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Soil biodiversity, biological indicators and soil ecosystem services—an overview of European approaches

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Soil biota are essential for many soil processes and functions, yet there are increasing pressures on soil biodiversity and soil degradation remains a pertinent issue. The sustainable management of soils requires soil monitoring, including biological indicators, to be able to relate land use and management to soil functioning and ecosystem services. Since the 1990s, biological soil parameters have been assessed in an increasing number of field trials and monitoring programmes across Europe. The development and effective use of meaningful and widely applicable bio-indicators, however, continue to be challenging tasks. This paper aims to provide an overview of current knowledge on the characterization and assessment of soil biodiversity. Examples of biological soil indicators and monitoring approaches are presented. Furthermore the value of databases for developing a better understanding of the relationship between soil management, soil functions and ecosystem services is discussed. We conclude that integration of monitoring approaches and data sets offers good opportunities for advancing ecological theory as well as application of such knowledge by land managers and other decision makers.

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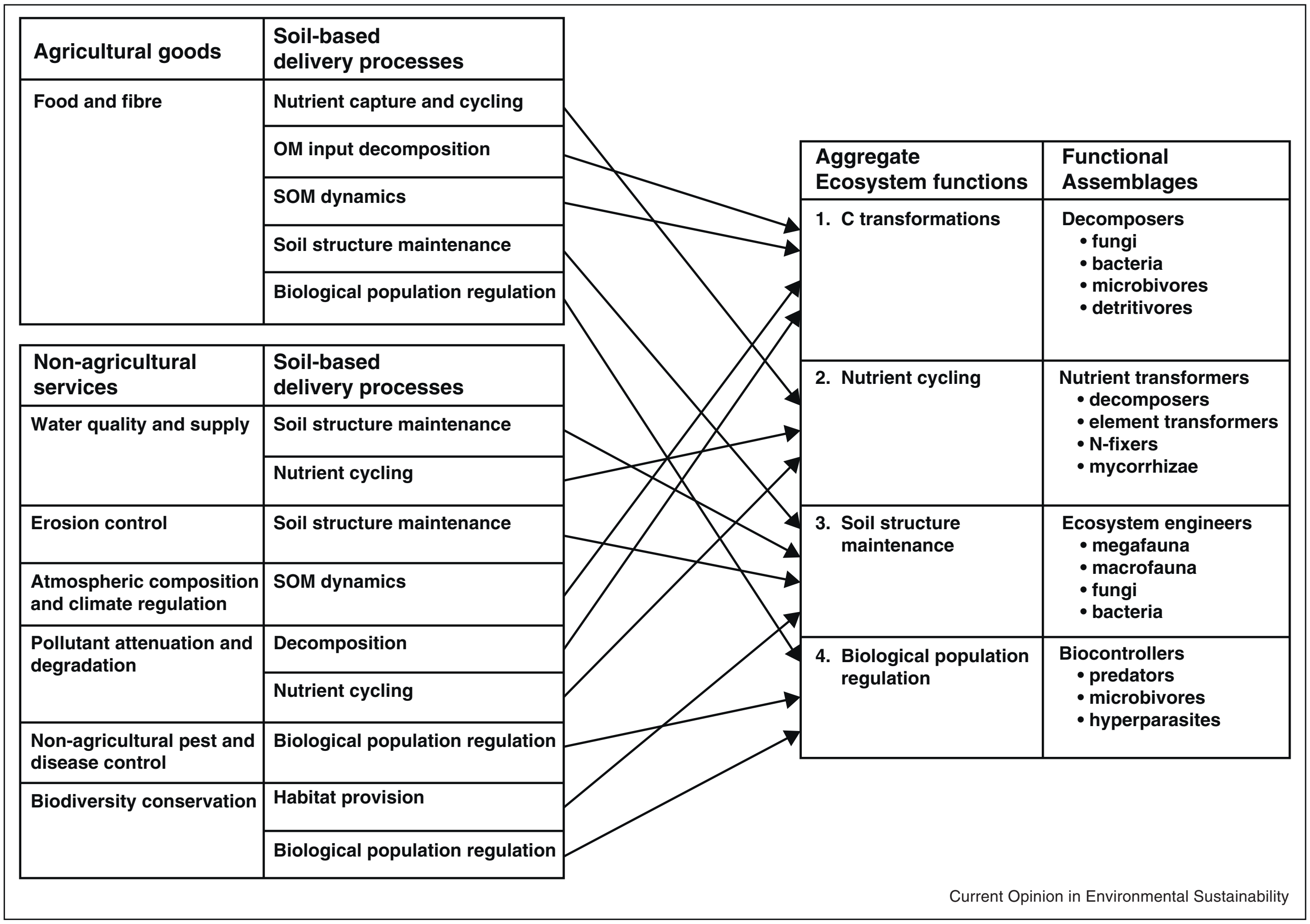
Introduction

The Convention on Biological Diversity (CBD; URL: http://www.cbd.int/) and the Millennium Ecosystem Assessment [1] have underlined the relationships between biodiversity loss and a decline in the capacity of ecosystems to support human well-being. Being the legally binding international agreement for the conservation and sustainable use of biological diversity, the CBD has stimulated a demand for indicators suited to monitor trends in the state of biodiversity and natural resources [2]. Soils are a natural resource that must be secured for future generations, as rates of soil formation or recovery are often too slow to cope with current rates of soil loss and degradation. Soils also host an enormous biodiversity, in terms of abundance, numbers of species and functions of organisms. The organisms and their interactions are fundamental to many soil processes and functions, including organic matter decomposition, nutrient cycling, soil structure formation, pest regulation and bioremediation of contaminants. In aggregated form these processes and functions relate to ecosystem services that are essential to humans, such as food production, climate regulation and provision of clean water [3,4•,5•] (Figure 1). Although biodiversity that is 'hidden' belowground has long received little attention, this attitude has started to change. Loss of soil biodiversity caused by the expansion, intensification and mechanization of agriculture has been identified as a major problem across Europe. Related pressures include soil erosion, organic matter decline, compaction, contamination, salinization and climate change [6,7].

