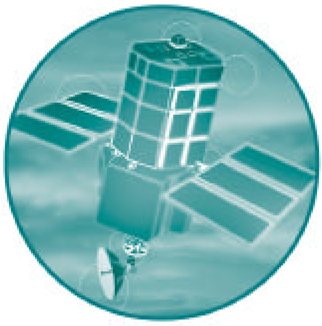
Identification and development of a set of national indicators for soil quality



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P5-053/PR/02

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Identification and development of a set of national indicators for soil quality

R&D Project Record P5-053/PR/02

Edited by:

P.J. Loveland and T.R.E. Thompson (SSLRC)

On behalf of the consortium:

Soil Survey and Land Research Centre
Cranfield University, Silsoe, Bedfordshire MK45 4DT
ADAS Research
Woodthorne, Wolverhampton WV6 8TQ (J. Webb, B. Chambers)
Department of Agriculture and Rural Affairs
Newforge Lane, Belfast BT9 5PX (C. Jordan, J. Stevens)
Forest Research
Alice Holt Lodge, Farnham, Surrey GU10 4LH (F. Kennedy, A. Moffat)
Institute of Arable Crops Research-Rothamsted
Harpenden, Hertfordshire AL5 2JQ (K. Goulding, S. McGrath)
Macaulay Land Use Research Institute
Craigiebuckler, Aberdeen AB15 8TQ (E. Paterson)
NERC Centre for Ecology and Hydrology
Merlewood Research Station, Grange-over-Sands LA11 6JU (H. Black, M. Hornung)

Publishing Organisation
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury
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Tel: 01454 624400 Fax: 01454 624409
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Contact details
P.J. Loveland, Soil Survey and Land Research Centre, Cranfield University, Silsoe, Bedfordshire MK45 4DT
Tel: 01525 863246 (direct); 01525 863000 (Switchboard) Fax: 01525 863253
Email: p.loveland@cranfield.ac.uk

Name and Location of Agency project Manager: Malcolm Lythgo, Head Office

Further copies of this report are available from:
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CONTENTS

1. THE PURPOSE AND OBJECTIVES OF THE PROJECT

The purpose of this project is to start the development of a national set of indicators of physical, chemical and biological soil quality and the extent and diversity of soil. The indicators should allow for the heterogeneity of soil type and land use, to aid in both the reporting of soil health and promotion of management practices for UK soils that do not result in their degradation. Different indicators may often be needed for different uses of soil and even different soil types.

The specific objectives for the project are:

a) To identify, from first principles, a list of potential indicators for soil quality for the main UK soil types and land uses.
b) To assess those that are currently available.
c) To assess the feasibility of those not currently available, in particular the work required to develop them into useful indicators.
d) To recommend a strategy for using the indicators as part of long term monitoring of soil.

2. AN OVERVIEW OF PREVIOUS WORK

This Chapter is not an exhaustive review of the literature for and against the development and use of soil quality indicators, as many of the papers tend to repeat the same messages. An electronic Bibliography with several hundred items relevant to soil quality is available.

The *concept* of soil quality can be traced back to ancient literature (for example, Plato's Dialogue '*Critias'* gives a graphic account of the effects of soil erosion) and is undoubtedly much older. However, *attempts to quantify it* (rather than describe it) are more recent, e.g. the early 1940's in the USA (Kellogg, 1943) and the early 1950's in the UK (Clark, 1951). The Council of Europe (1972) recognised the need for the conservation of the soil resource in its European Soil Charter (Resolution 72-19), which it summarised as a series of headings, the accompanying texts to which are not reproduced here:

- Soil is one of humanity's most precious assets. It allows plants, animals and man to live on the earth's surface;
- Soil is a limited resource which is easily destroyed;
- Industrial society uses land for agriculture as well as for industrial and other purposes. A regional planning policy must be conceived in terms of the properties of the soil and the need's of today's and tomorrow's society;
- Farmers and foresters must apply methods that preserve the quality of the soil;
- Soil must be protected against erosion;
- Soil must be protected against pollution;
- Urban development must be planned so that it causes as little damage as possible to adjoining areas;
- In civil engineering projects, the effects on adjacent land must be assessed during planning, so that adequate protective measures can be reckoned in the cost.
- An inventory of soil resources is indispensable;
- Further research and interdisciplinary collaboration are required to ensure wise use and conservation of the soil;
- Soil conservation must be taught at all levels and be kept to an ever-increasing extent in the public eye;
- Governments and those in authority must purposefully plan and administer soil resources.

It has often been argued that this Charter has been more ignored than acted upon (although its message was reinforced in Recommendation (92)8 in which much the same points were made (Council of Europe, 1990, 1992)), with only Germany incorporating soil protection within Federal legislation (FRG, 1998). In particular, Recommendation (92)8 explicitly promulgated the operational or *functional* approach to soil protection.

An early example of the use of soil indicators is Directive 86/278/EEC of the Council of the European Communities on the use of sewage sludge in agriculture (EEC, 1986), in which concentrations of metals in soils are used for soil protection purposes. These limits were incorporated into UK legislation through the Sludge (Use in Agriculture) Regulations 1990, SI 1990 880. Within the UK, the principles of soil protection were reviewed on behalf of Government by the then Institute of Terrestrial Ecology and the Soil Survey and Land Research Centre (DoE, 1989). Recommendations for the elements of a soil protection policy were given as:

- Characterization and assessment of the soils of the UK and their current status;

- Monitoring of change in soils over time;
- Assessment of the impact of man's activities on soils, particularly the impact of changes in land use and management;
- Definition of acceptable loads of man-induced stresses and means of controlling those stresses;
- Development of alternative management methods and techniques to reduce the impact of man's activities on soils;
- Definition of target values of soil variables to be used in rehabilitation of damaged soils.

Adriaanse (1993) presented indicators as measures of environmental policy performance, very much targeted at meeting obligations under Agenda 21. Although not giving any indicators specific to soils, his basic tenets were that *any* indicator should:

- have significance beyond that obtained directly from observation;
- be simple;
- be quantitative;
- be relevant to policy issues or processes.

This approach is, in effect, a statement of the P[ressure] - S[tate] - R[esponse] model, developed originally by OECD for the analysis of economic performance (OECD, 1998). This model is discussed in more detail below.

During the 1990s, several publications began to address the issues surrounding the derivation and / or quantification of indicators for soils. For example, the UK Government published the White Paper *'This Common Inheritance'* (Cmnd1200, 1990), which essentially put in place a formal mechanism for environmental reporting. An important outcome of this was the publication of *'The UK Environment'* (DoE, 1992), which was effectively the first attempt in England and Wales to form an overview of soil quality in terms of environmental concerns such a urbanisation, erosion, acidification, heavy metal concentration, etc. although no attempt was made to attach indicator values to this assessment. Packer (1993) applied soil functional analysis to the planning process and the concept of sustainability within the context of a local authority (Bedfordshire). She concluded that the then practice of only protecting certain soils was inadequate, and that any consideration of soil use had to be planned against full consideration of a framework of potential function. Thompson and Peccol (1995) developed this concept further and proposed a range of indicators suitable for policy performance (Table 2.1) as well as criteria for their selection (Table 2.2).

The UK Government committed itself to sustainable development at the Earth Summit in Rio in 1992, and produced its Strategy for this in 1994 (Cm2426, 1994). The publication of *'Indicators of Sustainable development for the United Kingdom'* (DoE, 1996b) was a major step forward in trying define what we mean by indicators in this context. The key messages were that indicators:

- are quantified information which help explain how things are changing over time;
- provide to the policy-makers and the public reasonable indicators of changes….;
- assist economic policy-making and allow the public to judge for themselves how the economy is performing overall.

This reference to environmental indicators as part of the measure of the economic performance of the UK was at a much higher level than had been seen previously in assessments of the UK environment. Two indicators were given for soil, one based on nutrient and organic matter status, and the other based on concentrations of heavy metals in soils. Future development of more indicators for soils was deferred until after the Royal Commission of Environmental Report: *Sustainable Use of Soil* (RCEP, 1996). As well as recognising that soil is a vital resource, this Report made 91 recommendations, among which the following stand out in relation to soil indicators:

- *Recommendation* 1: that the Environment and Agriculture Departments jointly draw up and implement a soil protection policy for the UK;
- *Recommendation* 7: the setting-up of a national soil quality monitoring scheme;
- *Recommendation* 89: the inclusion in future surveys of biological measures of soil quality;
- *Recommendation* 91: that comprehensive resource inventories be developed which quantify trends in physical terms, so that losses and gains in soil assets, including urbanisation and contamination, can be evaluated.

