Soil Quality Assessment and Management

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The XX International Grassland Congress took place in Ireland and the UK in June-July 2005. The main congress took place in Dublin from 26 June to 1 July and was followed by post congress satellite workshops in Aberystwyth, Belfast, Cork, Glasgow and Oxford. The meeting was hosted by the Irish Grassland Association and the British Grassland Society.
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Key points

1. Soil quality is related to the capacity of soil to deliver ecosystem services on a sustainable basis.
2. Effective management of soil within grasslands can deliver many benefits to mankind but poor management may cause loss of soil quality from erosion, loss of organic matter, physical deterioration etc.
3. Services are delivered from soil by biological processes. Soil quality depends on the form and condition of the soil habitat. Fixed factors (e.g. texture) are useful for assigning soil to types. Variable factors (e.g. organic carbon) can then be used to assess quality within soil types, by reference to percentiles of the distribution of values for a given type.
4. Systematic monitoring of soil quality is useful for identifying the possible need for field level actions at regional to landscape scales. Assessment and management of soil quality at a local scale is supported more efficiently and effectively by in-field observation of soil profiles.

Keywords: soil protection, habitat, ecosystem services

Introduction

There is a new focus on soil protection (e.g. European Commission, 2002) driven by a realisation that soil provides much of the ecological capacity within land to support the growing footprint of human activities. This puts soil management at the heart of sustainable land management. As a key compartment in the terrestrial environment, soil needs to be given the same levels of protection as air and water, especially since soil can take orders of magnitude longer to recover from damage.

In 2002, 27% of global soil resources were in grassland (FAO, 2004). A key concern is the extent of more intensively managed grassland where the risk to soil quality is likely to be greater. For example in the United Kingdom, where grassland occupies almost half the land area, there is both extensively managed semi-natural grassland and intensively-managed permanent grass, as well grass-arable rotations. However, in all circumstances, it is clear that the effective management of soil within grassland systems has a leading part to play in the overall management of soil resources.

When considering soil, it is important to distinguish it from land. Land represents space within which different activities, human and otherwise, can take place. It is a finite resource. Soil is a habitat within land, containing ecological communities that deliver a range of services that are critical to sustainability. One key ecosystem service delivered by soil is support for food and fibre production, but there is increasing recognition that the range of services is much wider. Six types of ecosystem service are identifiable; 1) food and fibre production, 2) biodiversity conservation, 3) environmental services, 4) cultural heritage (e.g. archaeology and landscape conservation), 5) provision of platforms for built infrastructure, and 6) supply of primary materials (e.g. peat). Moreover, the economic value of these ecosystem services is large. For example, the environmental services appear to have the same order of value as agricultural outputs for some soils (Environment Agency, 2002), although this value is not included within current financial transactions. Thus semi-natural grassland soils that are of lower agricultural value may have significant overall economic value, when account is taken of their delivery of environmental and other services relating to water, atmospheric and biodiversity management.

When the effects of population increases and anticipated economic growth are combined, a tightening global food market is anticipated, especially for animal-derived protein. Soil management within grasslands is critical to meeting additional demand for protein in a sustainable framework. The productivity of grassland soils must be increased, while simultaneously protecting, and where possible raising, their capacity to deliver other ecosystem services. This requires measures of soil quality that can be used to target and monitor the efficacy of soil management measures. The key question that arises is *"What is good quality soil - taking full account of all the ecosystem services that it delivers?"*

Definition and assessment of soil quality is challenging for several reasons, including difficulties with defining both soil-based services and the variety of soil types, as well as limited scientific understanding of soil systems. The result is a gap between the current needs of policy makers and the scientific development of necessary, well-founded options for soil quality definition and monitoring. In the absence of new scientific approaches, measures of soil quality may be adopted that are convenient but lack a robust rationale in terms of indicator choice and target setting. This paper explores some of the impacts of grassland management on soil quality; it then describes a possible conceptual framework for arriving at a set of quality indicators and targets for soil, and explains how this framework can be applied to the assessment of soil quality in grasslands in support of their sustainable management.