Different EU policies, e.g. on water quality, pesticide use, waste management or nature conservation, contribute in some way to soil protection. However, regulations are very specific to the threat of concern and do not consider soil biodiversity as such, nor the wider context of soil quality. The adoption of the EU Soil Thematic Strategy in 2006 was a first step towards a coordinated approach to ensure the protection of soils in Europe [8]. Further integration of soil biodiversity conservation into EU legislation, however, is hampered because the level of knowledge has been considered insufficient to recommend policy [4•]. A better understanding of soil organisms, their distributions, interactions and functions in soils and how they translate into ecosystem services is therefore essential to guide action [7]. A necessary first step is a better knowledge on spatial and temporal distribution of soil biodiversity and how this relates to soil

Figure 1



The relationships between functional assemblages of soil organisms, aggregate ecosystem functions and ecosystem services. Ecosystem services represent aggregations of functional outputs of biological processes that are of direct benefit to the society.
Kibblewhite *et al.*, 2008 [3].

management and habitat quality. A crucial second step is to better communicate the implications for ecosystem services, such that soil biodiversity conservation is taken into account in decision making. In the face of those needs, monitoring of biological soil parameters has been initiated in several countries and data are becoming increasingly available. This paper combines a literature review on soil biodiversity and biological soil indicators, with examples of monitoring programmes across Europe. We aim to address the following objectives:

1. To provide a brief overview of current knowledge and developments related to soil biodiversity characterization.
2. To discuss the development of biological soil indicators and monitoring systems, based on European experiences.
3. To discuss needs and opportunities for data integration and stakeholder involvement, to advance the sustainable management of soil biodiversity and soil ecosystem services.

Soil biodiversity

Soil biota comprise the organisms that spend all or part of their life cycle belowground. Soil organisms range from the myriad of invisible microbes, such as bacteria, fungi and protozoa, to the macro-fauna, for example earthworms, ants and termites (http://www.fao.org/ag/AGL/agll/soilbiod/). Larger animals such as moles and voles are considered soil fauna, but rarely included in soil biodiversity assessments because of their small numbers. And although plants belong to the soil biota their role is beyond the scope of this review. It is however recognized that plant root exudates and plant residues form the major source of carbon and energy for heterotrophic soil biota. For an illustrated overview of different soil organisms, their functions and important threats we refer to the European Atlas of Soil Biodiversity [9].

One of the most complete definitions of soil biodiversity is derived from the CBD definition of biodiversity: Soil biodiversity comprises 'the variation in soil life, from genes to communities, and the ecological complexes of which they are part, that is from soil microhabitats to landscapes' [4•]. This variation is generally described in terms of three interrelated attributes of biodiversity: composition, structure and function [10]. We then consider soil biodiversity as the quantity, variety and structure of all forms of life in soils, as well as related functions [11]. Soil organisms have traditionally been classified according to their taxonomic position, throphic interactions and body size class [12•,13]. Taxonomic identification can be problematic because a vast amount of soil organisms has not yet been identified, especially in the microbial community. Moreover, technical and labor constraints may apply as a result of the huge diversity of certain groups, such as microorganisms, nematodes and mites. Relations between soil biodiversity and ecosystem functions, however, tend to depend more on structural and functional diversity than on species richness or taxonomic parameters *per se* [14,15,44••]. This phenomenon is partly explained by the high level of functional redundancy within species-rich soil communities [15]. As an exception, so-called 'keystone species' have been identified for their unique role in specialized soil processes [16]. Examples are fungal species that are capable of decomposing recalcitrant organic compounds [17], symbiotic micro organisms involved in atmospheric N fixation or P uptake by plants [18] or bioturbators like earthworm species (Box 1).

Considering the complex of biotic interactions in the soil, in conjunction with the abiotic environment, it is essential to determine soil processes and functions using a comprehensive as possible characterization of soil biodiversity. Like ecosystems in general, soils are hierarchical systems with internal processes operating at each level of organization and interacting across levels. Hierarchy theory suggests that higher levels facilitate or constrain the behavior of lower levels. An extensive discussion on the hierarchical relations between habitat characteristics, soil organisms and implications for ecosystem functions is provided by Lavelle [19••]. The microbial world represents the major part of the soil community in terms of total biomass and is largely responsible for organic matter decomposition, nutrient transformations and degradation of toxic compounds (Box 3). The soil micro and mesofauna regulate the activities of the microbial community, mainly through predation, thereby releasing nutrients [20]. The soil macrofauna, in turn, can possess a strong effect on the distribution and activities of those smaller groups of soil organisms. For instance, the soil macrofauna comprises ecological groups that have the ability to dig in the soil profile, create burrows, nests and galleries while mixing, ingesting and/or excreting organo-mineral soil material. As they can modify the soil habitat in terms of physical structure and availability of resources to other soil organisms, those soil animals have been characterized as 'ecosystem engineers' [19••] (Box 1). Soil organisms with larger body sizes, including the ecosystem engineers, have frequently been found to be more sensitive to anthropogenic disturbances than smaller organisms [21–23]. Hierarchical theory suggests that the disappearance of soil ecosystem engineers can have strong impacts at lower levels of organization, including biological regulation by smaller soil fauna.

Box 1 Examples from different broad functional groups that have frequently been used as biological soil indicators: Earthworms (photograph: R.G. de Goede.

Earthworms: These invertebrates belong to the functional group of ecosystem engineers [3,4•]. By producing soil structures such as burrows and excrements they strongly modify the habitat for other soil organisms, including plant roots. Earthworms can play a particularly large role in litter transformation and incorporation as well as soil structure formation [22]. Earthworms are used as bioindicators in contaminated soils because of their sensitivity to soil pollutants (e.g. heavy metals and organic contaminants) [28••]. They also respond strongly to agricultural practices (e.g. tillage, crop rotations, pesticides application, organic matter inputs) [22,28••,32,37,44••,53]. Species (e.g. approximately 100 in France) are classified into three ecological groups (anecics, endogeics and epigeics) that provide different functions and show different sensitivity to soil disturbances or chemical contamination [28••,53,32,54]. Epigeic earthworms live at the soil surface and feed on plant litter. Anecics create permanent vertical or subvertical burrows and feed at the soil surface. Those two groups are negatively affected by soil tillage. Endogeics feed on mineral soil enriched in soil organic matter, and therefore benefit from organic matter incorporation either through tillage or the activities of epigeics or anecic earthworms [55]. Anecic and endogeic earthworms play a key role in the formation and maintenance of soil structure, enhance water infiltration and remediation of soil pollutants and reduce soil erosion [30,37]. Total abundance or biomass of earthworms are commonly used as indicators (Table 2). Nevertheless the functional group diversity may be a better proxy for habitat quality and soil functions [11,28••,53]. An important advantage of earthworms as indicators is that taxonomic identification is relatively easy. Earthworms can be observed with the naked eye and are commonly known, and are therefore suitable for communication purposes with stakeholders. However, their spatial variability in the field can be high, which makes representative sampling a laborious task.