UK Government subsequently consulted publicly on the concept of a set of 'headline' indicators (DETR, 1998), and then issued these and a set of 'core' indicators (DETR, 1999) on the *state* of the soil. Disappointingly, soil did not feature as part of the headline indicators and featured in only two core indicators; one of the amount of land lost to development (for which there was inadequate data) and the other to the change in soil organic matter status between about 1980 and 1995; this was little advance on the *state* indicator given by DoE (1996b). MAFF (2000) listed a number of indicators for agriculture, of which two were specifically targeted at soils, namely, organic matter content of agricultural topsoils and accumulation of heavy metals in agricultural topsoils. However, a number of the other indicators, e.g. pH, aggregate stability, loss of land to the built environment, a biodiversity index, keystone species, buffering capacity; many are discussed later in this Record, illustrate other *pressures* on land and might have a valid role in a wider assessment of soil quality. Similarly, the Environment Agency reported on the *state* of the environment in England and Wales (EA, 2000) and discussed a large number of issues which relate to the *pressures* and *state* of the soil, and highlighted those areas in which further effort was required:

- Climate change;
- The use of land-based resources;
- The condition of soils;
- The loss and degradation of habitats;
- The risk of flooding;
- Urban and landscape quality.

Throughout this report there is considerable emphasis on the role of *function* in the assessment of the state of the land, a role first most clearly articulated by Blum (1993), who stated the by-now well-known demands on soils as:

- a medium for biomass production: food crops, animal production, timber and wood products;
- an interface between the atmosphere and water resources in terms of the soils' ability to buffer and filter;
- a bio-geochemical reactor or regulator to facilitate the re-cycling of (largely organic) wastes and to de-toxify organic chemicals;
- supporting the built environment;
- a reservoir and source of biodiversity;

- preserving the archaeological record.

Although progress has been made towards identifying and understanding indicators of soil functions in some of these areas, there continues to be emphasis on agriculture. This is largely to be expected, given that it tends to occupy the largest area of land in many countries, and there is no escaping the fact that large areas of land are inevitably needed to feed a growing world population. This translates - at least partially - into the concept of the 'ecological or environmental footprint' (e.g. http://www.mec.ca/Apps/ecoCalc/). However, it is difficult to see how the land or soil component of an ecological footprint could be separated clearly enough from the other components to function as a soil indicator.

The soil quality concept became intimately linked with that of soil health and, for a time, the two concepts were used interchangeably (e.g. Harris and Bezdicek, 1994; Acton and Gregorich, 1995), although the former term now seems to be the norm. There have been numerous attempts to define soil quality and, thereby, clarify thinking about the indicators needed to quantify those definitions and monitor any changes in them. Larson and Pierce (1991) employed the concepts of 'capacity' and 'function':

"*The capacity of a soil to function within the ecosystem boundaries and interact positively with the environment external to that ecosystem*."

Within two years this has been reduced to: "*Simply put: Fitness for use.*" (Pierce and Larson, 1993).

In both these definitions, there is a clear need to identify function and purpose and, in an era with increasing demand (pressure) on resources, there is an equally clear need to link function to process. Much of the seminal literature on soil quality makes two important points in this respect. One is that the measurements of soil properties which are available as indicators are Indicators of State; it is re-measurement or application of the data in some way which reveals the Impact and / or response. The other point is the need to move away from the assumption that the measurements themselves might necessarily represent the norm or the desirable. The fact that measurements show a range or distribution does not mean that they encompass the ideal or optimum or target value(s); the system might have degraded to a level outside that. Degradation is often taken to mean a decline in a value, but it can equally well be used to describe an unacceptable increase

Table 2.1 Soil quality indicators for policy performance evaluation

Soil indicator	Functions influenced	Measured soil variable(s)	Comment
Chemical qualities			
Acidity	A B C e	Topsoil pH in water	pH can vary significantly under the influence of percolating rainfall
Organic matter status	A B C e	Topsoil organic carbon	
Nutrient status	A B C	MAFF indices for P, K, Mg	Point- based aggregate index
Degree of contamination	A B C E	Inorganic - total topsoil Cd, Cr, Cu, Ni, Pb, Zn	An aggregated index value based on concentrations expressed in relation to the national mean values in 1980 (McGrath and Loveland 1992)
ditto	A B C E	Organic	Problems with the extraction of some adsorbed chemicals
Physical qualities			
Structural status	a b c	Total porosity Aggregate stability	Direct reproducible measurement of the structure of soil (the organisation of solid, liquid and gas phases) is difficult but the total pore space and the stability/strength of solid aggregates are useful indirect indicators of structure
Density	a b c	Topsoil bulk density	Problems of consistency in agricultural soils due to cycle of cultivation , difficulties of definition and measurement in soils with high stone content
Rate of erosion	a b c d f		Erosion is episodic and difficult to measure systematically and reliably; wind, water and oxidation (of peats) are the prime vectors but water is the most widespread influence. A computed value of vulnerability or risk based on inherent soil and land properties, land use and weather may be the best option, or suspended solids in rivers (dependant on bank contribution)
Sterilisation by construction	A B C E F	Field survey/remote sensing	Aggregated data may be available from planning process given Government intentions to implement 'brown field' site targets

Table 2.1 (Continued) Soil quality indicators for policy performance evaluation

Soil indicator	Functions influenced	Measured soil variable(s)	Comment
Physical disruption/removal	A B C D F	Field survey/remote sensing	
Moisture storage capacity	A b C e	0.05 - 15 bar v/v available water capacity integrated for A horizon depth (replicated samples at mid-horizon depth)	For agricultural land, point in rotation and previous cultivations can affect results; topsoils provide bulk of available water for plant growth and are a measure of the storm water storage capacity of the soil
Biological qualities			
Biomass	A B C e	Soil microbial content	Microbial content fluctuates naturally with soil water, nutrient and thermal state; analytical methods are the subject of debate
Biodiversity	a b C	Viable populations of indicator groups	Soil biota are extremely complex and naturally dynamic; sampling is complex and it is difficult to produce reliable, reproducible results; choice of keystone species is frequently arbitrary and subject to debate
Rooting zone?		Quantitative classification of root density at various depths	
Functional qualities			
Productivity (agricultural)	A	Agricultural land class	ALC provides a raw indication of agricultural productivity; land in grades 1, 2 and 3a are regarded as 'productive'; analogous system in place in Scotland giving UK perspective
Productivity (biomass)	A	pH, nutrient and water supplying status	No factors relating to trafficability or harvesting need be incorporated and pH, nutrient and water supply are the prime controls over plant and soil biota growth

Table 2.1 (Continued) Soil quality indicators for policy performance evaluation

Soil indicator	Functions influenced	Measured soil variable(s)	Comment
Nutrient retention	B	Mean annual ground/surface water NO_3 concentrations	NO_3 concentrations vary significantly with season and, for rivers, with flow
Ability to neutralise applied wastes	B	Surface water chemistry - BOD, ammonium-N	Dependent in part on nature of waste
Ability to support diverse ecosystems	C		Problems of data collection and the definition of 'diverse'
Physical stability for construction	D		Range of engineering materials tests for shrinkage, plasticity, corrosivity etc. Unlikely to change except following gross physical degradation of soil
Source of raw minerals	E		Extraction will 'degrade' the resource
Source of raw water	E	Groundwater recharge	Difficult, if not impossible, to measure

Functions
A - Biomass production
B - Filtering, buffering and transforming substances
C - Protection of gene pool
D Provision of spatial base
E Source of raw material
F - Protection of heritage sites

Direct influences on functions are represented by upper case letters; indirect by lower case.

