Soil Biodiversity Indicators for Agricultural Land: Nature Conservation Perspectives

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Abstract
This paper highlights requirements for multi-functional uses of soil and research priorities for the development of indicators of soil biodiversity in agricultural land. Soil biodiversity embraces genetic, taxonomic and functional forms which interact to provide a wide range of ecological services. Traditionally, the value of soil biodiversity in agricultural land has been considered from a production perspective. However, it is equally important to recognise the wider benefits of soil biodiversity in support of nature conservation and environmental protection through maintaining soil functions (e.g. breakdown and retention of organic matter, denitrification, pathogen transfer) and their significance to sustainable land use (e.g. organic farming, restoration of damaged/impoverished soils, maintenance of water quality and biodiversity conservation). Adopting a multi-functional approach will confer benefits not only for production but also for nature conservation and environmental protection interests and this needs to be recognised explicitly in management policy and guidance. The impacts of agricultural practices on soil biodiversity are assessed alongside other environmental pressures such as atmospheric pollution, climate change and land development. We examine the feasibility of, and limitations to, measuring or monitoring soil biodiversity in agro-ecosystems. Particular requirements are for standardised methods and benchmarks for individual soils, as well as better understanding of what regulates spatial and temporal variability in soil biodiversity. Monitoring soil biodiversity should be closely integrated with wider monitoring of environmental quality.

Keywords: biodiversity, soil, agriculture, nature conservation, indicators, monitoring, multi-functional approach

1. Introduction

The soil is home to some of the most fascinating organisms on earth. Below our feet there is an immensely complex web of life that includes the smallest bacteria and fungi to burrowing mammals. The diversity in soils is several orders of magnitude higher than that above ground (Heywood, 1995) and is seen as the last frontier for biodiversity on earth (Swift, 1999). For many centuries, humans have relied directly on this diversity to provide food (e.g. mushrooms, roots or rabbits) and medicinal products (e.g. leeches to antibiotics). We have also relied upon soil biodiversity for less obvious, but no less important, requirements. The biology within soil interacts with soil chemical and physical properties to maintain the diverse, multi-functional value of soils. Habitats above ground rely upon the intimate interaction with the biodiversity below, whether the habitat is a crop being produced for economic reasons or indigenous plants

integral to the character of semi-natural habitats. Numerous plant species also have intimate symbiotic relationships with soil fungi (van der Heijden et al., 1998). Many insect species are soil dwellers for at least some part of their life-cycle (Bater, 1996), while many mammals and amphibian species of conservation concern rely on the soil for food and shelter (Harris et al., 1995).

There are many reasons why we should be measuring/monitoring soil biodiversity in agricultural land. Sustainable land use must be concerned with maintaining soil multi-functionality: biomass production, environmental protection, nature conservation and heritage interests, as well as other potential economic uses of soil. Environmental protection measures can have significant impacts on soil biodiversity but soil biodiversity itself has an essential role to play in ensuring that soils can be managed for pollution abatement, carbon sequestration, flood control, land remediation, soil restoration and waste disposal. Even in the most intensive agriculture, there are opportunities, by maximising the benefits of soil organisms, to restore degraded agricultural land and improve natural habitats. Nature conservation and heritage interests (e.g. landscape value) are important but often little acknowledged functions of agricultural land. Soil biodiversity lies at the foundation of maintaining habitats, species of conservation value and heritage interests in agricultural land. Soil biodiversity *per se* also needs to be valued in its own right; thus, there are over 100 species of soil invertebrates and fungi in the UK Biodiversity Action Plans. There are, however, many uncertainties regarding how to set goals for soil biodiversity in the context of nature conservation or heritage interests. We have yet to clarify which elements of soil biodiversity might merit conservation action.