Accordingly, Kibblewhite *et al.* [3] and Turbé *et al.* [4•] classified soil organisms into functional assemblages that act at different spatio-temporal scales, and are associated with different functional domains [19••] (Figure 1). A distinction is made between:

1. 'Decomposers' and 'nutrient transformers' [3] (grouped as 'chemical engineers' by Turbé *et al.* [4•]), that is soil microorganisms (Box 3);
2. 'Biocontrollers' [3] (or 'biological regulators' [4•]), that is small invertebrates, such as nematodes (Box 2), springtails and mites, which act as herbivores or predate on other invertebrates or micro-organisms;
3. 'Ecosystem engineers', that is soil macrofauna such as termites, earthworms (Box 1), or ants.

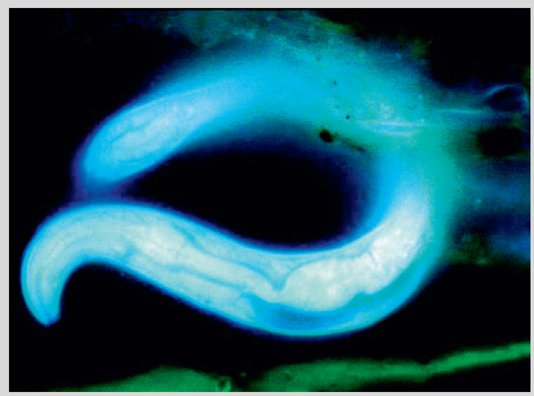
It should be noted that this broad classification does provide a generalization as multiple functions can be performed by different functional assemblages and overlap in functions occurs across all levels (e.g. microbes can contribute to soil aggregate formation [24]). Furthermore, the functional assemblages do not operate in isolation. This implies that an intervention that affects one function will inevitably alter other functions [3,19••] (Figure 1).

Biological soil indicators

The concept of indicators is widely used in environmental monitoring, mainly in relation to anthropogenic disturbances. Indicators are measurable surrogates for environmental end points that are in themselves too complex to assess. Such indicators, either biological, physical or chemical, give information about the state and trends as well as the seriousness of the situation, and should support environmental decision making [2,4•,10]. The soil community provides many potentially interesting indicators for environmental monitoring in response to a range of stresses or disturbances [3,25–27,28••]. According to Gerhardt [29], we define biological indicators as (characteristics of) organisms whose response, in terms of presence/absence, abundance, activity, morphology, physiology or behavior, gives information on the condition of a habitat or ecosystem. They are useful in situations where the environmental end point is difficult to measure directly, or where the environmental stressor is easy to measure but difficult to interpret in terms of ecological significance [29]. Biological soil indicators have been applied in environmental risk assessment and monitoring of responses to land use (e.g. [30,31]), agricultural management (e.g. [28••,30,31,32,33•]) and soil contamination (e.g. [26,28••]). The parameters measured include different soil organisms selected for their sensitivity to soil management or environmental pressures, and/or for their relevance for soil functions (such as organic matter decomposition, N mineralization or soil structure formation) or for soil quality or soil health in general [3,25].

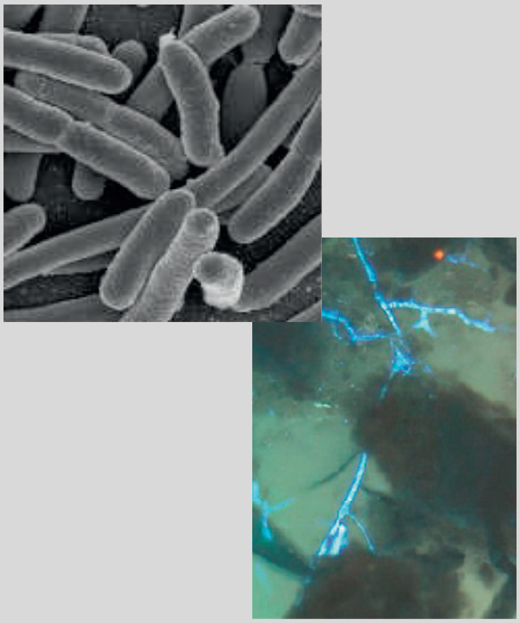
The hierarchical organization of the soil community and ecosystems suggest that soil biodiversity be monitored at multiple levels of organization (organism, population, community, ecosystem) and at multiple spatial scales (e.g. from plot to farm to landscape) [10,19]. Different organisms from the three functional groups or hierarchical levels described in the previous section have frequently been used as biological soil indicators (see Boxes 1–3 for examples). Other organism groups that have commonly been measured in monitoring programmes are microarthropods, for example collembola (springtails) and acari (mites) [31,34] and other mesofauna, for example enchytraeids (potworms) [31] (Table 2). In addition to the organisms themselves, soil structures created by soil biota, especially biogenic soil aggregates formed by eco-

Box 2 Examples from different broad functional groups that have frequently been used as biological soil indicators: Nematodes. The picture represents a nematode curling through the soil pore space (photograph: K. Ritz).



Nematodes are biological regulators and represent one of the most numerous and speciose groups in soils. Soil nematodes are trophically diverse and include economically important plant parasites. They show a high and diverse sensitivity to pollutants and because of their trophic diversity nematode assemblages do not only reflect their own fate, but also the condition of the bacterial, fungal and protozoan communities. These characteristics make them potentially interesting bio-indicators for soil health and soil disturbances [56]. Although nematodes can easily be sampled and extracted from soil, their identification is time consuming and requires expert knowledge. Previous studies demonstrate that the small subunit ribosomal DNA (SSU rDNA) gene harbors enough phylogenetic signal to distinguish between nematode families, genera and often species [57]. A robust and affordable quantitative PCR-based nematode detection tool for agricultural and scientific purposes, and comparable tools for the assessment of the ecological condition of soils, are being developed [58]. Briefly this works as follows: after nematodes extraction from soil the nematode community is lysed and after DNA purification the lysate is used to quantitatively characterize nematode assemblages. The difference in DNA contents of various life stages is limited and different distributions of the life stages barely interfere with quantitative community analyses. Verification in recent field studies suggests that Q-PCR based analysis of nematode assemblages is a reliable alternative for microscopic analysis. The availability of an affordable and user-friendly tool might facilitate and stimulate the use of this ecological informative group of soil inhabitants.