Table 2.2 Relative suitability of indicators according to selection criteria

Indicator	Criteria for selection of indicators								
	Relevance	Representativeness	Relation to policies	Good basis	Interpret?	Responsiveness to change	Verify/ repeat	Sources /quality of data	Total score
Acidity	***	***	**	***	***	***	***	***	21
Organic matter status	***	***	**	**	**	***	***	***	20
Nutrient status	***	***	**	***	***	***	**	***	20
Degree of contamination	***	***	***	***	**	***	**	***	22
ditto	***	***	***	***	**	***	**	***	22
Structural status	***	**	*	*	*	**	*	*	12
Density	**	*	*	**	*	*	*	*	10
Sterilisation by construction	***	***	***	***	***	***	***	***	24
Physical disruption/removal	***	***	**	***	***	***	***	***	23
Moisture storage capacity	***	**	*	***	**	**	*	*	15
Biomass	***	**	*	**	**	***	*	**	16
Biodiversity	***	**	***	**	**	***	*	*	15
Productivity (agricultural)	***	**	***	***	**	***	**	**	20
Productivity (timber)	***	**	**	***	**	**	*	*	16
Productivity (biomass)	***	***	**	*	*	**	*	*	14

Table 2.2 (Continued) Relative suitability of indicators according to selection criteria

Indicator	Criteria for selection of indicators								
	Relevance	Representativeness	Relation to policies	Good basis	Interpret?	Responsiveness to change	Verify/ repeat	Sources /quality of data	Total score
Nutrient retention	***	***	***	**	**	**	**	**	19
Ability to neutralise applied wastes	**	**	*	**	*	**	*	*	12
Ability to support diverse ecosystem	**	**	***	*	*	**	*	*	13
Physical stability for construction	*	*	**	**	**	*	**	**	13
Source of raw minerals	***	***	***	***	***	*	***	***	22
Source of raw water	**	**	***	*	*	*	*	*	12
Protection of heritage sites	*	*	***	**	**	*	**	*	13

Key -

***	Good
**	Moderate
*	Poor

NOTE - the main problem with many measures of soil microbial diversity is *interpretation*. Diversity can go up as well as down with stress. Diversity changes may not be linked to changes in function, because of functional redundancy in microbial groups. Down-rated 'relevance' as the most appropriate category. Finally METHODS are at the research stage.

Doran and Parkin (1994) linked the major issues of concern with regard to soil function, by defining soil quality as:

"*The capacity of soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health*."

They proposed that soil quality indicators should meet the following criteria:

- encompass ecosystem processes and relate to process oriented modelling;
- integrate soil physical, chemical, and biological properties and processes;
- be accessible to many users and applicable to field conditions;
- be sensitive to variations in management and climate;
- where possible, be components of existing soil databases.

They went on to propose the following basic indicators of soil quality:

- soil texture (i.e. particle size class - clay, clay loam, sandy loam etc.);
- depth of soil and rooting;
- soil bulk density and infiltration;
- water holding capacity and water retention characteristics;
- water content;
- soil temperature;
- total organic C and N;
- pH and electrical conductivity;
- mineral N (ammonium- and nitrate-nitrogen), P and K;
- microbial biomass C and N and potentially mineralisable N;
- soil respiration, biomass C/total organic C ratio and Respiration/biomass ratio

The interpretation of these basic indicators was less clear, in that Doran and Parkin (1994) refer to work published mostly in the early 1980s, which - on inspection - was based on a rather limited number of experiments. Many of these indicators would be of 'State', e.g. particle size distribution, water retention characteristics, which would have a limited ability to reflect change and thus 'Impact'. Others would change very rapidly, possibly on a seasonal basis, and their interpretation could be problematical, e.g. water content. This approach was modified (Doran and Parkin, 1996) by the proposal for a minimum data of quantitative indicators of soil quality, summarised below (Table 2.3).

Other attempts were made to derive soil indicators through a scorecard system of farmer (i.e. stakeholder) perceptions of soil quality / soil health linked to land management practices and sustainability (e.g. Doran *et al*., 1996; Romig *et al*., 1996; Sarrantonio *et al*., 1996). The properties of a 'healthy' soil were perceived as (reported in Acton and Gregorich, 1995):

- Easier to plough - with lower fuel costs and wear and tear, and to work in the Spring;
- Sponge up and hold more water, but dry out sooner;
- Deeper and darker and break down autumn crop residues sooner and have higher organic matter and less erosion;
- Have greater numbers and variety of earthworms, but have fewer problems with insects and disease;
- Have a sweet, fresh-air smell;

- Require less fertilizer;
- Give greater yields, with better feed crops, healthier animals and lower veterinary bills;
- Have a greater variety of weeds.

This farmer-oriented approach has undergone considerable refinement in the USA and has culminated in the recent publication of the *'Soil Quality Thunderbook'* (USDA, 1999), in which questions are posed in terms of soil observations for the landowner to make and gives simple tests by which they can be graded. The links between farmer perceptions and some of the measures proposed on Table 2.3 are clear. In Canada, whilst taking note of the perception approach, attempts have been made to quantify soil quality indicators, *and their change over time*, at so-called *benchmark sites*. These are located in all the major *farmland* soil type / land use regions in Canada. The objectives of these 23 sites, first sampled between 1989 and 1993 (and to be re-sampled at 10 year intervals thereafter) were to provide (Acton and Gregorich, 1995):

- Baseline and re-sampling data sets for assessing changes in soil health and productivity…….of typical farm production systems;
- A way to test and validate simulation models that predict soil degradation and productivity;
- A way to evaluate whether farming systems in the major agricultural regions of Canada are sustainable;
- A national network of sites that can be used by Government and non-Government groups to conduct co-operative research.

Although these Canadian benchmark sites are exclusive to farmland, many of the objectives are similar to those of the UK Environmental Change Network, especially the detection of long-term change, the provision of baseline data that can be used for modelling, and their function as a focus for co-operative research (Sykes and Lane, 1996). The question of which ECN data might underpin indicators is, however, still open for discussion. It is also possible that small, but intensively investigated networks of sites such the ECN could act a control points for the quality assurance of a larger soil monitoring network.

There have been numerous attempts to rank indicators in order of importance and to give them weighting factors. For example, Doran and Parkin (1994) proposed a soil quality index system consisting of six elements SQ1 = food and fibre production; SQ2 = erosivity; SQ3 = ground-water quality; SQ4 = surface water quality; SQ5 = air quality; SQ6 = food quality). The overall soil quality index (SQ) is a function of these individual indices:

$$SQ = f(SQ1, SQ2, SQ3, SQ4, SQ5, SQ6)$$

However, it should be recognised that the interaction between these different aspects may be complex and require trade-offs in terms of land use and management. For example, the quality of alluvial soils may be high for food and fibre production (SQ1), given suitable inputs, but optimal inputs to maximise SQ1 may significantly reduce SQ2, SQ3, SQ4 and even SQ5. The other problem is achieving a wide consensus on the values of each of the weighting factors.

Table 2.3 Indicators of soil quality (from Doran and Parkin, 1996)

Indicators of soil condition	Relationship to soil condition and function; rationale as a priority measurement	Ecologically relevant values or units; comparisons for evaluation
	Physical	
Texture	Retention and transport of water and chemicals; modeling use, soil erosion, and variability estimate	% sand, silt, & clay; less eroded sites or landscape positions
Depth of soil, topsoil, and rooting	Estimate of productivity potential and erosion; normalizes landscape and geographic variability	cm or m; non cultivated sites or varying landscape positions
Infiltration and soil bulk density (SBD)	Potential for leaching, productivity, and erosivity; SBD needed to adjust analyses to volumetric basis	Minutes/2.5 cm of water and g/cm^3 row and/or landscape positions
Water holding capacity (water retention characteristic)	Related to water retention, transport, and erosivity; available H_2O: Calculate from SBD, texture, and OM	% (cm^3/cm^3), cm of available H_2O/30 cm; precipitation intensity
	Chemical	
Soil organic matter (OM) (total organic C and N)	Defines soil fertility, stability, and erosion extent; use in process models and for site normalization	kg C or N/ha-30 cm; noncultivated or native control
pH	Defines biological and chemical activity thresholds; essential to process modeling	Compared with upper and lower limits for plant and microbial activity
Electrical conductivity	Defines plant and microbial activity thresholds; presently lacking in most process models	dS/m^1; compared with upper and lower limits for plant and microbial activity
Extractable N, P, and K	Plant available nutrients and potential for N loss; productivity and environmental quality indicators	kg/ha-30 cm; seasonal sufficiency levels for crop growth
	Biological	
Microbial biomass C and N	Microbial catalytic potential and repository for C and N; modeling: Early warning of management effects on OM	kg N or C/ha-30 cm; relative to total C and N or CO_2 produced
Potentially mineralizable N (anaerobic incubation)	Soil productivity and N supplying potential; Process modeling; (surrogate indicator of biomass)	kg N/ha-30 cm/d; relative to total C or total N contents
Soil respiration, water content, and temperature	kg C/ha/d; relative microbial biomass activity, C loss vs. inputs and total C pool	Microbial activity measure (in some cases plants) process modeling; estimate of biomass activity