There are many initiatives, policies and guidance that will impact on soil biodiversity, though few mention soil biodiversity explicitly. At the international level there is the UN Convention on Biological Diversity, the European Union Habitats and Water Framework Directives and the forthcoming Thematic Strategy on Soil Protection, as well as the transboundary initiatives for atmospheric pollution control and the World Conservation Union (IUCN) Red Data Book species. At a UK national level there are numerous examples which include Biodiversity Action Plans, Department for Environment Food and Rural Affairs (DEFRA) Good Practice Guidelines for soils, nitrate sensitive zones, the new Strategy for Sustainable Farming, sewage sludge regulations and regulations on disposal of other wastes, management requirements of Areas Of Outstanding Natural Beauty (AONBs), Sites of Special Scientific Interests (SSSIs), Local Nature Reserves and National Parks, as well as stringent environmental protection standards, in particular for water quality.

In this paper we put the case for considering soil biodiversity as a fundamental component of nature conservation and heritage interests and the relation to the multi-functionality of soils in agricultural land. We consider some approaches to monitoring and policy that could be implemented now and built upon following further research.

2. What is soil biodiversity?

Soil biodiversity encompasses all organisms that live in the soil, whether they are single-cell organisms or multi-cell animals or plants, which can be classified using traditional taxonomic techniques or genetically via unique DNA or RNA. It also embraces an immense ecological diversity manifested through behaviour patterns and feeding or habitat preferences. The combination of all these aspects is expressed in the functional diversity of soil organisms.

Taxonomic diversity is typically defined by species richness, as simple counts of species recorded or relative differences in species composition. As far as we aware, there has not been a full species inventory from an agricultural ecosystem, or indeed any ecosystem. Taxonomic diversity can also be defined at various higher taxonomic levels (e.g. phyla, orders or families). This approach has been proposed as a

more realistic level at which, in the first instance, to carry out inter-site comparisons (Hawksworth and Ritchie, 1993; Wardle, 2002).

An inventory of soil biodiversity would require considerable resources and significant investment in taxonomic developments. Several international and national initiatives have taken on various aspects of this challenge e.g. the UN initiative of Biodiversity, the UK Darwin Initiative, the USA led Global Litter Invertebrate Decomposition Experiment, the UK Natural Environment Research Council (NERC) Soil Biodiversity Programme and the CIAT Tropical Soil Biological Fertility Institute. In all these initiatives, there has been much interest in the use of molecular genetic techniques to identify species since they can be relatively fast and cost-effective although their initial development still requires expert knowledge to resolve the relationships between different species. Digital image recognition is also showing potential in reducing the effort and technical expertise required in characterising the invertebrate component of soil biodiversity.

Genetic diversity can identify individual organisms from some unique part of their DNA or RNA and so provides definitive information on soil biodiversity. It would be a massive exercise to extract all the DNA or RNA information from the soil but advances in data processing will make this possible in the not too distant future. These approaches have already highlighted the immense scale of soil microbial diversity (Ward et al., 1990), which has also been recognised for its economic potential through bioprospecting (Franco and McClure, 1998).

Soil biodiversity can also expressed as *ecological diversity* in terms of differences in body size, behaviour and food and habitat preferences of individual organisms or communities. Thus, soil organisms can be grouped in terms of their feeding preferences, often expressed by trophic levels of the soil food web; for example primary consumer, bacterial or fungal feeder, omnivore, predator (de Ruiter et al., 1998). Although remarkably little is known about the habitat preferences of the majority of soil organisms, each will have its own preferences for water requirements, soil chemical and physical properties, space to grow and reproduce, food preferences and climatic conditions. Some soil organisms are widespread while others are extremely restricted in their distribution. Many live in, or on, the soil for all of their life while others live in the soil for varying durations for feeding, hibernation, defence or key stages in their development or reproduction (e.g. Bater, 1996). They may inhabit different layers of the soil at different times of the year and may favour particular areas within a field or soil profile due to the environmental conditions (Wallwork, 1970). Many of these preferences are linked to the intimate relationship between soil organisms and plants, the primary source of nutrients and energy inputs into the soil via rhizosphere deposition and plant litter. Plant species composition, and therefore habitat, has a significant, but as yet unquantified, control on below ground biodiversity (Wardle, 2002).

Functional diversity reflects the range of ecological services provided by soil organisms and may be expressed in terms of the species or groups important to the maintenance of different soil functions, for example ecosystem engineers that mediate nutrient flows and soil (Brussaard, 1998; Jones et al., 1994). This approach has focussed on the provision of soil functions for agricultural production or environmental protection but has been modified (Figure 1) to address the importance of biodiversity *per se* in soil resilience and its relevance to nature conservation, heritage interests and other economic uses.