Box 3 Examples from different broad functional groups that have frequently been used as biological soil indicators: Microorganisms. The picture on the left side represents bacterial cells. The picture on the right shows fungal hyphae in soil (blue stained) as observed in a soil thin section (photograph: K. Ritz).



Microorganisms: Chemical engineers decompose organic matter and transform nutrients. Soil microorganisms dominate this functional group [3,4•]. They indicate environmental changes by modifications in (i) quantity/biomass, (ii) structure and/or (iii) activity [36,38]. Until now the impact of microbial biomass versus community structure on ecosystem processes and function is uncertain [38,59,60,62]. Levels of functional redundancy among microorganisms depend largely on function and environment considered [15,16,61]. Disconnections between factors driving microbial community structure and those driving its function further complicate indicator selection [62]. To comprehensively assess soil microbial diversity it is recommended to include indicators of each parameter group: quantity, structure and activity [11]. However, the number of studies and monitoring networks using indicators of all three groups is limited (Table 2). Different methods [41] are used to describe and quantify microbial diversity at the genotype, phenotype or metabolic level, and thousands of microbial species can occur in just a few grams of soil. To achieve progress in the area of microbial indicators it is important to work on the definition and identification of microbial functional groups and their response to environmental changes [61]. Beside molecular approaches new conceptual models and experimentation are needed to link microbial diversity to ecosystem functions. The development of concepts describing the relationship between the stoichiometry of soil microorganisms (e.g. the C, N and P status) and nutrient cycling is promising [39].

system engineers, have been identified, quantified and proposed as indicators [22,35].

Criteria for the selection of indicators that are suitable for monitoring purposes have been summarized by Ritz *et al.* [36] and Turbé *et al.* [4•] (Table 1). No single indicator will comply with all these criteria. In practice, focus is on the development of sets of complementary indicators, including both biotic and abiotic parameters. However, despite the fact that a multitude of indicators estimating some aspect of soil biodiversity exists, no reference set of standardized indicators is available. This issue, as well as promising avenues for progress on indicator development and application, are discussed in the remainder of this paper.

Table 1

Seven criteria for the selection of biological soil indicators

1.	Meaningful – Indicators must relate to important ecological functions
2.	Standardized – Parameters should be standardized to ensure comparability of data
3.	Measurable and cost efficient – Parameters should be assessable not only by experts, in order to ensure that the indicators will be used in practice and can be routinely collected
4.	Policy relevance – Indicators should be sensitive to changes at policy-relevant spatio-temporal scales, and allow for comparisons with a baseline situation to capture progress towards policy targets
5.	Spatio-temporal coverage – Indicators should be validated in a wide range of conditions and should be amenable to aggregation or disaggregation at different spatial scales, from ecosystem to national and international levels
6.	Understandability – Indicators should be simple and easily understood
7.	Accuracy – The value of the indicators should be precise and robust reflecting the changes they monitor

Source: Turbé *et al.* [4]

Examples of European approaches

Since the late 1980s biological parameters have been assessed in an increasing number of studies, ranging from long-term agricultural field trials [20,21,32,37] to regional or national monitoring programmes (e.g. [30,31,36,38]). Currently there are over 15 European countries that have collected soil biological parameters as part of a large scale monitoring programme [4•]. Some examples are provided in Table 2. Ideally this would provide the foundation for integrated assessments of soil biodiversity across a wide range of situations in Europe. However, the information has been collected for different objectives and using a variety of methods, and few indicators have consistently been used in national-scale monitoring [31,36]. Recent attempts to develop standardized indicator sets that comply with the criteria listed in Table 1 are briefly reviewed here.

Frameworks for selecting biological indicators for national soil monitoring have been devised in, for example, France [28••], the Netherlands [31] and the UK [36]. These frameworks adopted a similar approach; a wide range of candidate indicators were assembled and tested for

Table 2

Examples of European national or regional soil biodiversity monitoring networks, their geographical coverage and types of indicators measured

Country	Programme	Geographical coverage	Starting year	Indicators	
				Soil fauna	Microbial parameters
Netherlands	DSQN-BISQ (Dutch Soil Quality Network – Biological Indicator of Soil Quality)	Nationwide, approx. 400 sites	1997	Micro-arthropods (collembola and mites), earthworms, enchythraeids and nematodes	*Quantity*: Bacterial and fungal biomass *Activity*: Potential C and N mineralization, anaerobic mineralization, thymidine and leucine incorporation rates *Structure*: Functional bacterial diversity (Biolog-ECO-plates), bacterial structural diversity (DGGE)
France	RMQS-BioDiv (Reseau de Mesures de la Quality des Sols de France)	Nationwide, 109 sites	2006	Earthworms, micro-arthropods (collembola and mites), nematodes, total macrofauna	*Structure*: B-ARISA, F-ARISA
France	BioIndicator Programme	Pilot, 47 sites differing in land use, agricultural practices or contamination origin	2009	Nematodes, micro-arthropods (collembola and mites), earthworms, total macrofauna, bioaccumulation in snails, biomarkers in earthworms (methalotionein)	*Activity*: Enzymatic activities *Structure*: B-ARISA, F-ARISA, PLFA, TTGE
UK	Countryside Survey- SQID (Scoping biological indicators of soil quality)	Nationwide, 256 sites	2000	Micro-arthropods (collembola and mites), nematodes	*Structure*: Bacterial 16S tRFLP, fungal ITS tRFLP, archaea amoA, PLFA, culturable bacteria
Germany	Several programmes organized in regions, data collated in two databases (UBA & EDAPHO-BASE)	Almost nationwide	2000	Earthworms, micro-arthropods (collembola and mites), enchytraeids, myriapods	*Activity*: Basal respiration, substrate-induced respiration
Switzerland	NABO; Nationalen Bodenbeobachtung Schweiz	Almost nationwide, 69 sites	2004		*Quantity*: Microbial biomass (fumigation-extraction), *Activity*: Basal respiration, substrate-induced respiration *Structure*: B-ARISA, F-ARISA, fungal and bacterial TRFLp
Ireland	Cre-Bio Survey	Nationwide, 61 sites	2006	Micro-arthropods (collembola and acari), nematodes, earthworms	

Source: Turbé *et al.* [4•] and unpublished data from the ECOFINDERS project their suitability to be used in systematic soil biodiversity assessment. Selected indicators had to comply with requirements such as (i) pertinence to predefined soil functions, including agricultural production, environmental interactions and habitat support, (ii) applicability to the range of ecosystems under consideration, (iii) ability to discriminate between soil types and (iv) technical, practical and financial criteria [36]. Ritz *et al.* [36] and Rutgers *et al.* [33•] used a systematic approach of stakeholder consultation taking into account a diversity of end-user requirements and priorities. It was concluded, however, that further work is needed to confirm the sensitivity of the indicators, their ability to discriminate between soil-land use combinations and their ecological interpretation [36].

