Agricultural Management Practices

There is a wide range of 'soil bio-technologies' with the potential to increase and sustain productivity that are currently under-utilised because of the lack of critical evaluation for application in tropical small-scale agriculture. The soil biota may be manipulated by both direct and indirect means. ***Direct*** management is usually by inoculation with species of soil biota including N_2-fixing bacteria, mycorrhizal fungi, control agents for pest and diseases and beneficial macrofauna such as earthworms. Modern molecular research is also increasing the potential for genetic manipulation of some of these organisms prior to inoculation. ***Indirect*** management is achieved through appropriate design and management of cropping system, including the genetic manipulation of the plant component, management of organic inputs and other soil amendments and soil tillage. Indirect approaches probably have the greater potential and relevance to the circumstances of most farmers.

The most appropriate practices for conservation of the soil biota are therefore many of those associated with sustainable agriculture (eg.Pretty and Hine 2001). In general terms these include all management practices that maintain soil cover and return organic matter to the soil as well as ensuring that nutreint inputs and outputs are kept in balance. Such practices include:

a) Integrated Soil Fertility Management (ISFM) ie the use of both organic and inorganic sources of nutrients rather than either alone;
b) The use of legume cover crops and green manures by fallow rotation or inter-

cropping;

c) Agroforestry practices that provide for deep nutrient cycling and/or return of nutrient to the soil through biomass transfer, fallowing etc;
d) The use of conservation tillage rather than continuous deep ploughing;
e) Returns of farmyard manures and household wastes, with or without composting;
f) Choice of crops and associated plants which have high nutrient use efficiency.

2. Culture Collections

Many countries maintain cultures of micro-organisms of importance in agriculture but in many cases these are under threat due to lack of resources for their maintenance. The most common collections are those of micro-organisms such as ***Rhizobia*** or mycorrhizal fungi, but earthworm collections for vermi-composting are also available in many places (eg. India). Legislation should address the maintenance of culture collections as well as in situ conservation and management.

MODELS

1. Inventories and Databases

Both NBSAPs and the equivalent agricultural strategy documents often fail to address issues to do with soil biodiversity directly or explicitly. Nonetheless the NBSAPs of several countries refer to this sector of biodiversity in more indirect ways. The importance of micro-organisms is addressed by several countries (eg. India, Phillipines, Ethiopia, Brazil) by suggesting that inventories should be developed. In a few cases there are direct references to soil biodiversity (eg. Cuba) and even to specific groups such as ***Rhizobia*** (eg. Ethiopia, Brazil)

The Brazilian government recognises the importance of soil biodiversity. Soil biodiversity was one of the key aspects, together with pollinators, of a proposal on agrobiodiversity presented by the Brazilian Government to the second meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) in 1996.

It is important that legislative documents be made more explicit with respect to soil biodiversity and the principles governing the monitoring of conservation and management practices which are described above.

2. Promotion of Sustainable Soil Management

If there is little direct reference to soil biodiversity in most legislation, there is more widespread acknowledgement of the importance of maintaining soil ‘quality’ or ‘health’ ie there is recognition of the risk to essential ecosystem services if soil is degraded. Thus the majority of countries make reference to the promotion of sustainable soil management practices. In some cases these references focus largely on soil conservation and prevention of erosion (eg. South Africa) but in others more explicit mention is made of the importance of maintaining the organic status of soil (eg. Cuba, Mexico, Brazil, Ethiopia, Kenya). Some approaches are mentioned specifically as sustainable management practices eg: minimum tillage (Brazil, Mexico) and organic agriculture (Mexico).

Two specific examples may be referred to. In Cuba, as a response to the food crisis after the collapse of its trade relation with the socialist block, sustainable and biological approaches to agricultural production have become government policy. This includes promotion of management systems for soil improvement and conservation such as minimal tillage, rotations, organic fertilisers, green fertilisers and green cover. Salinity in rice fields is being addressed by using ***Sesbania*** in rotations, which provides organic matter in conditions with salinity stress (Rosset & Altieri, 1994; Rosset, 1996).