Smith *et al.* (2000) ranked soil quality indicators for agro-ecosystems, e.g. crop productivity is Rank 1; soil nutrient-holding capacity is Rank 3; erosion is Rank 2 and so on, the list of potential indicators being expressedly open-ended, and the rank assignment being a matter of judgement by experts. The latter is not unlike the farm-scoring system mentioned above and, indeed, Smith *et al.* (2000) encourage the use of such systems to populate soil quality indicators. Thus, the problem of the quantification of soil indicators was left open as is the problem of getting agreement on the magnitude of any weighting factors involved. Schipper and Sparling (2000) approached this difficulty with respect to New Zealand soils by examining the data for 13 primary indicators (total C; total N; cation exchange capacity; extractable P (Olsen' method); pH; CO_2 production; microbial biomass-C; potentially-mineralizable N; bulk density; moisture release characteristics; hydraulic conductivity; particle size distribution; particle density) at 29 sites (0-10 cm depth) across 9 great soil groups with matched examples of indigenous forest, plantation forest, pastures, and crops. Multivariate analysis showed that:

- Relatively constant soil properties such as particle size distribution were of little value in distinguishing different land management practices (however, they might be important in determining the impact of land management practices on other environmental media);
- It was necessary to be able to detect a change of 10% in an indicator value at the 90% confidence level if the indicator was to be of practical value in the assessment of change;
- Some measurements, e.g. microbial biomass-C and readily-mineralizable N, were so strongly related that it is only necessary to determine one of them;
- Interpretation of other indicators, e.g. soil respiration, is too difficult to be useful over large areas of land.

This process of assessment and rationalisation led to the selection of a *reduced set* of six indicators: potentially-mineralizable N; pH, bulk density; total C; Olsen P; macroporosity. Principal Components Analysis of these data for these six indicators grouped the land uses tolerably well (32% of the variation explained) and the individual measures all contributed significantly to the grouping (26% of the variance explained). However, Schipper and Sparling (2000) made two important points:

- Soil quality indicators are dynamic (and can thus be related to changes in Drivers and Pressures);
- The reduction in the number of indicators needs to be assessed carefully as by far the greatest costs are incurred in site visits and related field-work, rather than analysis. It may also be important to identify correlation between indicators, if one objective is to sum the indicators to derive an overall assessment.

Currently, New Zealand is experimenting with a simple soil quality indicator system (SINDI), which is available to users through a web-site (http://.www.landcare.cri.nz/). The system requires the selection of a soil type from among the 11 groups of New Zealand soils offered, offers 3 land uses (pasture, cropping, forestry), and either an expert interpretation of data or comparison with the complete data set of the national soil database. Figure 2.1 shows the data entry form and Figure 2.2. shows a typical output, whereby the soil indicator properties are presented as a ranking. In many ways, this approach represents the common dilemma associated with soil quality indicators. Are these six indicators a real reflection of 'quality', i.e. quality of which 'function' or functions in terms of the current project, and the emphasis on agriculture, which is discussed elsewhere.

Not everyone agrees with the soil quality concept or indicators of it. Sojka and Upchurch (1999) question the current '*institutionalising*' of soil quality, by which they mean that the concept has been accepted prematurely without adequate thought as to what it means or how it might be defined or used effectively. They also criticise the concentration of effort on attempts to define soil quality mostly on the basis of a narrow range of land uses (very heavily oriented towards agriculture in the USA, from where they are writing. The concentration of this type of work on semi-arid former grasslands, where demand for N is limited by water supply, and the N supply to crops is mainly from organic matter breakdown, leads to a greater emphasis on SOM than is the case in more intensive, more humid areas.). The core of their criticism is the near-impossibility of both quantifying soil quality in a multi-functional and often conflicting series of demands upon soil use, i.e. you can only effectively discuss soil quality once you have decided what particular function a soil is expected to perform. This is not altogether dissimilar to the view expressed below, where land use or land use change is usually the driver of any assessment of soil quality. In conclusion, they recommend quality soil management, rather than soil quality management. Davidson (2000) reinforces the message that soil quality is not a single function or concept, but is driven by the demands made on the soil; what is 'good' in one context will be 'poor' in another.

A series of papers (*ed*. Dumanski, 2000), returns to the measurement of *land* quality, rather than soil quality *per se*, arguing that it is land use rather than simply soil that is at the core of sustainable development for most of the world. There is pertinent discussion of the necessary interaction between the political, economic and scientific assessment of land use change, especially in the area of development. The '*MERIT*' approach is formulated, i.e. **M**onitoring - **E**xperimentation - **R**esource assessment - **I**nformation - **T**raining. Indicators do not feature specifically in this system, although they are implicit in the Monitoring, Resource assessment and Information modules. Within the following discussion of soil quality, two key (and very broad) questions were singled out for future research:

- Do current land management practices maintain, enhance or reduce the capacity of soil organic matter to support soil biological 'functional' groups;
- Do current land management practices maintain the biological life and biodiversity of the soil, and thus enhance the environmental resilience of the soil for maintenance of global life support functions. Reduced biodiversity is probably inevitable if land use changes from ‘natural’ to agricultural, but we have no clear idea of what would be the minimum *satisfactory* level of biodiversity.

Other papers in the series refer to indicators based on yield gaps (the difference between yield obtained and yield regarded as feasible), soil nutrient balance, soil cover by crops, indicators for water and soil erosion (through a 'bare-soil' index in Canada, or a soil water retention / crop cover assessment in France), salinisation, productivity ratings, changes in rates of processes such as deforestation, erosion, productivity, and a raft of socio-economic factors. Much of the work reported in these papers is qualitative or, at best, semi-quantitative. As Dumanski (*loc. cit.*) says, *'This series of papers is a step along the way, intended to provide a focus and guidance for further evolution of the programme*'. **The perennial difficulties of populating soil quality indicators with numerical values and interpreting these values in a range of contexts is made very clear**.

This leads inevitably to the need to accept that indicators of soil quality are not static and need to be reviewed at intervals to ensure that they are still performing a useful role. A balance needs to be found between indicators that change little, but are valuable by showing just that, and those which the data show are unlikely to change over a significant time-span. An example of the former might be biomass production, where the indicator shows that the nations are still producing adequate levels of foodstuffs, compared with the loading of metals to soils, where all the data show that the risk of reaching a target value within any meaningful time-span is very low indeed. Thus the first indicator would continue, whilst the frequency of measurement of the latter might change from, say, 5 years to 20 years.