Impacts of grassland management on soil quality

Trends in land-use are a key influence on overall soil quality. Conversion of natural and semi-natural forest to grassland causes losses of soil organic matter and alters soil physical properties. Improvement of semi-natural grassland or rough grazing land by drainage or irrigation, tillage, nutrient additions, burning, or re-seeding alters soil conditions. Where the conversion or subsequent management or both are not appropriate or effective, irreversible losses of soil quality may occur. By contrast, conversion of arable land to permanent grassland or the inclusion of grass in crop rotations increases soil organic matter levels, and may assist recovery of soil quality lost during previous cultivation.

Erosion is a natural process, which can be accelerated by poor management of grasslands. High stocking rates may lead to bare soil exposure and surface compaction. This increases the intensity of surface water runoff during storms and the consequent risk of soil erosion, especially on sloping land with soil that is susceptible to erosion. The loss of soil quality from gully erosion is obvious, but more insidious and widespread are sheet erosion losses, commonly rising to 10 to 40 t/ha per year. These are important because of the slow rate of soil formation.

Soil organic matter provides a store of soil nutrients and contributes to good soil physical conditions. The intensity of management of grasslands and their longevity between periods of arable cultivation affect both soil organic matter composition and levels, and thus soil quality. Intensification may lead to losses or gains in soil organic matter. Nutrient additions, improvements in species composition (including legume introduction), and optimisation of the soil-water regime for plant growth all increase net primary production and so tend to increase inputs of organic carbon to soil. Conversely, increased frequencies of grazing, mowing and burning all reduce these inputs. A further complication arises from the different temporal cycles of different pools of organic carbon in soil. Levels of less degraded plant litter in the surface horizon of soil profiles vary seasonally and with changing sward management. Changes in the soil organic carbon in more-recalcitrant microbial products are less rapid. Yet these products of microbial degradation and conversion of plant materials are perhaps more strongly associated with soil quality improvement, in terms of better soil structure and aggregate stability. This suggests that short-term conversion of arable land to grassland, including ley-arable rotations and set-aside (where nutrient additions and grazing are discontinued), may bring only relatively weak and ephemeral benefits to soil quality.

Animal, machinery and human traffic can cause compaction at the surface and within the soil profile, particularly when soil moisture is above the plastic limit. This impedes root growth and drainage, and these effects may extend over years, unless corrected by remedial intervention. The potential for this loss in soil quality depends on soil texture, natural or artificial drainage and climate.

Intensification of grassland management sometimes introduces materials that may cause contamination and a consequent loss of soil quality. A particular hazard arises from excessive spreading of slurries and manures. These may contain contaminants, such as copper and zinc, or veterinary products, which can accumulate in soil and may pose a threat to soil quality if spreading is frequent and over long periods.

Soil system performance and soil quality

Figure 1 shows an idealised performance curve for systems in general. As inputs are increased, outputs increase proportionally within the 'working-range' of the system. The efficiency of the system falls progressively above the working-range until the peak rate is reached, after which it becomes overloaded and further increases of input rates cause a reduction in output rates. Above the working range and up to peak capacity, the system remains resilient, so that when output demand temporarily exceeds the working range limit, the system 'recovers' without any permanent damage once excess demand is removed. The sustainable capacity of the system is defined by the conversion efficiency within the working range and the extent of that range.

A common definition of quality is that it is a measure of the extent to which a system is 'fit for purpose'. In the context of soil systems, the corresponding definition of a soil's quality is the extent that it is able to provide delivery of a portfolio of ecosystem services in a sustainable manner, with conversion efficiencies that meet wider ecosystem requirements, without exceeding working ranges.

Soil is a multi-functional system that delivers different outputs simultaneously. A set of performance curves can be imagined corresponding to these different outputs. These curves are not independent of each other. Maximising capacity to deliver one type of output will reduce capacity for other outputs, because common supporting processes have finite capacities. The management challenge is to devise a means of optimising capacity to support the sustainable delivery of a varying mix of services.