One example of such work is the ongoing (2006–2012) French national BioIndicator programme [28••]. Using homogeneous procedures, 47 biological parameters were assessed in a large number of sites differing in land use, agricultural management, contamination type and pollution levels. Those included microorganisms, fauna and flora at the community level (e.g. abundance, biomass, species and functional composition and ecological traits) as well as the organism level (e.g. gene expression) (Table 2). Their potential to be used as a bioindicator for national scale monitoring was validated based on their sensitivity to different environmental conditions and disturbances, and their accessibility and applicability by experts and non-specialist stakeholders.

In parallel with national initiatives, European research projects have been initiated to promote standardization of biological soil indicators, mainly through Framework Programmes (FP) [4•]. Among those, the FP6 project ENVASSO (Environmental Assessment of Soil Monitoring) was the first attempt to develop a harmonized system for soil biodiversity monitoring across Europe. Standardized indicator sets were defined and organized into different priority levels [11]. 'Level I' indicators included organisms, corresponding with the functional classification of Kibblewhite *et al.* [3], as well as ecological functions:

(1) abundance, biomass and species diversity of earthworms (or enchytraeids if no earthworms are present, for example in soils with low pH);
(2) abundance and species diversity of collembola;
(3) microbial respiration

Depending on local objectives and available resources, the key indicators could be complemented with 'level II' or 'level III' indicators [11]. Procedures and protocols, based on ISO standards [39–41], have been tested in pilot sites in France, Ireland, Portugal and Hungary to assess the efficiency and sensitivity of the indicators across European land-use categories [11].

The abovementioned projects showed that different biological parameters were (more) discriminative to different types of disturbances, for example soil cultivation versus heavily contaminated soils [28••]. Comparison of data between consecutive samplings over multiple years indicated that species composition tends to be relatively stable, but abundances and biomasses were more variable, depending for example on weather conditions and crop rotations [11,28••,31]. In order to interpret the results, there is a strong need to define reference values for certain combinations of land use, soil type and climatic conditions. Such references do not yet exist at a European scale, although density ranges for different groups of organisms have been published for a selection of soil and land use types in the Netherlands [31] and France [42]. Among the objectives of the ongoing FP7 project Ecofinders are the standardization of methodologies for the assessment of biological soil indicators, and characterization of normal operating ranges for soil biodiversity according to climatic zones, soil and land uses types [43]. The increasing availability of ISO standards [39–41] for sampling procedures and analyses is an important step towards homogenization of procedures, but further work is still required [11].

Another important challenge for biological soil indicators is to capture the spatio-temporal scales over which environmental changes occur. Depending on life history traits and dispersal characteristics, certain groups of soil organisms can respond slowly to land use or management changes [32,44••]. Those observations emphasize the need for sampling designs with wide spatiotemporal coverage [3,11,32]. Long-term field experiments remain important to enhance our understanding of biotic responses with time after changes in management or land use occur, as well as the underlying mechanisms [32,37,44••].

Linking biological soil indicators and ecosystem services for decision support

The rationale behind soil monitoring and the use of biological indicators is to assess trends in the state of soil resources as a habitat for soil organisms, as well as their capacity to support human well-being. Monitoring should further provide information to decision makers on what needs to be done to halt or revert negative trends. The decision support function of the indicators therefore implies that they facilitate communication with a variety of end users such as policy makers and land managers. Interpretation of the data in terms of ecosystem services, defined as the beneficial flows arising from natural capital stocks and fulfilling human needs [5•], is a first step. It has been shown that pragmatic choices enable quantification of soil quality through the performance of multiple ecosystem services, based on data derived from monitoring of biotic and abiotic soil properties [31,33•,45,46]. Velasquez *et al.* [46] and Ruiz *et al.* [45] showed how synthetic indicators of soil quality can be developed through the evaluation of different soil ecosystem services. These compound indicators are derived from physical, chemical and biological soil parameters using multivariate analyses. These approaches allow for monitoring of change through time and variation between sites or farms, without relying on expert opinion. Values need to be calibrated and validated with respect to the regional or national context of the study, but the methodology used to derive these indices can be applied everywhere [45,46]. Through a system of reference values for certain soil and land use types performances can be compared on a relative scale [31,33•].

Stakeholder involvement and weighting of trade-offs between multiple ecosystem services is central to the identification and prioritization of ecosystem services by different end users [33•,47]. The abovementioned approaches [31,33•,45,46] are examples of communication tools that can be applied in awareness raising and multi-stakeholder processes and have already be implemented in practical situations [28••,33•]. When spatially presented, derived models can demonstrate that different options in land-use planning and management result in highly different impacts on soil biodiversity, including differences in functional attributes [12•,48]. For proper quantification of ecosystem services indicators should be fitted to so called 'utility' functions which transform the specific units of the indicator to a uniform scale for ecosystem service performance [49]. This is not straightforward because ecosystem services act on different spatial and temporal scales. For a detailed overview of current thinking on, and approaches for, the classification and quantification of soil ecosystem services we refer to Dominati *et al.* [5•].