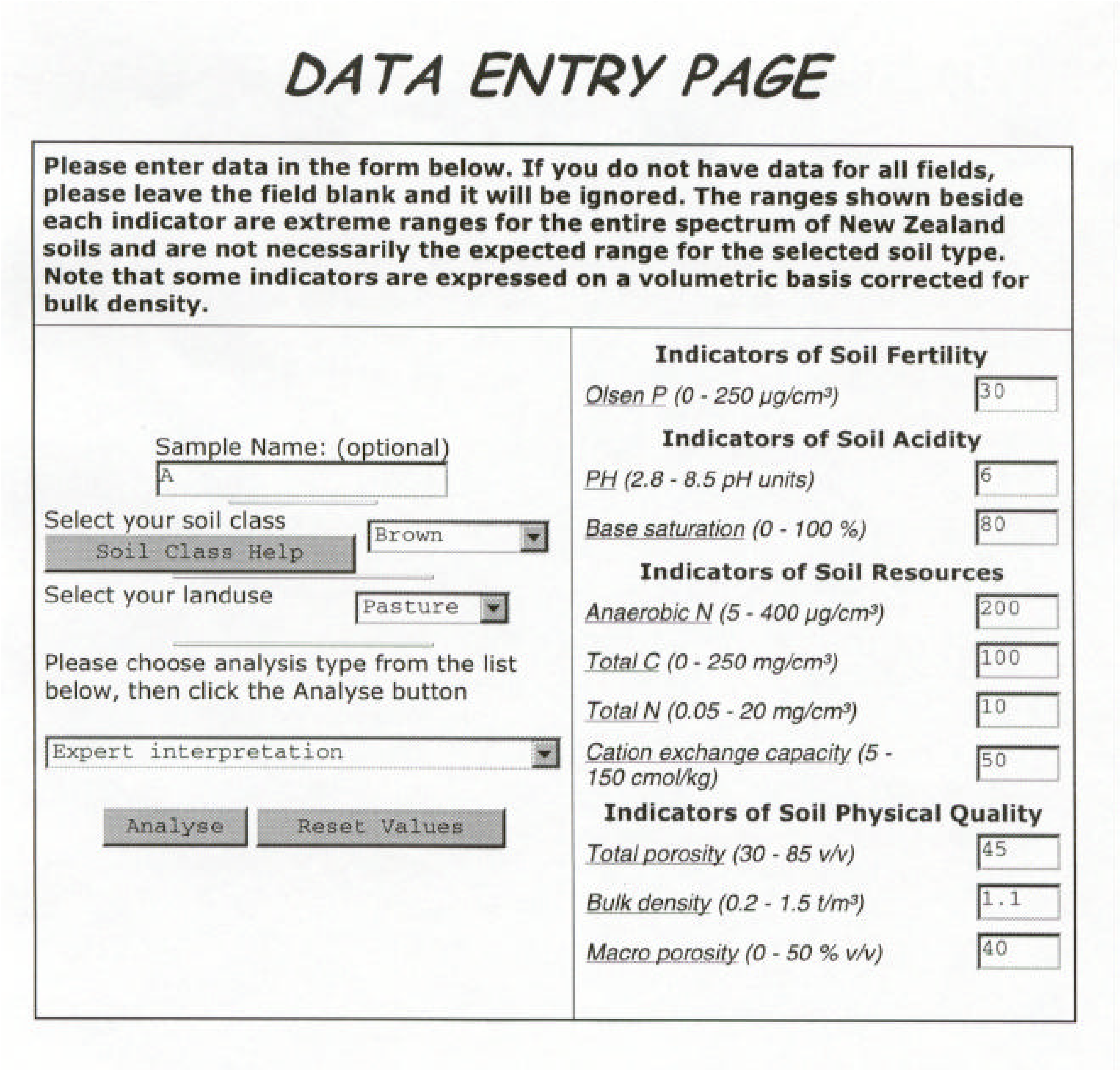


Figure 2.1: The data entry system for the New Zealand Soil Quality Indicators Project.

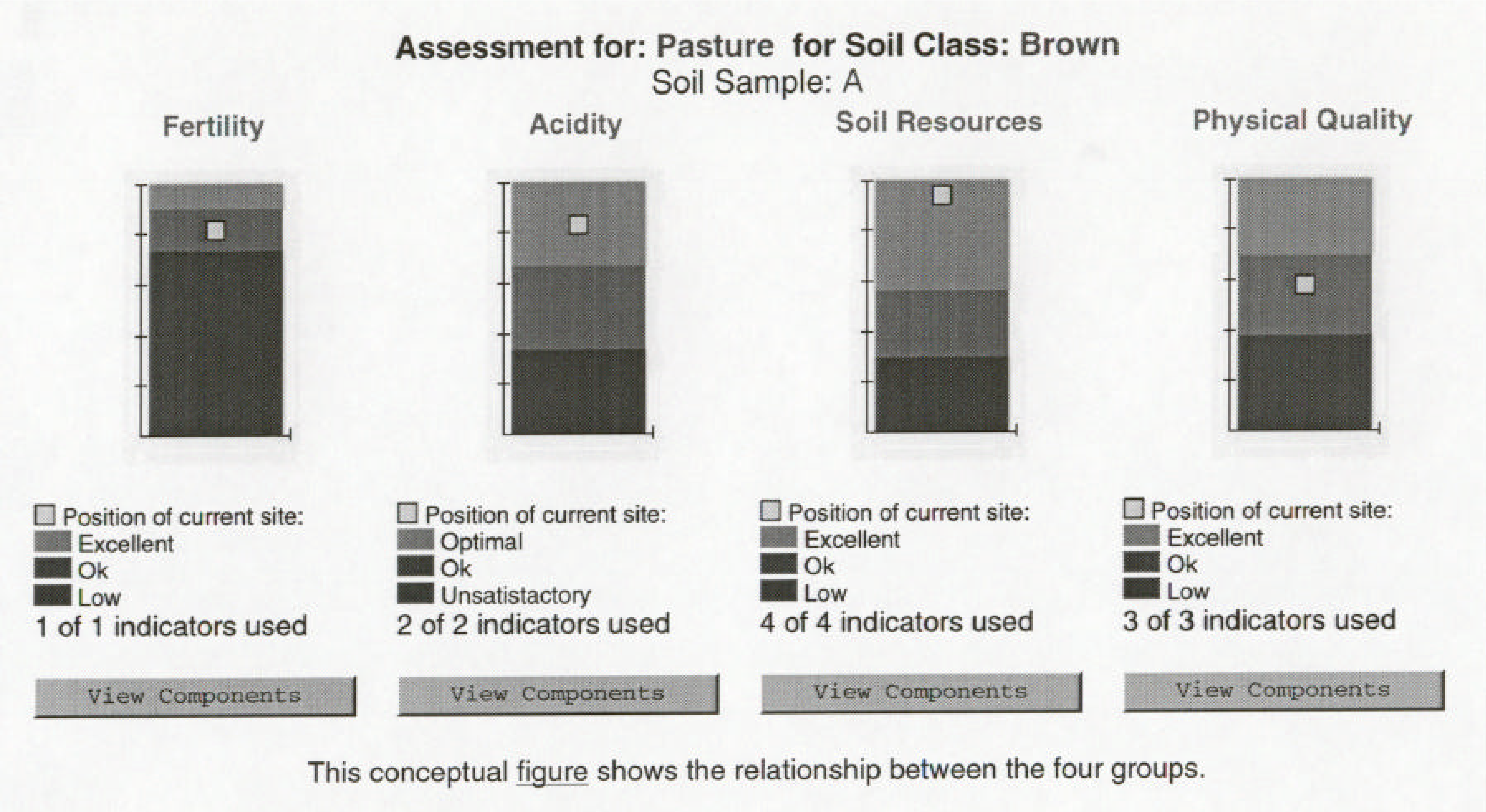


Figure 2.2 A typical output from the New Zealand Soil Quality Indicator System showing an expert assessment (pale squares) of the data entered in Figure 2.1.

Throughout the literature which forms the basis of this overview, reference is continually made to **P**ressure, **S**tate and **R**esponse (PSR). These references derive from the economic model of that name originally developed by OECD (1998). This is discussed in more detail below, but it is worth noting at this point that much of the work on soil indicators refers, inevitably to their *State*, i.e. their properties measured at some point in time (e.g. DETR, 1999; MAFF, 2000). This is not entirely surprising given the history of the collection of significant soil data throughout the world and the UK. Thus, a common response to questions about indicators for soil has tended to be an examination of the data we have, in an attempt to estimate the state of the nations' soils and, more rarely, an attempt to estimate whether the *quality* of soil is improving or declining, e.g. Loveland *et al*. (2000). However, as the review has made clear, there is a strong need to move beyond this point and examine whether potential soil indicator data can be used to inform debate about function.

3. ASSESSMENT OF THE SOIL FUNCTION APPROACH

3.1 Introduction

Any set of indicators which attempts to deal with the level of heterogeneity in UK soils in both space and time clearly needs to be fitted into a framework, whereby the various demands made on the soil now and in the future may be considered. The starting point for any such development is the premise that indicators are a handy and simple mechanism for measuring the state of whatever they relate to, i.e. the often asked question of *'soil indicators for what ?'*. This apparently innocuous question is at the heart of the problem whereby indicators of soil quality can very easily become all things to all people. This has the potential to reduce soil indicators to an ever-moving and unfocussed collection of disparate data. In order to minimise the risk of this, identification and calibration of an indicator requires the establishment of the values of the indicator which equate with:

- no loss or significant impairment of function,
- an expression of concern against some given time-scale, and
- a demand for immediate or remedial action.