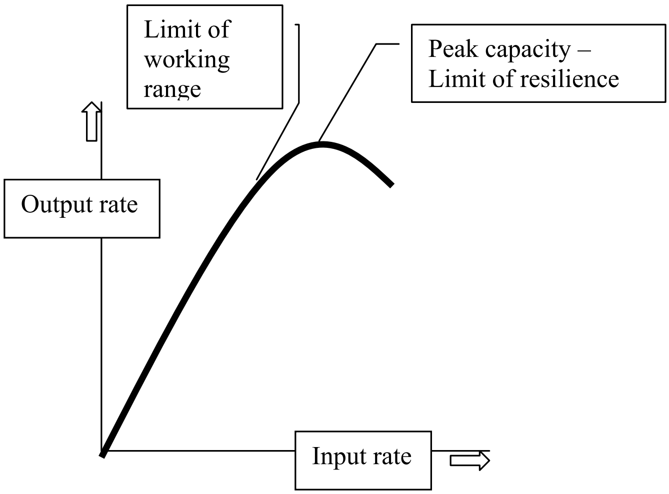

Figure 1 Idealised performance curve for systems

Assessment of soil quality should start with definition of the possible kinds and levels of soil-based ecosystem services, but the understanding necessary to complete this is not yet available. For example, the nature of biodiversity in soil is still being explored; a full description of soil services relating to air and water quality is not yet complete; and, cultural services (e.g. those related to landscape aesthetics) are not easily quantified. Without adequate definition of the ecosystem services provided by soil, it is clearly not possible to define their optimal mix. Nonetheless, a workable means of defining soil quality holistically and for setting quality targets is essential to support better soil management.

Soil is first and foremost a living system made up of biological communities existing within a habitat characterised by a highly complex architecture, that is moderated by soil-water physical processes (Young & Crawford, 2004; Ritz & Young, 2004). This perspective demands that assessment of soil quality focuses on the nature and condition of the soil habitat, as this determines fitness for purpose to support systems that deliver ecosystem services.

A basis for defining and assessing soil quality even in the absence of a complete description of services and a definition of their optimal mix, is to consider soil processes and the capacity for delivery of services as inherently biological. If the soil system is viewed as a physical habitat within which sets of biologically-mediated processes convert or control fluxes of air, water, carbon, nutrients, contaminants, etc. into products and services, the overall quality of the soil system - in terms of sustainable capacity for delivering different ecosystem services, should depend on the type and condition of the physical habitat. Although this emphasis on habitat condition in relation to soil quality is relatively new, it can also be seen as a re-interpreted rationale for using traditional soil quality measures, specifically physical and chemical parameters, such as texture, bulk density, organic carbon, nutrients or contaminant concentrations.

A wide range of soil habitat conditions can exist depending on fixed and variable factors (see Table 1). The fixed factors define the envelope of possible habitat conditions and contribute to the definition of soil type within a continuum of possibilities. The variable factors define the habitat condition within an envelope of possibilities set by the fixed factors and characteristics of the soil type. Sub-envelopes corresponding to different land use can also be set, e.g. permanent grass, grass-arable rotations, etc.

Table 1 Fixed and variable factors defining soil habitat condition

Fixed factors	Variable factors
Texture, stone content, slope angle, topographic position, annual precipitation, mean temperature, etc.	Water holding capacity, bulk density, soil organic carbon level, pH and depth (affected by tillage and erosion), plant cover, etc.

By comparing observed values for these variable factors with reference values for the soil type, the condition of the soil habitat can be assessed as an indicator of soil quality, and used as a basis for decisions about soil management. In principle, reference values for variable factors for a given soil type can be defined either by making measurements on 'benchmark' soil profiles that are judged to be of good quality, or by choosing percentile values within the distribution of values observed for the whole population of profiles within a given soil type.

Assessment of soil quality

Assignment to soil type

For soil quality assessment based on soil habitat condition, populations of soil profiles need to be identified corresponding to different soil types. These may be selected by reference to fixed factors (Table 1). The soil types identified will correspond closely to existing soil profile taxonomic classes because the same factors are used in classification systems. However, developments in remote sensing and in information sciences are allowing better capture and description of spatial and temporal variations in natural systems, and this is changing ideas about soil variety and variability. In the last century, deterministic taxonomic systems were developed to describe characteristic types of soils that evolve in response to particular combinations of soil forming factors (pedogenesis). Application of digital information systems is confirming the correctness of the concept of a three-dimensional continuum of soil properties (Fitzpatrick, 1971), with the properties associated with particular soils even within narrow spatial limits being better described in a stochastic fashion than an absolute one. The result is a realisation in the policy as well as the scientific community that a 'one-size-fits-all' approach to soil quality criteria is inadequate.

Digital information techniques have an important advantage over traditional soil taxonomy, because assignment to type is both objective and can also be qualified by an estimate of the confidence of assignment. The application of these new techniques is just emerging from the development phase and will lead to new digital soil information systems over the coming years, which can be used to assign soil profiles (including those in grassland), to populations appropriate for soil quality assessment. In the meantime, soil maps can be used to make assignments, albeit less effectively.