3. Why is soil biodiversity important in agricultural land?

Soil organisms provide essential ecological services that maintain terrestrial ecosystems and support soil multi-functionality. In production, soil organisms contribute amongst other things to drainage, soil structure, rooting, nutrient supply and pest control. But agricultural soils also carry out other functions that are essential for environmental protection, heritage interests and nature conservation and for which soil biodiversity is important (e.g. protection against erosion, trace gas emission, sequestration of carbon,

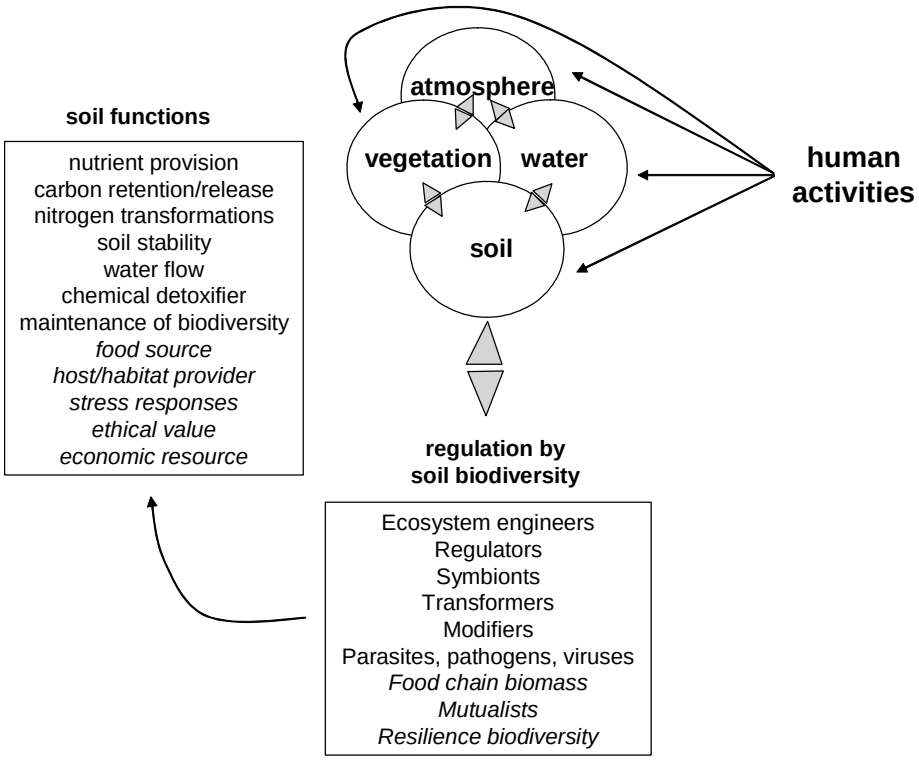


Figure 1. Diagrammatic representation of the functional significance of soil biodiversity in maintaining soil functions in the terrestrial environment.

maintenance of soil structure, restoration of degraded land, preservation of sub-fossil plant and insect remains and maintenance of Red Data Book species). This multi-functionality encompasses the ecologically based concepts of soil health and soil quality (Doran and Ziess, 2000), where soil health is the capacity of soil to function as a vital living system to sustain soil biological productivity, promote environmental quality and maintain plant and animal health whether that is in a natural or managed ecosystem.

The capacity of any soil to maintain multi-functionality is influenced by the diversity of the soil community; indeed a number of the functions are biologically mediated. A wealth of research has highlighted the role of individual species or functional groups in soil processes such as organic matter decomposition, nitrogen fixation, water infiltration or pest control, though the importance of biodiversity *per se* remains elusive (Wardle, 2002). Recent research indicates that nutrient cycling may be maintained by a few species (Bradford et al., 2002; Hunt and Wall, 2002) and, thus, there is a great deal of redundancy in soil biodiversity (Andren et al., 1995). But this does not mean that soil biodiversity *per se* is unimportant in terms of mediating nutrient cycling and other soil functions. It is widely believed that soil biodiversity, as displayed by the complexity of the soil food web, is fundamental for the resistance, resilience and recovery of soil functions to environmental perturbation in the short-term (Mikola et al., 2002; Wardle, 2002). Much of this research is still very much in its infancy but has obvious implications for the importance of soil biodiversity and maintenance of soil functions in agricultural land. It is, however, vitally important that this research widens its approach to address the role of soil biodiversity in sustaining the multi-functionality of soils.