Finally, until now, interpretation of biological soil indicators in terms of ecosystem services has largely been based on expert judgements [33•,36]. A more robust and quantitative approach relies on empirical testing and development of models. Datasets derived from soil biodiversity monitoring provide potentially important sources of information. One promising avenue for linking anthropogenic disturbances, soil biodiversity and ecosystem services is based on ecological traits, that is the morphological, physiological, behavioral or life-history attributes of organisms. Identifying traits that determine the response of soil organisms to (changing) environmental conditions, and/or can be linked to effects on ecosystem functions has several advantages. Those include a better mechanistic understanding of the relationships and possible generalizations across eco-regions, independent of taxonomy [28••,50,51]. Information on trait values of soil organisms being accumulated in databases can be connected with the occurrence of a species as an indicator [28••]. For example, the body size of organisms strongly determines their spatial aggregation patterns and dispersal distances, as well as their lifetimes and sensitivity to habitat disturbances with consequences for multiple, interconnected soil functions [21,23]. Mulder *et al.* [12•] showed how mining of databases of abiotic and biotic soil variables can be used to explore general relationships between habitat characteristics, the (trait) structure of the soil community and ecosystem functioning. Ecological concepts such as allometry, that is size-abundance relationships amongst organisms in the soil community, and stoichiometry, that is the biotic relationships of plants and soil organisms in terms of chemical compositions (e.g. nutrient-to-carbon ratios) were explored. Such ecological concepts provide opportunities to develop mechanistic models of invertebrate responses to environmental changes. Detritus-based food web modeling has already been used successfully for quantification of nutrient and carbon flows based on soil biodiversity assessments [20,52]. A next step is to develop these models for predicting multiple functions and services [3,50], provided that hierarchical organization of the soil community into functional assemblages and interconnectedness of soil ecosystem functions are taken into account.

Conclusions

To support policy and decision making towards the sustainable management of soils across Europe, there is a need for the monitoring and communication of biological soil indicators that are linked to soil functions and ecosystem services. No single indicator is universally applicable and different indicators, including biotic as well as abiotic parameters, are needed for different functions and environmental conditions. Functional assemblages of soil organisms have been distinguished and their hierarchical organization should be reflected in soil biodiversity assessments and biological soil indicator sets. The development of sets of complementary indicators requires validation across a wide range of environmental conditions using standardized methods to produce accurate and consistent results. Despite considerable progress and several initiatives contributing to indicator selection and homogenization of methods, major scientific and practical issues remain to be addressed. Those include (i) adequate funding to allow sufficient spatiotemporal coverage in soil monitoring systems; (ii) definition of reference values for different combinations of land use, soil type and climate; (iii) obtaining a better predictive understanding of the relationships between anthropogenic disturbances, soil biodiversity and ecosystem services. Detailed assessments in long-term trials or observatories (LTO's) across Europe remain important. Additionally, integration of datasets across national borders offers data mining opportunities to develop ecological concepts and modeling of ecosystem services. Promising avenues include approaches based on the analysis of ecological traits, and studying the extent to which driving forces behind the partitioning of energy in the soil food web affect multiple ecosystem services. Finally, the knowledge thus generated should be applied in decision making, which requires simple and clear communication with end users. Databases of biological soil indicators have already been applied to societal questions and for the development of tools for stakeholder processes and awareness raising.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Texier C: *Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis*. Washington, DC: World Resources Institute. Island Press; 2005.

2. Mace GM, Cramer W, Díaz S, Faith DP, Larigauderie A, Le Prestre P, Palmer M, Perrings C, Scholes RJ, Walpole M *et al.*: **Biodiversity targets after 2010**. *Curr Opin Environ Sustain* 2010, **2**:3-8.

3. Kibblewhite MG, Ritz K, Swift MJ: **Soil health in agricultural systems**. *Philos Trans R Soc B* 2008, **363**:685-701.

4. • Turbé A, De Toni A, Benito P, Lavelle P, Lavelle P, Ruiz N, Van der Putten W, Labouze E, S M: **Soil biodiversity: functions, threaths and tools for policy makers**. In *Bio Intelligence Service, IRD, and NIOO, Report for European Commission (DG Environment)*. 2010.

This report provides an extensive review of the state of knowledge of soil biodiversity, its contribution to ecosystem services and its relevance for the sustainability of human society

5. • Dominati E, Patterson M, Mackay A: **A framework for classifying and quantifying the natural capital and ecosystem services of soils**. *Ecol Econ* 2010, **69**:1858-1868.

Building on current thinking on ecosystem services and scientific understanding of soil formation, functioning and classification, this paper develops a framework to classify and quantify soil natural capital and soil ecosystem services.

6. Creamer RE, Brennan F, Fenton O, Healy MG, Lalor STJ, Lanigan GJ, Regan JT, Griffiths BS: **Implications of the proposed Soil Framework Directive on agricultural systems in Atlantic Europe – a review**. *Soil Use Manage* 2010, **26**:198-211.

7. Gardi C, Montanarella L, Arrouays D, Bispo A, Lemanceau P, Jolivet C, Mulder C, Ranjard L, Römbke J, Rutgers M *et al.*: **Soil biodiversity monitoring in Europe: ongoing activities and challenges**. *Eur J Soil Sci* 2009, **60**:807-819.

8. COM: **Thematic strategy for soil protection**. *Commission of the European Communities* 2006, **231**.

9. Jeffery S, Gardi C, Jones A, Montanarella L, Marmo L, Miko L, Ritz K, Peres G, Römbke J, van der Putten WH: *European Atlas of Soil Biodiversity*. Luxembourg: European Commission, Publications Office of the European Union; 2010.

10. Noss RF: **Indicators for monitoring biodiversity: a hierarchical approach**. *Conserv Biol* 1990, **4**:355-364.

11. Bispo A, Cluzeau D, Creamer R, Dombos M, Graefe U, Krogh PH, Sousa JP, Peres G, Rutgers M, Winding A *et al.*: **Indicators for monitoring soil biodiversity**. *Integr Environ Assess Manage* 2009, **5**:717-719.

12. • Mulder C, Boit A, Bonkowski M, De Ruiter PC, Mancinelli G, Van der Heijden MGA, Van Wijnen HJ, Vonk JA, Rutgers M: **A belowground perspective on dutch agroecosystems: how soil organisms interact to support ecosystem services**. *Adv Ecol Res* 2011, **44**:277-357.

The authors show how datasets of biological and abiotic variables derived from the long-term monitoring frameworks can be explored to capture interrelationships between soil community structure and ecosystem functioning.

13. Swift MJ, Heal OW, Anderson JM: **Decomposition in Terrestrial Ecosystems. Studies in Ecology**. UK: Blackwell Scientific Publications; 1979.