This, in turn, requires understanding of:

- how the natural system works under normal circumstances (processes etc.),
- how the natural system reacts to perturbation such as human interference,
- how far the natural system can be disrupted by interference before irreversible change results (elasticity/resilience, buffering capacity, critical loads etc.)

In an ideal world, everything would be measured at a very large scale (many sites). However, with financial constraints, there is a need to be selective and to attempt to measure or derive a set of critical variables that inform policy and regulation on the sustainable management of soil.

Some of these functions are summarised in Table 3.1. For the wider environment it seems most appropriate to concentrate on the non-anthropic grouping. Our current interpretation of the nations' soil resource is that there is a workable model of soil function - the goods and services provided - but we don’t have a comprehensive understanding of how soil works or reacts to perturbations or of its ability to resist change (buffering capacities) or recover (critical loads and resilience). For instance, we could easily argue over the significance of organic matter depletion, although the spatial scale at which it is applied can give some clue as to its significance. Thus, the use of soil organic matter content to indicate structural vulnerability may be best interpreted at a field scale whereas, at the national scale, soil organic matter content might be a better guide to potential for climate change mitigation. At intermediate spatial scales, such as the water catchment, its role in relation to nutrient fluxes from land to water may be critical. For each of these, the optimum values might differ or, with a change of Driver, Pressure etc., vary. In a pragmatic sense, the UK does not have a sufficiently well-integrated land policy system that could react coherently to any indicators, were we to produce them, although the EC Water Framework might require such a response.

3.2 The proposed Framework

The consortium thus approached the topic with the following framework in mind, refining it in later Chapters. We think it important to stress the point that we are looking to deliver a robust and flexible *system* usable by the non-specialist. The system should be capable of accommodating changes in Drivers. Pressures etc. and priorities, without requiring extensive revision. We believe that this is what we have developed:

- 1. Definitions - for example, soil as the ecological component of land; land as an economic resource; summary of what have others said about soil indicators in the world literature.
- 2. Expert knowledge: update of views expressed in the literature (stakeholders through face-to-face interviews, email etc. (below).
- 3. Agreement over the national goods and services/function model for soil/land a movement toward the 'soil capacity' concept. This has been approached through a component chain:

  land use ® soil function ® key processes ® soil attribute(s)
- 4. The effective use, or otherwise, of the DPSIR approach.
- 5. Agreement over which indicator properties can be used to monitor the important pressures, states and responses for soil/land management policies.
- 6. Establishment of a primary list of past, present and future indicators for soil.
- 7. Scoring of these indicators according to various criteria, e.g. how much would each indicator cost to implement and/or maintain; what data do we have to support this indicator; has this indicator been applied or tested (if so, where and at what scale); where does the indicator fit in terms of a soil functional hierarchy; can the indicator be used as a surrogate for a desirable property which is difficult/expensive etc. to measure; does the indicator fit into current monitoring frameworks in time and space.
- 8. Assignment of the indicator to a 'fitness-for-purpose' ranking, and giving a weighting for robustness.
- 9. Establishment of a revised list of indicators.
- 10. Prioritisation of this list to obtain core or headline indicators to meet needs now and in the future
- 11. Assessment of the requirement for the monitoring of soil to supply data for these indicators at appropriate temporal and spatial intervals to meet multiple needs.

This approach has two advantages. Firstly, it allows a consensus of views to be established as to what is required of an indicator and what can be gained from previous work. Secondly, it allows for iteration in the assessment of indicators, so that modified views can be accommodated in a structured way. Thus, the prioritised list can be presented as a consensus.

These scenarios translate into a number of conclusions:

1. The indicators must relate to the soil's ability to provide mankind with 'goods and services', i.e. the functions we rely on it to perform.
2. Soil is a finite resource and therefore there have to be policy decisions made about how much of each good or service the community requires from a given area of land/volume of soil. This might relate, for example, to the planning process.
3. It is highly desirable that the indicators can be fitted into a formal framework, in which to identify what shapes a system, what condition it is in, and how it might respond to an adjustment. This minimises the development and use of indicators in an unstructured and /

or divergent way. One such framework is the **D**(river) - **P**(ressure) - **S**(tate) - **I**(mpact) - **R**(esponse) [DPSIR] model (OECD, 1998).

This framework has, for example, been used recently by the European Environment Agency (Düwel & Utermann, 1999; Luiten, 1999). Although the DPSIR model is also used by the EEA in its discussion of so-called *'Environmental Signals'* (EEA, 2000), soils do not - unfortunately - feature significantly in this Report, which is mostly concerned with economic indicators.

Table 3.1 Some soil functions

SOIL FUNCTIONS
ECOLOGICAL:
BIOMASS PRODUCTION
Agriculture (crops, animals, animal products)
Forestry
Semi-natural vegetation
Soil biomass
FILTERING, BUFFERING, TRANSFORMATION
Acidity
Nutrients (N, P)
Wastes (carbon based)
Persistent Organic Pollutants
BIOLOGICAL HABITAT, GENE POOL
Soil Biota
Terrestrial Habitats
ANTHROPIC:
SUPPORT FOR THE BUILT ENVIRONMENT
Buildings
Transport
Transmission structures
Recreation - formal/informal
RAW MATERIALS
Bulk minerals
Water
CULTURAL HERITAGE/ARCHAEOLOGY
Educational
Archaeological

4. THE DPSIR MODEL

4.1 Introduction

The **D**[river] - **P**[ressure] - **S**[tate] - **I**[mpact] - **R**[esponse] model is now in widespread use across Government for linking policy to environmental effect both pro-actively with policy as the driver and retro-actively with it as the response (see, for example, DETR/MAFF, 2001). However, certain points need to be borne in mind:

- The identification of **Drivers** in relation to soils can be unproductive, as they are often seen as self-evident concepts such as 'agricultural production' or 'wealth creation'. This is amply borne out by the overview of the literature, above. In one respect, however, the concept of Drivers becomes crucial, where this indicates that the soil might be completely lost, e.g. if it disappears under roads, buildings, water and so on. Even this drastic outcome might, however, require assessment because of the knock-on effects of such development on the air and water cycles, loss of important habitat(s), effects on biodiversity and so on.
- All soils are subject to **Pressures**, whatever the use of the soil at any one moment. Pressures may act locally or on a wider, even national, scale and may be acute or chronic in nature. Pressures reflect forms of land use and management (direct) and indirect human activities such as industrial production. They include the practices associated with the need to obtain a certain crop yield, the spreading of waste such as agricultural waste and sewage sludge, the deposition of emissions from industry, the desire to change land use.
- The **State** of a soil is what is most commonly measured, e.g. its pH, its carbon content, microbial biomass, heavy metal content and so on. State variables should not, however, be selected indiscriminately or simply on the basis of *'this is what we have'*, because they must be able to reflect response to impacts adequately, i.e. they must inform policy effects.
- **Impacts** are often less easy to define and may be represented as a change of state, e.g. pH changes from acid to less acid or carbon content increases. Changes in state can be very subtle and can be difficult to link categorically to an impact. A change in soil copper content may impact on soil biodiversity, **but the exact effect is at best difficult and costly to identify and, in the majority of situations, impossible under current technological and economic constraints**. Certain impacts will link into DPSIR models for other environmental resources such as water, air and wildlife, but that does not make the assessment of the effect any simpler or easier - often it becomes much more difficult.
- The **Response** is usually seen as the *policy response*, i.e. how should the soil system be managed to produce a change in impact, if that is what is deemed necessary, in order to achieve a more desirable state?

The DPSIR model has been employed in a current project aimed at identifying a set of soil indicators and it is therefore proposed as the basis of a conceptual approach to prioritisation of issues for soil protection. Figure 4.1 illustrates the place of the model and of a structured approach to risk assessment at the core of a wider conceptual framework that includes land use policy and proposed structures for soil functional and state models.