Assessment of soil quality within type

Measurement methods for the variable factors proposed in Table 1 and others are well established, and data are available on their spatial (and in some cases temporal) variability, at regional, landscape and sometimes field levels. The key problem is to define targets for the factors that indicate a soil habitat is 'fit for purpose' for delivery of ecosystem services.

In principle, habitat condition in 'working soils' could be assessed by comparison of measured values for variable factors, with those observed for 'benchmark' soils that are in a 'good' semi-natural condition. The case for this rests on the assumption that the latter should have evolved to optimise natural overall ecological capacity. Certainly, this approach would be appropriate when the purpose of soil management is to restore soils to their natural condition, for example as part of natural grassland restoration. However, within sustainable development, modification of soils to optimise their delivery of services to support human quality of life is as important as biodiversity conservation. Thus highly modified soils can be of good quality because they have a greater capacity to deliver a desirable mix of services than did the natural soils from which they were created, and to which they might be restored. For example, artificial drainage and sustained additions of organic matter over many years are capable of producing a modified soil that has an increased capacity to support both highly productive grassland and additional capacity to deliver other ecosystem services.

An alternative to assessing soil quality by benchmarking against semi-natural soils, is to compare values for variable factors found for a particular soil profile with measured ones for a representative population of the relevant soil type. For each factor and soil type, percentile values can be chosen to indicate good, fair or poor soil quality. It should be stressed that unless there is clear evidence for any threshold value below which soil performance is impaired, the choice of percentile values that correspond to different quality assessments is arbitrary. Such evidence is generally absent, so the choice of percentile value will be informed mainly by policy considerations, such as the proportion of soils that are to be targeted for improvement, perhaps taking account of available support funding.

One variable factor that has already been proposed (MAFF, 2000) as an indicator of soil quality is soil organic matter. The definition of soil organic matter may need elaboration, but for illustration, organic carbon may be used as a proxy. Figure 2 shows the distribution of organic carbon in shallow lime-rich soils over chalk and limestone in England and Wales. This soil type was mainly in permanent grass in the first half of the last century, but is now largely in arable production. For purposes of assessment and management, it could be proposed that all values of organic carbon that fall within the highest quartile are 'good', those in the two middle quartiles are 'satisfactory', and those in the lowest quartile 'need improvement'. Options for improving the quality of soil in the lowest quartile will include returning arable land to permanent grassland.

As another example, bulk densities in the lowest quartile for a soil type could be assessed as 'good', those in the second and third lowest quartiles as 'satisfactory' and those in the highest quartile as 'needing improvement'. The overall quality of the soil could then be assessed by completing similar assessments for a set of variable factors, including depth of surface horizon and pH, as well as organic carbon and bulk density.

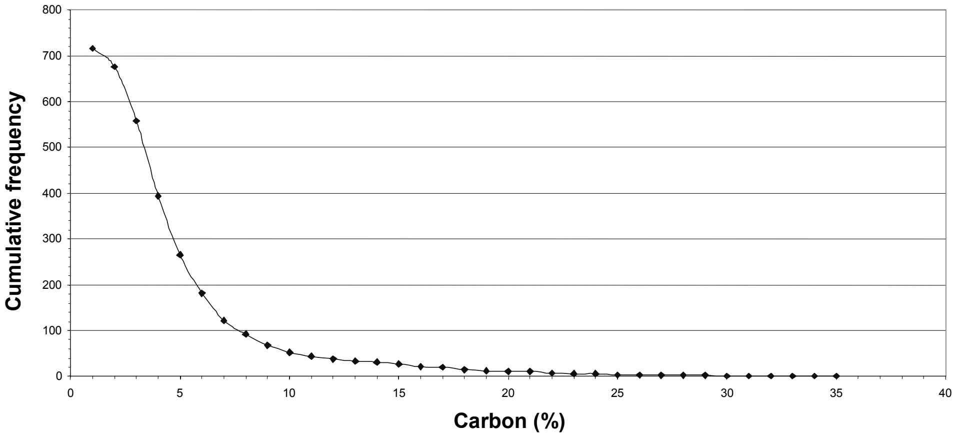

Figure 2 Cumulative frequency of measured values for organic carbon in shallow lime-rich soils over chalk and limestone in England and Wales (data extracted from the 5x5 km grid sample data held in the National Soil Inventory, NSRI, Cranfield University)