From a production perspective, the use of agrochemicals in intensively managed agriculture has reduced our reliance on soil biodiversity, but a dependence on biologically mediated soil functions is an important principle in organic and bio-dynamic farming systems. Optimising the benefits of these functions should be

an important consideration for restoring soils with any de-intensification of farming (c.f. Beare et al., 1992; Brussaard et al., 1998; Andren et al., 1990). In tropical agriculture, there has been considerable research effort in developing and maximising the potential of biological regulation of soil fertility, principally for small-holder farmers (Swift, 1999). Many of the objectives have direct parallels to current issues in Europe. Of particular significance is the management of soils using indigenous soil biodiversity to sustain crop production and soil fertility with minimum agrochemical inputs. The UNEP Global Environment Fund has just provided multimillion-dollar funding to develop this research further.

Soil biodiversity has a crucial role to play in mediating the other soil functions. This includes environmental protection by retaining and breaking down pollutants, carbon, nitrogen and phosphorous compounds; stabilising soil; enabling water percolation and incorporating organic matter. These activities all serve to protect soil against erosion, aid in restoration of degraded land, maintain water quality and, increasingly, influence carbon sequestration and reduction of trace gas emissions. Soil biodiversity in the context of nature conservation and heritage interests within agricultural land has been largely neglected. Opportunities to manage both may be limited in arable and grassland areas managed intensively with agrochemicals. They should, however, not be ignored since there will be opportunities to restore degraded agricultural land and carry out habitat restoration, while the potential for providing wildlife refuges/corridors and food resources for other species (e.g. the links between soil invertebrates as a food source for farmland birds, including migratory species) are well established (Benton et al., 2002). Agricultural land also covers a wide range of semi-natural habitats which are, or have been, used for grazing and/or cultivation for many years. In many of these areas, there may already be some policy or guidance relating to known conservation species or habitats but the importance of soil biodiversity in mediating the many functions of soil remains largely ignored.

Thus, there is a need for much greater recognition and integration of soil related issues into management policy or guidance. The challenge for agriculture is to balance the various demands on soils using a multi-functional approach which aims to optimise soil management to maintain all soil functions and for the benefit of all who rely on the soil for their livelihood. In this instance, soil biodiversity needs to be valued for its own worth as well as the maintenance of agricultural habitats, and associated flora and fauna, with conservation importance.

There are, however, wider economic benefits from soil biodiversity (Table 1). Thus Pimentel and co-workers (1997) highlighted that soil biodiversity provides considerable economic benefit to agriculture but this is not solely related to crop or livestock production goals. Their figures do not, however, include the important values of soil biodiversity for many aspects of environmental protection, bio-prospecting or wildlife and biodiversity conservation. It would be timely to assess the economic value of soil biodiversity within Europe to address these important issues.

4. What can change soil biodiversity in agricultural land?

Agricultural practices

The impacts of individual agricultural practices on various components of soil biodiversity has been researched for several decades and there have been many reviews (e.g. Andren et al., 1990; Bardgett and Cook, 1998; Curry, 1994; Paoletti et al., 1992). Agricultural land use and management practices can have significant (positive and negative) impacts on different components of soil biodiversity. For example, ploughing generally reduces diversity while liming tends to increase species richness in nutrient-poor semi-natural grasslands, and the over-use of agrochemicals or industrial/domestic organic wastes will, in general, have a detrimental impact on soil organisms. The use of chemical fertilisers can also alter the foundation of the soil food web by favouring bacterial driven primary production, rather than the fungal dominated system prevalent in semi-natural habitats. This has knock-on consequences for the composition

Table 1. An assessment of the economic benefits of soil biodiversity. Adapted from Pimentel et al., 1997.