In the ***National Environment Action Plan*** (NEAP) of Kenya,1994 actions relating to agrobiodiversity are proposed such as the need for: "efficient and appropriate use of fertilizer, pesticides, tillage methods, crops and cropping patterns to avoid environmental degradation. In the long run, greater use of animal and compost manures need to be promoted as a supplement to mineral fertilizers. Integrated pest management strategy should be given high priority. To reduce pollutants reaching water bodies, the run-off water should be filtered through the soil as an integral part of soil conservation structures. Greater attention needs to be given to drought-resistant indigenous food plants."

3. Case-Studies of Specific Soil Technologies

There are a multitude of examples of agricultural practices that, on the basis of the principles of best practice described above, favour and utilise soil biodiverstiy and the ecosystem services it provides (eg see the compilation by Pretty and Hine, 2001). Relatively rarely however has rigorous monitoring of the soil biota or its functions been carried out. The following is a small selection of practices mainly drawn from the countries covered in the case-studies and selected to show a spectrum of effects that are relatively less well known than for instance use of N-fixing ***Rhizobia*** inoculants. More examples may be found by consulting the attached bibliography.

Soil conservation

It is estimated by FAO that about 1.93 million households in 20 countries now have more than 4 million ha of land under conservation tillage with significant improvements in production and agricultural biodiversity at all levels

a) Enhancing soil biodiversity in intensive crop production through conservation tillage, Brazil (Adapted from case study presentations by José Benites and Theodor Friedrich, FAO, and Helvecio Mattana Saturnino, President of APDC (the Zero Tillage Association of the Cerrados), Brazil.

As a result of the uptake of conservation tillage in Santa Catarina, there has been a sustainable increase in production of maize and wheat with yields up by more than 200%. The benefits are not only in production but also to the wider environment through improved water quality owing to less erosion and more regular flow of streams from better infiltration and soil moisture storage and reduced losses of applied inputs in run-off. Conservation tillage results in 70% less herbicide run-off, 93% less erosion and 69% less water run-off as compared with mould-board or disc-ploughing. There is also reduced release of carbon gases and reduced air pollution. The uptake of conservation tillage in Santa Catarina was successful because of well organized farmer groups, who developed the necessary technologies, together with scientists, technicians and the private sector, and farmer-to-farmer extension. Large areas of Brazil's soya crop are now under zero tillage systems.

b) The South African National Landcare Programme is a community-based programme supported by both the public and private sector through a series of partnerships. It is a process focussed on the conservation of the natural resources (soil, water and vegetation) through sustainable utilisation and the creation of a conservation ethic through education and awareness both for farmers and the broader land-user communities and young people. The purpose of this element is to promote a better understanding of factors that can lead to unsustainable use of resources in agriculture and of policies and institutions, which can address this.

2. Improving Nutrient Cycles at the Landscape Scale.

Poultry Manure Use, USA: Meat poultry farms in the USA range in size from over 500 hectare to less than 2 hectare. The size of the farm is often not related to the number of chickens grown and therefore the manure produced may be a credit for the farmer because of its fertilizer value or a debit for the cost of disposal. An industry of clean-out companies has developed to service those farms where manure is a disposal problem. The clean-out companies remove the manure for a fee and then sell the manure to other farmers.

A second feature is that State Governments have begun to legislate mandatory nutrient management programs to protect the environment. For instance those farmers with excess nutrient must adopt transport or treatment measures to prevent excess application of N and P on their land. State funded programs pay farmers a transport fee to move manure to farms that can utilize it effectively. Assistance can also be obtained for the development of new or improved treatment technologies by research institutions and private enterprise.

3. Improvement of Soil Structure and Nutrient Cycling through Macrofauna Manipulation.

a) Restoring tea gardens in India through soil fauna and organic mattter (Giri 1995; Lavelle et al 1998, Senapati et al 1999).