4.2 DPSIR and Soil Function

For a number of reasons it is necessary to approach soil protection at a landscape, catchment or administrative area level, rather than the individual soil profile. The objective of soil protection strategies and **land use policy** must be to achieve or maintain sufficient diversity in the soils of an area to support the land use objectives of the community and of regulatory or planning agencies and authorities. Soil multi-functionality and the range of direct and indirect services and ‘goods’ supplied by soil dictate such an area-based approach. Individual soils can only supply certain of these goods, never all of them.

Practicality argues for an approach to **soil function** that is land use based, and Figure 4.1 outlines the role of a suite of **soil function models** that define the functional requirements of soils under a number of primary land uses (farming, forestry, urban land etc). We take this view because users of soil indicators will often be non-specialists and will, not unreasonably, start by looking at the current situation. Table 4.1 illustrates one such functional model, that for farmland soils. The requirements in terms both of function and of soil properties for a farmland soil are very different from those required of soils beneath semi-natural vegetation used for the conservation of biodiversity. With land use policy formulation still segregated in industry and ministerial silos, it makes sense to have separate, individual functional models for each of the main policy sectors.

Soil-based land use planning seeks to optimise the match between soil use and soil capability, thus minimising soil impacts regarded as damaging or undesirable. In the present framework, land use policy is currently represented as a driver or pressure for change in the soil state. It is anticipated that the individual policies stated in Local and Regional Environment Agency Plans will become the main vehicles by which the Environment Agency will effect soil use - capability optimisation at the local level in the foreseeable future. Nationally and regionally, Vision Statements and the Environment Agency’s Soil Strategy will lay the foundations of policy.

Past attempts at definition of soil quality (see Chapter 3) have been hindered by either the belief that soil quality is measurable on a single axis and / or the desire to attach value judgements to estimations of soil quality in the absence of an end-use. Multi-functionality introduces multiple objectives and it is believed by the project team to be unhelpful to define soil quality in terms that do not refer to an intended **primary** function. Failure to do so opens the way for an almost endless catalogue of possibilities, many of which would be regarded as contextually absurd, and would run the risk of bringing the system into ridicule. **For this reason, a clear difference is recognised between soil state, when no value judgement is involved, and soil quality, which depends on the interpretation of the soil state.**

A multi-attribute system for quantifying the state of an individual soil is proposed (Figure 4.2), in which its state is described by reference to a series of relevant physical, chemical and biological attributes. For some of these attributes, the desirable range of values for a given primary function such as agricultural production is well-known. For instance, the target range of pH for farmland topsoils is long established, as is the undesirability of salinity. For other attributes and functions, knowledge is less developed, especially of processes (functions) and links between them. For example, despite considerable research, the real impact of contaminants, even common heavy metals, on soil components and functions is poorly understood. For some of the attributes, there is plentiful information, for others, such as the biological variables, there is virtually no information. There is a range of complexity and interactions between soil attributes which are simply not understood and are not likely to be understood over a short time-scale. It has to be borne in mind that the absence of knowledge of an effect does not mean there isn't one; it might be it has never been considered, or studied, or it is simply too complex to be considered as a viable target for research at present.

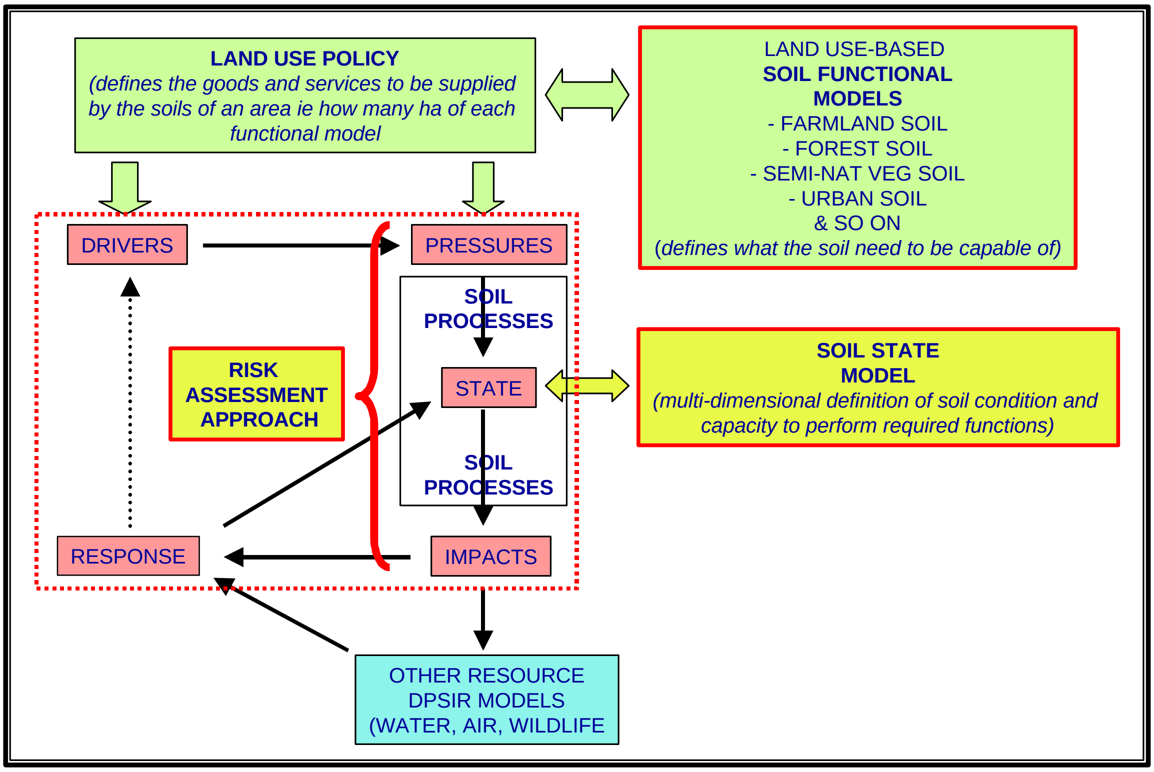


Figure 4.1 Proposed conceptual framework for prioritisation of soil protection objectives

Table 4.1 The functional requirements of a farmland soil

Primary function	Production of crop/animal biomass
Ancillary functions (Note: there could be a need to prioritise these in relation to primary function, but the order will differ depending on this).	Habitat for farmland plants and animals Degradation of xenobiotics used in crop/animal protection and production Controlled sink/source for nutrients Food source for farmland birds Carbon sink Controlled sink/source of water from precipitation (flood defence/water resources) Bio-digestor of organic wastes and associated contaminants Controlled source/sink for inorganic contaminants/trace elements Self-containment (i.e. it should not erode and contribute sediment to river systems/roads etc.)

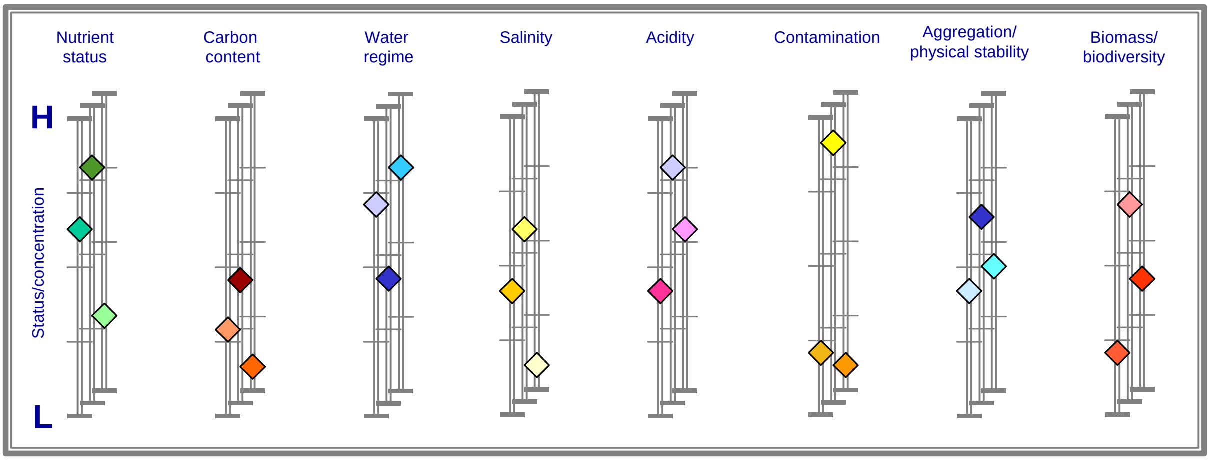


Figure 4.2 Multi-attribute system for quantifying soil state

With further research and development, **some** of the attribute value bars can be furnished with information indicating the desirability of particular values (Figure 4.3) and, therefore, the degree of fit between state, capability and primary use/function. Other attribute values will have to await the outcome of further research, and others might never be effectively populated (see also Chapter 9). With time, some attributes will be replaced by others deemed more suitable, perhaps based on better science, understanding, methods of measurement and so on, especially as Drivers and Pressures change, but the system proposed can readily accommodate such change (see earlier comments). In addition to soil, most models of land use capability or suitability incorporate landscape and climatic factors, but these are largely immune from the influence of human drivers and pressures other than by long term processes such as climate change. Such scenarios might lend themselves to the use of indicators in modelling. Certain of these attributes are candidates for indicators of soil quality.