Activity	*Soil biodiversity involved*	*World economic benefits of biodiversity (x$10^{9})*
Waste recycling	various saprophytic and litter feeding invertebrates, fungi, bacteria, actinomycetes	760
Soil formation	diverse soil biota facilitate soil formation e.g. earthworms, fungi, ants	25
Nitrogen fixation	biological nitrogen fixation by diazotroph bacteria	90
Bioremediation	maintaining biodiversity in soils and water is imperative to the continued and improved effectiveness of bioremediation and biotreatment	121
Biotechnology	nearly half of the current economic benefit of biotechnology related to agriculture involving nitrogen fixing bacteria, pharmaceutical industry	6
Biocontrol	soil provides microhabitats for natural enemies of pests, sol biota (e.g. mycorrhiza) contribute to host plant resistance and plant pathogen control	160
Pollination	many pollinators may have edaphic phase in their life-cycle	200
Wild food	e.g. mushrooms, earthworms, small arthropods etc	180
TOTAL		**1542**

of the soil community (Bardgett et al., 1997; Beare et al., 1992; de Ruiter et al., 1994). However, at prescribed rates/levels, responses of individual soil organisms to individual practices are often contradictory, inconclusive or idiosyncratic, while we have little understanding of how different crop types may affect soil organisms (Wardle et al., 1999). The largest knowledge gaps, however, are the impacts on soil biodiversity as an entity, as opposed to individual taxonomic or functional groups, and the impacts of cropping or farming systems as opposed to more easily studied individual farming practices. Research has also often focussed on the functional role of one or two individual species or groups.

There are unresolved issues of scaling up from pot or plot to a field or landscape level. How do we extrapolate from field, or even laboratory, experiments to fields being cultivated to meet the current demands of agriculture where there are local and regional variations in soils, soil biodiversity and land use? Results from experiments must be placed in the context of actual farming practices through an understanding of what farming practices are carried out, for how long, on what soils and, importantly, under what market/policy conditions. For example, what are the implications for soil biodiversity in areas where land is being taken in and/or out of use due to changes in subsidies? There is a pressing need to validate hypotheses tested in experiments before results can be used for policy or guidance development.

All agricultural practices have serious implications for conservation status species, whether they live in the soil or are reliant upon soil organisms. Recent research indicates that declines in farmland birds may correspond to declines in the availability of soil invertebrates and weed seeds. We know that converting semi-natural land into arable or more-intensive managed grassland will reduce soil biodiversity but we know much less about what is happening as marginal agricultural land is taken out of agricultural use. This raises the more general question of the economical value of conservation versus production in land use management. Future research needs to balance the contribution of soil organisms in maintaining soil functions for production and environmental protection with considerations of habitat conservation or

heritage interests. We need to resolve these difficult issues in order to clarify where and how we should manage soil biodiversity.

Other land use practices, introduction of exotics, pollution and global climate change

The loss of agricultural land to other land uses such housing and infrastructure development will have obvious, but little quantified, impacts on soil biodiversity. If managed appropriately, then biodiversity impacts can be successfully limited in areas not sealed by development but options are expensive and often untested (Marren, 2002). Afforestation can both reduce and increase biodiversity; in the British context, native woodland is likely to increase biodiversity while coniferous plantation often reduces it. The loss or drainage of organic soils has significant ecological and conservation implications, with the loss of rare soil species and preserved remains of insect and plant in anaerobic condition, which inform on past climates or land use. Consequences for soil biodiversity with change in land use must be considered against the biodiversity value of the land being developed or planted e.g. semi-natural grasslands may contain species that will not survive in woodlands, while restoration of Scots Pine may be a conservation improvement.

Pollution at high concentrations or levels, will, in general, reduce soil biodiversity and have implications for maintaining soil functions (Spurgeon and Hopkin, 1999) but at lower levels, impacts are more subtle and results are often contradictory (Wardle, 2002). Exotic species may also reduce soil biodiversity and/or functions but it is often the case that introductions of alien soil organisms are only noticed because they become pests or pathogens e.g. termites in Devon (Verkerk and Bravery, 2001) or the New Zealand flatworm in Northern Ireland (Boag et al., 1997). We have little knowledge of less conspicuous invasions below ground and their potential impacts on soil health and quality, especially in relation to global climate change.