Management of soil quality

Sustainable management of grassland soil requires that the demand for ecosystem services does not exceed sustainable capacity within the soil (see Figure 1). In particular, stocking rates must be set at levels that do not place excessive demand on the soil system. Loss of plant cover through overgrazing (especially when combined with burning) puts soil quality at risk by reducing organic carbon (and so substrate) inputs to the soil system, and by increasing the risk of soil erosion. When the sustainable capacity of a soil is exceeded continuously in this way, and especially if the peak capacity is exceeded, permanent damage to the soil habitat and loss of soil quality are probable.

Monitoring at regional and landscape scales of variable factors can indicate whether soil quality is being compromised generally. For example, a high proportion of soils with organic carbon contents that are below target may indicate excessive grazing pressures. Where there is an indication that soil quality is at risk in a landscape (because values for variable factors fall within percentiles identified as unsatisfactory), an appropriate initial response is farm-level investigations to explore the true nature, extent and level of possible soil damage. High costs mean that it is normally not feasible to extend systematic monitoring of variable factors down to field scale. The best tool for assessing grassland soil quality at field scale is the spade. Opening of soil profiles and basic field observation of soil conditions allows the land manager to identify soil quality problems directly (see NSRI, 2001). However, effective responses to adverse trends in soil quality identified in soil monitoring require action to be taken throughout the wider landscape. The key to achieving this is field scale demonstration of solutions in support of effective uptake of advice and training, ideally with area-based financial incentives to changed practices.

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be subject to higher prices and stricter regulation. With strong societal pressure for improved environmental quality, allocations for environmental uses of water will increase, reducing pressure on wetlands.

In the 'sustainable water scenario' the world consumes 20% less water than under 'business as usual' but reaps greater benefits, especially in developing countries. These water savings will increase environmental flows by 1,030 km^3 globally, well over triple the annual flow of the Mississippi River. A key finding in this scenario is that, with higher public investment in crop breeding for rainfed areas, together with improved farm management (including increasing water harvesting, conservation tillage, and precision farming), rainfed production increases significantly. Faster growth in rainfed yields will make up for slower growth in harvested area and irrigated yields, and as a result total cereal production in 2025 is 1% greater than under 'business-as-usual'.

Climate change, pasture and land use

Hopkins (2004) showed that grassland production is strongly influenced by climatic variability, particularly temperature and rainfall. Variation in pasture yield and production can be over 100% between different localities depending on length of growing season, rainfall distribution and soil type. Under the climate change scenarios that were developed by Hopkins (2004), grassland production is likely to be influenced by increasing temperatures and changing seasonal patterns of precipitation.

The impact of climate change on pasture and other land use is also examined by the Millennium Ecosystem Assessment (MA), an international effort to provide scientific information to policymakers and the public on the effect of ecosystem change on human well being, and to offer options for dealing with those changes. As noted above, the MA scenarios were analysed using several global models; greater consistency between the calculations of the different models was achieved by 'soft-linking' the models, in the sense that output files from one model were used as inputs to other models. The scenarios were implemented by:

- *specifying a consistent set of model inputs* based on the scenario storylines;
- 's*oft-linking' the models* by using the output from one model as input to another;
- *compiling and analysing model outputs* about changes in future ecosystem services and implications for human well-being.

As a part of the MA, a Global Scenarios group assessed plausible scenarios for land use on a global scale, using the 'soft-linked' models mentioned above, and incorporating the impact of climate change on land use and production.

These scenarios account for the impact of climate change, and represent plausible alternative futures of the world. They explore the outcomes of increased globalisation versus increased regionalisation on the one hand, and increased economic growth versus increased emphasis on local adaptive management of ecosystems and their services on the other hand. Both the Global Orchestration (GO) and Techno Garden (TG) scenarios focus on increased globalisation, with GO emphasizing economic growth and public goods provision, while TG strives for greener technologies. The Order from Strength (OS) scenario has a regionalised approach focusing on national security and self-sustenance, whereas the Adapting Mosaic (AM) scenario focuses on local adaptation and flexible governance. The GO scenario assumes low population growth, high income growth, high investments in human and physical capital, medium to high levels of development in technology, rapid irrigation