14. De Deyn GB, Quirk H, Yi Z, Oakley S, Ostle NJ, Bardgett RD: **Vegetation composition promotes carbon and nitrogen storage in model grassland communities of contrasting soil fertility**. *J Ecol* 2009, **97**:864-875.

15. Nielsen UN, Ayres E, Wall DH, Bardgett RD: **Soil biodiversity and carbon cycling: a review and synthesis of studies examining diversity–function relationships**. *Eur J Soil Sci* 2011, **62**:105-116.

16. Wall DH, Bardgett RD, Kelly E: **Biodiversity in the dark**. *Nature* 2010, **3**:297-298.

17. Edwards IP, Zak DR, Kellner H, Eisenlord SD, Pregitzer KS: **Simulated atmospheric N deposition alters fungal community composition and suppresses ligninolytic gene expression in a Northern Hardwood Forest**. *PLoS ONE* 2011, **6**:20421.

18. Van Der Heijden MGA, Horton TR: **Socialism in soil? The importance of mycorrhizal fungal networks for facilitation in natural ecosystems**. *J Ecol* 2009, **97**:1139-1150.

19. •• Lavelle P: **Soil as a habitat for organisms**. In *Oxford Handbook of Soil Ecology and Ecosystem Services.* Edited by Wall DH. Oxford University Press; 2012.

This chapter provides an extensive description of self-organization and hierarchical organization in soil communities. It also discusses the consequences for the interlinkages between soil functions and soil ecosystem services, and implications for sustainable soil management.

20. Didden WAM, Marinissen JCY, Vreeken-Buijs MJ, Burgers SLGE, de Fluiter R, Geurs M, Brussaard L: **Soil meso- and macrofauna in two agricultural systems: factors affecting population dynamics and evaluation of their role in carbon and nitrogen dynamics**. *Agric Ecosyst Environ* 1994, **51**:171-186.

21. Hendrix PF, Parmelee RW, Crossley DA Jr, Coleman DC, Odum EP, Groffman PM: **Detritus food webs in conventional and no-tillage agroecosystems**. *Bioscience* 1986, **36**:374-380.

22. Jongmans AG, Pulleman MM, Balabane M, van Oort F, Marinissen JCY: **Soil structure and characteristics of organic matter in two orchards differing in earthworm activity**. *Appl Soil Ecol* 2003, **24**:219-232.

23. Wardle DA, Begon M, Fitter AH: **Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices**. *Adv Ecol Res* 1995, **26**:105-185.

24. Oades JM: **The role of biology in the formation, stabilization and degradation of soil structure**. *Geoderma* 1993, **56**:377-400.

25. Doran JW, Zeiss MR: **Soil health and sustainability: managing the biotic component of soil quality**. *Appl Soil Ecol* 2000, **15**:3-11.

26. Rutgers M, Breure AM: **Risk assessment, microbial communities, and pollution-induced community tolerance**. *Hum Ecol Risk Assess* 1999, **5**:661-670.

27. Sousa JP, Bolger T, da Gama MM, Lukkari T, Ponge JF, Simon C, Traser G, Vanbergen AJ, Brennan A, Dubs F *et al.*: **Changes in Collembola richness and diversity along a gradient of land-use intensity: a pan European study**. *Pedobiologia* 2005, **50**:147-156.

28. •• Pérès G, Vandenbulcke F, Guernion M, Hedde M, Beguiristain T, Douay F, Houot S, Piron D, Richard A, Bispo A *et al.*: **Earthworm indicators as tools for soil monitoring, characterization and risk assessment. An example from the national Bioindicator programme (France)**. *Pedobiologia* 2011, **54(Suppl.)**:S77-S87.

Based on data of the French 'Bioindicator' programme, a large number of potential soil bioindicators were tested in several sites differing in environmental conditions and disturbance types. This paper deals with different earthworm descriptors, showing that different parameters were discriminative in agricultural sites than in contaminated soils.

29. Gerhardt A: **Bioindicator species and their use in biomonitoring**. *Environmental Monitoring I. Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO*. Oxford: Eolss Publishers; 2002.

30. Pérès G, Bellido A, Curmi P, Marmonier P, Cluzeau D: **Relationships between earthworm communities and burrow numbers under different land use systems**. *Pedobiologia* 2010, **54**:37-44.

31. Rutgers M, Schouten AJ, Bloem J, Van Eekeren N, De Goede RGM, Jagers Op Akkerhuis GAJM, Van Der Wal A, Mulder C, Brussaard L, Breure AM: **Biological measurements in a nationwide soil monitoring network**. *Eur J Soil Sci* 2009, **60**:820-832.

32. Pelosi C, Bertrand M, Roger-Estrade J: **Earthworm community in conventional, organic and direct seeding with living mulch cropping systems**. *Agron Sustain Dev* 2009, **29**:287-295.

33. Rutgers M, van Wijnen HJ, Schouten AJ, Mulder C, Kuiten AMP,
• Brussaard L, Breure AM: **A method to assess ecosystem services developed from soil attributes with stakeholders and data of four arable farms**. *Sci Total Environ* 2012, **415**:39-48.
This paper presents a pilot study on the valuation and quantification of ecosystem services at four arable farms in the Netherlands, based on biological soil indicators and abiotic parameters and involvement of stakeholders.

34. Griffiths BS, Donn S, Neilson R, Daniell TJ: **Molecular sequencing and morphological analysis of a nematode community**. *Appl Soil Ecol* 2006, **32**:325-337.

35. Velasquez E, Pelosi C, Brunet D, Grimaldi M, Martins M, Rendeiro AC, Barrios E, Lavelle P: **This ped is my ped: visual separation and near infrared spectra allow determination of the origins of soil macroaggregates**. *Pedobiologia* 2007, **51**:75-87.

36. Ritz K, Black HIJ, Campbell CD, Harris JA, Wood C: **Selecting biological indicators for monitoring soils: a framework for balancing scientific and technical opinion to assist policy development**. *Ecol Indicators* 2009, **9**:1212-1221.

37. Castellanos Navarrete A, Rodríguez-Aragonés C, Brussaard L, De Goede R, Kooistra MJ, Sayre KD, Pulleman M: **Earthworms, soil carbon and aggregation: soil quality changes in conservation agriculture under semi-arid conditions**. *Soil Tillage Res* 2012, **123**:61-70.