Global climate change is a further uncertainty though there will undoubtedly be soil biodiversity losses and gains as changing temperatures, rainfall, carbon dioxide and trace gas levels and sea-levels alter the behaviour of soil organisms (Wardle, 2002). There are also uncertainties about whether climate change will result in increased losses of carbon from soils due or greater carbon sequestration (Cao and Woodward, 1998) due, in part, to changes in the decomposition of plant materials by soil organisms (Seastedt, 2000).

5. Measurement, monitoring and indicators of soil biodiversity

To help the development, implementation and assessment of soil policy, a monitoring framework will need to be identified with clear targets and means of achievement. This will require quantitative and qualitative indicators to monitor the status and measure the dynamics of the soil biodiversity using a range of direct, indirect and surrogate tools.

Measurement

In theory, most aspects of soil biodiversity can be measured but in practice there are many practical, technical and economic limitations. As discussed above, a full inventory of the biodiversity of any given soil, or comprehensive monitoring over time, would require significant capital and staffing investments and a concerted, multi-disciplinary approach. Measurement of soil biodiversity will almost certainly require a combination of both direct and indirect techniques. Therefore, as well as direct taxonomic, genetic or functional measurements of soil biodiversity, we will also need to employ indirect measurements that provide information on soil biodiversity behaviour as well as status through taxa inventories, process measures and environmental surrogates.

One option, for *direct measurement*, is to target and monitor key functional species or groups that are known to be important for the maintenance of individual soil functions. This can be justified since there is

increasing scientific evidence that soil functions are mediated by dominant organisms (Bardgett, 2002; Wardle, 2002) A weakness is that a targeted approach ignores the importance of biodiversity *per se* in enabling soils to cope with environmental perturbation. It is a widely held belief that soil biodiversity is essential to the resilience of the soil ecosystem by making it possible for soils to respond and recover from environmental stresses. Although this hypothesis remains to be fully explored, there is no doubt that biodiversity *per se* has a fundamental role in stabilising soil functions.

Indirect measurements include biochemical measures or processes which can assess an end product or activity of a given functional group e.g. enzyme activity, nitrification rate or potential, trace gas soil flux measurements, substrate utilisation patterns or organisms that luminescence with stress. The biochemical properties of soil organisms are also being increasingly used to measure biodiversity, especially microbial, though the significance of compounds derived from soil organisms has been recognised for many centuries (Franco and McClure, 1998). For example, in much the same way that species richness is used to assess diversity, the relative abundance of compounds specific to bacteria and fungi can be used to assess community structure e.g. phospholipids fatty acids (PLFAs) (Frostegard and Baath, 1996) and fungal-specific ergosterol (Stahl and Parkin, 1996). This is an active research field which will yield 'biomarkers' for other groups.

Indirect *environmental surrogates* should also be explored. Soil chemical or physical properties could be used to determine the 'suitability' of the soil for a given organism or community, while the presence of certain plant species indicates the presence of specific soil fungi. Behaviour characteristics of individual organisms could indicate activity (e.g. presence/absence of earthworm casts, (Davidson et al., 2002). But the interpretation of any of these measures is highly dependent upon a much better understanding of what regulates the distribution and activity of individual organisms and communities and how these influence soil functions within specific habitats.

The lack of accredited standardised methods for soil biodiversity assessments is a severe handicap to accurate and comparable measurements or monitoring, whether these are taxonomic, genetic, ecological or functional. The methods used to date have differed in sample dimensions, storage of soils, extraction and identification processes and units of presentation. Timing of sampling also needs to be targeted to the specific period of activities of soil organisms. There are a few British Standards Soil Quality Methods for soil biological methods (e.g. earthworm sampling method, microbial biomass). It would seem sensible to extend these to include further, perhaps more relevant, standardised methods for measuring soil biodiversity. These should also address the issues of soil depth, sample size/volume or number and spatial and temporal sampling patterns. The shortfalls in our taxonomic uncertainties must also be resolved with investment in underpinning research and the development of non-expert tools for identification.