Long-term exploitation of soil under tea gardens has led to stagnation in yelds and quality together with significant changes in soil physical, chemical and biological conditions including decreasing organic matter content, cation exchange and water-holding capacity. The diversity and abundance of soil fauna has also declined. A patented technology entitled "Fertilisation Bio-Organique dans les Plantations Arborées" (FBO)has been developed and tested which improves the physical, chemical and biological soil conditions by inoculating a mixture of low and high quality organic materials (tea prunings and manure) and earthworms into trenches dug between the rows of tea plants. Measurements performed at two sites, beginning in 1994, have shown that this technique is much more effective than 100% organic or 100% inorganic fertilization alone, increasing yields on average by up to 276% and profits by an equal percentage (from around US$2,000 ha-1 using conventional techniques to about US$7,600 ha-1 in the first year of application). This technique has been extended to other countries and is now being widely used..

b) Restoring soil structure and plant production in crusted Sahelian soils through organic
matter applications and termite activity (Mando, 1997).

The area of bare and crusted soils in the Sahel has undergone a large increase in recent decades, seriously degrading the landscape and negatively impinging on crop production. Mulch was placed on crusted and bare soil in Burkina Faso attracted, termites which improved the physical structure and water regime by opening pores in the soil surface and throughout the soil profile. The termites also enhanced the decomposition of the mulch, releasing nutrients and increasing their availability to plants. In mulched plots where termites were artificially excluded, cowpea yields were more than 100 times lower than where termites were present and active. Termites are often regarded as being solely pests but can also be extremely important in promoting plant production and ecosystem function. This example shows that it is possible to manage their activities for human benefit.

c) Restoration of soil structure and pasture production in kaolinitic soils of the Amazon Basin (Barros, 1999; Chauvel et al., 1999)

In the Amazon, 95% of the deforested area is converted into pastures of which about 50% may be defined as degraded in terms of soil fertility and soil structure. When the forest is converted to pasture, heavy machinery and cattle of trampling soil leads to severe soil compaction. The native soil macro-faunal communities are also radically diminished and replaced by an opportunistic exotic, ***Pontoscolex corethrurus***, which may come to occupy nearly 90% of the total soil faunal biomass. This species produces more than 100 Tons ha-1 of castings which decreases the macroporosity of the soil to an extent equivalent to the compaction produced by the action of heavy machinery.

The potential for restoration was shown when soil monoliths were removed from the pasture and placed into the forest and similar blocks were taken from the forest and placed into the pasture. After one year, the structure of the compacted pasture soil was completely restored to levels of those typical in native forest soils by the action of the diverse community of forest soil organism. Meanwhile the forest soil incocualted with ***P.corethrurus*** showed levels of compaction and porosity levels similar to those of the degraded pasture.

TOOLS

1. Methods for Soil Biodiversity Assessment.

As described in 'Principles' there is still limited agreement on standard methods for rapid assessment of soil biodiversity but several important initiatives are underway to achieve this (see next section on websites). The following are some key references to methods:
Anderson and Ingram 1993, Bignell and Swift 2001, Hall, 1996, Jones and Eggleton, 2000, Schinner et al 1995

2. Institutions and Programmes in Soil Biodiversity

The following institutions have substantial programmes on soil biodiversity related to agriculture and are useful sources of information or advice on on-going activities in soil biodiversity:

Diversitas: the International Programme of Biodiversity Science (www.icsu.org/diversitas): Special Target Area on Soil and Sediment Biodiversity (www.nrel.colostate.edu)

FAO; Programme on Agricultural Biodiversity – Soil Biodiversity Portal at .www.fao.org/ag/ag1/ag11/soilbiod/fao.htm)

NERC: UK special programme on soil biodiversity research at soilbio@ceh.ac.uk or http://www.nmw.ac.uk/soilbio

TSBF: Tropical Soil Biology and Fertility Programme at TSBFINFO@tsbf.unon.org or www.tsbf.org

3. Bibliography

A reference list to literature cited and other useful documents is attached.

4. Education and Awareness

Awareness of the importance and current state of knowledge of soil biodiversity is limited in almost all sectors of society.