38. Griffiths BS, Philippot L: **Insights into the resistance and resilience of the soil microbial community**. *FEMS Microbiol Rev* 2012:1-18.

39. Hall EK, Maixner F, Franklin O, Daims H, Richter A, Battin T: **Linking microbial and ecosystem ecology using ecological stoichiometry: a synthesis of conceptual and empirical approaches**. *Ecosystems* 2011, **14**:261-273.

40. Maron PA, Ranjard L, Mougel C, Lemanceau P: **Metaproteomics: a new approach for studying functional microbial ecology**. *Microb Ecol* 2007, **53**:486-493.

41. Sharma SK, Ramesh A, Sharma MP, Joshi OP, Govaerts B, Steenwerth KL, Karlen DL: **Microbial community structure and diversity as indicators for evaluating soil quality**. In *Biodiversity, Biofuels, Agroforestry and Conservation Agriculture.* Edited by Lichtfouse E. Springer; 2011:317-358.

42. Cluzeau D, Guernion M, Chaussod R, Martin-Laurent F, Villenave C, Cortet J, Ruiz-Camacho N, Pernin C, Mateille T, Philippot L *et al.*: **Integration of biodiversity in soil quality monitoring: baselines for microbial and soil fauna parameters for different land-use types**. *Eur J Soil Biol* 2012, **49**:63-72.

43. Lemanceau P: **EcoFINDERS: characterizing biodiversity and soil functioning in Europe. 23 partners from 10 European countries and China**. *Biofuture* 2011, **326**:56-58.

44. Postma-Blaauw MB, de Goede RGM, Bloem J, Faber JH,
•• Brussaard L: **Agricultural intensification and de-intensification differentially affect taxonomic diversity of predatory mites, earthworms, enchytraeids, nematodes and bacteria**. *Appl Soil Ecol* 2012, **57**:39-49.
This study examined the effects of land use change on taxonomic diversity of 5 soil biota groups. It was shown that agricultural intensification had largest effects on larger soil biota and higher trophic groups, while restoration of grassland selectively stimulated taxonomic diversity.

45. Ruiz N, Jérôme M, Léonide C, Christine R, Gérard H, Etienne I, Patrick L: **IBQS: a synthetic index of soil quality based on soil macro-invertebrate communities**. *Soil Biol Biochem* 2011, **43**:2032-2045.

46. Velasquez E, Lavelle P, Andrade M: **GISQ, a multifunctional indicator of soil quality**. *Soil Biol Biochem* 2007, **39**:3066-3080.

47. Groot JCJ, Rossing WAH, Jellema A, Stobbelaar DJ, Renting H, Van Ittersum MK: **Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality—a methodology to support discussions on land-use perspectives**. *Agric Ecosyst Environ* 2007, **120**:58-69.

48. Van Wijnen HJ, Rutgers M, Schouten AJ, Mulder C, De Zwart D, Breure AM: **How to calculate the spatial distribution of ecosystem services across the Netherlands**. *Sci Total Environ* 2012, **415**:49-55.

49. EEA: **An experimental framework for ecosystem capital accounting in Europe. Technical report 13/2011**. Edited by European Environment Agency. Copenhagen, Denmark; 2011.

50. Brussaard L: **Ecosystem services provided by soil biota**. In *Oxford Handbook of Soil Ecology and Ecosystem Services.* Edited by Wall DH. Oxford: Oxford University Press; 2012.

51. de Bello F, Lavorel S, Díaz S, Harrington R, Cornelissen JHC, Bardgett RD, Berg MP, Cipriotti P, Feld CK, Hering D *et al.*: **Towards an assessment of multiple ecosystem processes and services via functional traits**. *Biodivers Conserv* 2010, **19**:2873-2893.

52. Holtkamp R, van der Wal A, Kardol P, van der Putten WH, de Ruiter PC, Dekker SC: **Modelling C and N mineralisation in soil food webs during secondary succession on ex-arable land**. *Soil Biol Biochem* 2011, **43**:251-260.

53. Capowiez Y, Cadoux S, Bouchant P, Ruy S, Roger-Estrade J, Richard G, Boizard H: **The effect of tillage type and cropping system on earthworm communities, macroporosity and water infiltration**. *Soil Tillage Res* 2009, **105**:209-216.

54. Pérès G, Piron D, Bellido A, Goater C, Cluzeau D: **Earthworms used as indicators of agricultural managements**. *Fresenius Environ Bull* 2008, **17**:1181-1189.

55. Giannopoulos G, Pulleman MM, Van Groenigen JW: **Interactions between residue placement and earthworm ecological strategy affect aggregate turnover and N_2O dynamics in agricultural soil**. *Soil Biol Biochem* 2010, **42**:618-625.

56. Bongers T: **The maturity index – an ecological measure of environmental disturbance based on nematode species composition**. *Oecologia* 1990, **83**:14-19.

57. Van Megen HHB, Van den Elsen SJJ, Holterman MHM, Karssen G, Mooijman PJW, Bongers AMT, Holovachov OV, Bakker J, Helder J: **A phylogenetic tree of nematodes based on about 1200 full-length small subunit ribosomal DNA sequences**. *Nematology* 2009, **11**:927-950.

58. Neilson R, Donn S, Griffiths B, Daniell T, Rybarczyk KD *et al.*: **Molecular tools for analysing nematode assemblages**. In *Nematodes as Environmental Indicators.* Edited by Wilson MJ, Kakouli-Duarte T. Wallingford, UK: CABI; 2009:188-207.

59. Hamer U, Makeschin F, Stadler J, Klotz S: **Soil organic matter and microbial community structure in set-aside and intensively managed arable soils in NE-Saxony, Germany**. *Appl Soil Ecol* 2008, **40**:465-475.

60. Rousk J, Brookes PC, Bååth E: **Fungal and bacterial growth responses to N fertilization and pH in the 150-year 'Park Grass' UK grassland experiment**. *FEMS Microbiol Ecol* 2011, **76**:89-99.

61. Allison SD, Martiny JBH: **Resistance, resilience, and redundancy in microbial communities**. *Proc Natl Acad Sci USA* 2008, **105**:11512-11519.

62. Potthast K, Hamer U, Makeschin F: **Land-use change in a tropical mountain rainforest region of Southern Ecuador affects soil microorganisms and nutrient cycling**. *Biogeochemistry* 2011 http://dx.doi.org/10.1007/s10533-011-9626-7.