There has been a global decline in taxonomic expertise and research funding so, paradoxically, while biodiversity issues now demand urgent attention, there is an extreme lack of fundamental skills to assess it (André et al., 2002). This is a pressing problem when one considers the probable number of species yet to be described; 70% of soil fungi (Hawksworth, 1997), 95% mites (Walter and Proctor, 1999), 97% of nematodes (Hawksworth and Mound, 1991) and ca. 99% of bacteria (Hawksworth, 1991) are not yet identified. For microbial diversity groups, taxonomic diversity is unlikely ever to be a suitable approach to measuring diversity since few species are culturable.

Monitoring

Monitoring requires that a system is established to assess status or changes in soil biodiversity for a *particular purpose*, in a *specified area* and over a *recognised time period*. There will be limited resources for the monitoring of all soil biodiversity in agricultural land. It is therefore important that the purposes of a monitoring scheme are identified before the scheme is developed. Sampling strategies can then be targeted according to national, regional or local priorities. Although, the development of monitoring

schemes is hindered by a fundamental lack of knowledge on the distribution of soil biodiversity, recent national-scale programmes have shown that monitoring of soil biodiversity is feasible. Significant advances with genetic and biochemical technologies, as well as data handling and processes, should aid any future assessments of soil biodiversity.

If the purpose of a monitoring scheme is to assess a change in status then there will also be the requirement for adequate standards i.e. benchmarks or ranges of values, from which to determine the significance of any changes in soil biodiversity. As outlined below, the current knowledge base is almost certainly too weak to finalise such standards at present. Important insights may be gained by reflecting upon the development of the RIVPACS monitoring system which assesses water quality using invertebrate presence/absence (Clarke et al., 2003; Weeks, 1997). This system is used globally and it is based upon a detailed understanding of the ecological preferences, seasonal activities and stress sensitivities of aquatic invertebrates. This knowledge, which continues to be built upon today, was developed over more than a decade of extensive research co-ordinated by a single group of researchers.

We are remarkably ignorant about which soil types host the highest biodiversity, how endemic soil organisms are or their habitat preferences. Although there is a wealth of published data about soil organisms, much of the data are incompatible since they have not used comparable methods (Weeks, 1997). There have been a few successful biogeographical studies of soil organisms that have identified habitat, climate or soil preferences that could be used to predict likely occurrence; reviewed by Black (1997) and Petersen and Luxton (1982). These, however, have mainly been in semi-natural habitats with single taxonomic species or groups; there is little information for functional groups. The Royal Commission on Environmental Pollution (1996) has highlighted that this knowledge gap must be addressed and recommended that assessments of soil biological properties must also obtain accompanying environmental data.

In recent years, regional and national initiatives have been established to gather some of the essential environmental and biodiversity data for the development of soil quality standards. These have not been comprehensive assessments of soil biodiversity but they will provide invaluable insights into the biogeography of soil biodiversity at regional and national scales. The UK carried out the first national assessment of soil biodiversity in 1998 and 1999 to explore large-scale relationships between soil biodiversity and the wider environment e.g. how does soil biodiversity differ amongst the major land uses from intensive arable to semi-natural habitats (Black et al., 2003 forthcoming)?

This highlights a slightly more fundamental point. Is it sensible to invest in assessments of soil biodiversity without collecting soil and other environmental monitoring data? There are many local, regional, national and some international monitoring schemes in place or being developed for purposes including monitoring of land use, vegetation and habitat cover or soil protection. Linking with these would not only reduce costs but would also go a long way to providing the essential supporting environmental data with which to interpret soil biodiversity data. For example the UK national survey of soil biodiversity was part of a much large survey of the British Countryside (Haines-Young et al., 2000) which makes detailed assessments of vegetation, land use and landscapes and is carried out every 6 years or so. There are on-going discussions to implement a similar scheme across Europe (Bunce, pers. comm.). In parallel, the EU Thematic Programme on Soil Protection is aiming to establish a Europe-wide soil monitoring scheme by 2006. It would be timely to develop a co-ordinated approach to monitoring of soils and agricultural land in general. At more local or regional scales, there are various conservation and agricultural schemes that could relatively easily incorporate assessments of soil biodiversity, whether functional groups or individual species of conservation importance.