Brazilian Government Proposal to SBSTTA: identified institutional and educational factors as the main constraints to effective use of soil biodiviersity (Perez Canhos et al., 1998). These included : low institutional capacity, lack of integration between different groups working on the topics, insufficient information exchange, and -lack of education of the population to appreciate the value of the soil biodiversity. The following goals and strategies were proposed in alleviation:

1. Establishment of a network of laboratories, scientific collections and technical centres.
2. Programmes for education of specialists (Post-graduate programmes in the country and abroad and short courses in the country)
3. Definition of standard sampling protocols

4. Definition of indicators of soil quality
5. Develop models to measure the economic value of the biodiversity of microorganisms and creation of fiscal incentives.
6. Establishment of specialised discussion groups of researchers
7. Establish thematic networks on soil and micro-organisms biodiversity.
8. Education targeting the appreciation of the value of the biodiversity of micro-organisms and their sustainable use and development.

These actions could act as a model for other countries.

Canada's Wormwatch program and Australia's "Earthworms Down-under" program,

Innovative programmes of public education have been started in Australia and Canada Worm Watch is a program which is being initiated by the Canadian government to promote awareness of the diversity of "life beneath our feet" through public participation in a nationwide earthworm census. The census-t akers will be students, farmers, and producer groups, conservation and naturalist groups, gardeners and interested individuals and families. They will be supplied with a Worm Watch kit containing background material on earthworm ecology and taxonomy, instructions on how to sample and record their data, data sheets, a photographic key showing the most commonly encountered earthworm species, vials for the preservation of earthworms that could not be identified, and a list of references, including a wormwatch website and a toll-free number. An instructional video demonstrating the various sampling techniques should also be available. Scientists will make use of the data collected to inventory and study the distribution of earthworm species in Canada, including correlations between landuse patterns (including undisturbed vs. disturbed habitats, cropping systems, and tillage practices) ecozones, and earthworm populations and species diversity. The data collected should significantly increase the scientific community's understanding of the biogeography of post glaciation earthworm populations, and the history of their distribution. It can also be used to evaluate the potential of using earthworms as one of a suite of bioindicators of environmentally sustainable land use practices, and the information on species diversity and preferred habitat will beuseful when considering policies on introducing earthworms for waste management, integrated pest management, soil improvement, and site reclamation.

Canada's WormWatch program is modeled on an Australian program, the Earthworms Downunder, run by CSIRO, the Australian Department of Eduction and the Double Helix Science Club. The program used Double Helix science club members to collect and determine the diversity and distribution of earthworm species in Australia. The program was very successful, and could accomplish within one year what woul d be expected of a team of scientists in five years.

Submission of the Canadian Government to SBSTTA on Wormwatch is available for download on the CBD website: http://www.biodiv.org/areas/agro/case-studies.asp. More information on website: http://www.cciw.ca/ecowatch/wormwatch/

INDICATORS

The adoption of the Key Functional Group methodology, described above in the Principles section, is itself an approach to developing indicators of soil biodiversity. An inventory of the FGs given in Box1 would represent only a small sub-set of the total diversity of a soil but one which is widely representative both in terms of taxonomy and function. As such the list is a good candidate for a set of indicators of change in soil biodiversity. Such sets have been used to investigate and monitor the impacts of land-use change.

Even a short list of such indicators represents however a very substantial investment, particularly where monitoring over time is required. The use of single groups has been advocated, and nematodes, because of their multi-functional role and their relative ease of sampling have often been advocated for this role.

An alternative approach is the use of surrogate indicators which assess the associated function rather than the diversity itself. The most widely advocated of these is soil organic matter (SOM.). Soil organic matter is a major integrator of soil-based functions (nutrient storage, soil structure modification, chelation of toxic chemicals, carbon sequestration etc) as well as providing an energy source for the soil biota. An equilibrium level of SOM content close to the maximum for a given soil type and land-use system has therefore been proposed as indicative of processes functioning close to optimum and a healthy and diverse soil biota. Additional insights may be gained from measuring the ratio of labile to re-calcitrant fraction of SOM in additon to the total (see Sparling 1991, Swift and Woomer, 1993). More research is needed however to clarify the weight of implication that such surrogate and catch-all indicators carry.