Indicators of soil biodiversity

Any indicator must be "fit for purpose" and therefore able to detect, and resolve, changes brought about by management, land use, pollution or climate change in a known soil at a given location against the backdrop of past land use history, pollution and ecological succession. This is a tall order but already partly achieved. Taxonomic, genetic and functional measures have already been deployed to provide assessments of the status of, and change in, soil biodiversity in agricultural land. Although there are large knowledge gaps, we know of agricultural practices, land use changes and pollutants that can have significant impacts on soil organisms that may, as a consequence, reduce the efficiency of soil functioning and productivity.

There is still, however, much research required to develop reliable indicators for an assessment of the health of soil biodiversity and maintenance of soil multi-functionality. In working towards these goals, it may be useful, in the short-term, to start with the measurement of one or two groups involved in the maintenance of each soil function identified in Figure 1. Such information would go a long way to addressing some of the shortfall in our knowledge of what soil biodiversity is present where, while research continues to develop reliable relationships between soil biodiversity and ecosystem function, what biodiversity is needed for soil resilience and a predictive understanding of what regulates soil biodiversity distribution.

6. Conclusion and recommendations

This paper has highlighted the importance of addressing soil biodiversity in the context of the multi-functionality of soils. Interest has, historically, been focussed on the role of soil biodiversity in maintaining production-related soil functions but it is time for a shift in priorities to take a wider view of the importance of soil biodiversity and balance the various requirements of crop production, environmental protection, heritage interests and nature conservation in the management of agricultural land. This shift in priorities also needs to be addressed with a much closer integration of current and future policy developments. There are clearly gaps in our knowledge of what soil biodiversity is, how we can measure it and what effects agriculture has on soil biodiversity. There is, however, sufficient knowledge to start the process of monitoring indicators of soil biodiversity in agricultural land. Although we have not thought long and hard enough about the why, where and how soil biodiversity should be monitored, it is better to start monitoring now and adapt new techniques as knowledge builds rather than simply say we do not know enough about how to monitor since there are measures of soil biodiversity that can be deployed to provide an assessment of the status of soil biodiversity in agricultural areas.

Any consideration of soil biodiversity in maintaining soil multi-funtionality, including the contribution to nature conservation and heritage interest, must address the importance of soil biodiversity *per se* in conferring soils with resilience to environmental perturbation. The following key considerations are as follows.

- There will be **benefits to optimising soil biodiversity** in all agricultural areas for supporting crop production, environmental protection, nature conservation and heritage interest but we need to improve our knowledge of the impacts of farming practices on soil biodiversity and the significance of soil biodiversity in maintaining each soil function at the field, farm and landscape scale.
- The development of appropriate sampling or monitoring schemes requires **standardised methods** for sampling and characterisation of soil biodiversity.
- We also require **benchmarks or ranges as standards for soil biodiversity in a given soil**, under a particular land use, at a particular time and in response to environmental stresses, if we are to be able to interpret and predict the significance of any changes in soil biodiversity.

- These require a much better predictive understanding of what **regulates spatial and temporal variability** in soil biodiversity. This information can also be used to: i) highlight areas of specific interest to individual soil functions (e.g. identify areas of highest nature conservation or heritage interest); and ii) support the development of reliable direct, indirect and surrogate indicators of soil biodiversity.
- There needs to be greater recognition of the intimate **relationships between soil biodiversity and the above-ground environment** since they are, together, key drivers in community and ecosystem-level attributes (Wardle, 2002) and in maintaining multiple soil functions.
- This needs to be reflected not just in the monitoring of soil biodiversity but also in the **wider context of environmental quality and associated policy,** guidance and initiatives that are in place or being developed to assess, monitor or manage our countryside.
- Greater consideration should be paid to **integrated environmental monitoring** as this would have significant scientific benefits as well as being more economic.

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