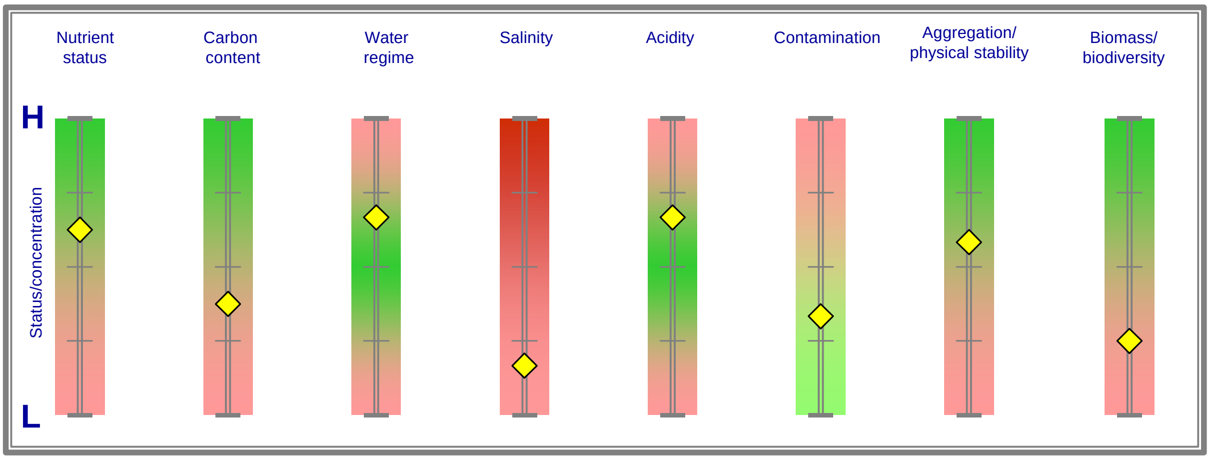


Figure 4.3 Multi-attribute quantification of soil state with target function attribute range information

Establishment of a DPSIR framework, and understanding and quantitative information on soil processes, would enable the Agency and others to prioritise issues forcing undesirable changes in soil state. However, it should be remembered that the most likely outcome of an initial assessment of priorities is the identification of hazards; risk assessment of these hazards comes later. This is outside the scope of this project.

5. THE APPLICATION OF THE DPSIR MODEL

5.1 Introduction

The previous Chapter examined ways in which the concept of the DPSIR model might fit into a pragmatic framework to assess soil quality. However, we still needed to know how the DPSIR approach actually functioned in an operational sense, i.e. could people use it as a practical tool and achieve something meaningful and consistent from it. Thus, the DPSIR model was applied to a number of sectors, with four main aims in mind:

- to test the practicality of the model when applied to land use questions in the UK;
- to see if the output of the approach leads to the identification of similar indicators for different sectors or land uses;
- to see if we could recommend its use as a pragmatic tool for non-specialists;
- to see at what point in the assessment process it might fit.

The Tables below give examples from a number of sectors, in some cases more than one Table (produced by different users) including the same land use system. This is deliberate and the manner of using the DPSIR framework is entirely up to the user, i.e. there is no formal guidance as to what can and cannot be done with this framework.

The following points emerged from this exercise:

- it was difficult to differentiate between Drivers and Pressures without descending into either platitudes or the obvious, or both;
- the DPSIR framework can be used in a preliminary assessment of the problem: it can be used as a 'checklist', as a means of deciding priorities, and as a means of more closely framing the question that is being asked;
- it can be very cumbersome, because it is completely open-ended. The more one considers the implications of using the framework, or the more one spends time using it, the greater the output can become. This is well-illustrated by Table 2.1;
- the framework tended to lead back to similar points from very different parts of the assessment. In this sense, the DPSIR framework can be useful for identifying common indicators;
- In many, if not all situations, the DPSIR framework was felt to add little to expert knowledge.

In conclusion, we found that the DPSIR framework could be a useful screening tool, but it was not an effective way of deriving soil quality indicators. There is a very real danger that the non-specialist could become very confused by its use as the major tool, with the real possibility that they would lose all faith in the whole value of assessing soil quality.

5.2 Examples of the Application of the DPSIR Framework

Table 5.1 Application of the DPSIR framework to Land Use System: Agriculture

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
MAFF	Biomass production	Farm profitability		Cultivation		Low organic matter	**Mean topsoil organic C%**	More erosion	**% of land eroding; Mean t/ha soil eroded**	Soil conservation measures	No of farm visits for soil conservation advice
										Set-aside	
										Increased river fish management spend	Salmonid fish stocks; salmonid egg survival rates
										Increased road cleaning spend	**Spend on road drain clearance; dirt on road prosecutions**
								Less biodiversity & living biomass	**Mean topsoil biomass; Mean topsoil biodiversity**	Increased conservation spending	Spend on conservation
								More capping & run-off	**% of fields with capping;** mean SPR and/or BFI	Increased flood defence spend	Spend on flood defence
										Conservation tillage systems	Spend on special equipment
								Less available water	Mean topsoil water content at field capacity	More irrigation	Irrigation water use
										Changed cropping	Growth in drought-tolerant crops
								Smaller nutrient store	**Mean topsoil total N**	Inc. fertiliser applications?	
								Weaker structure	Mean topsoil aggregate stability	Greater spend on larger cult machinery	Spend on cultivation equipment

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
MAFF	Biomass production	Farm profitability		Cultivation							**Mean energy consumption for cultivation; mean cultivation costs**
								Higher atmos C	Diffuse source contribution to atmos CO2	Greater controls over GHG emissions	
						More compact	Mean bulk density - topsoil or subsoil	Lower yields	Mean gross margins	Increased inputs	Spend on fertilisers and irrigation
								Lower infiltration/greater run-off	% of fields with surface water in winter; mean SPR and/or BFI	Greater spend on flood defence	Spend on flood defence
								Less biodiversity and living biomass	Mean topsoil biomass; mean topsoil biodiversity		
								More difficult cult conditions	**Mean energy consumption for cultivation; mean cultivation costs**	Inc cultivation spend	Spend on cultivation equipment
										Larger power units	Mean draught BHP of new units
						Less biodiversity & living biomass	Mean topsoil biomass; mean topsoil biodiversity	Poorer soil structure	Mean topsoil aggregate stability	Inc cultivation spend	**Mean energy consumption for cultivation; mean cultivation costs**

StHr	**Soil Fn**	**D**	**I_D**	**P**	**I_P**	**S**	**I_S**	**I**	**I_I**	**R**	**I_R**
MAFF	Biomass production	Farm profitability		Cultivation						Larger power units	Mean draught BHP of new units
								Poorer farmland wildlife	Populations of chosen farmland bird	More conservation spend/pressure	
						Lower permeability		Increased run-off	SPR; BFI	Increased flood defence spend	Spend on flood defence
								Increased erosion	**% of land eroding; Mean t/ha soil eroded**	Soil conservation measures	No of farm visits for soil conservation advice
										Set-aside	
										Increased river fish management spend	Salmonid fish stocks; salmonid egg survival rates
										Increased road cleaning spend	**Spend on road drain clearance; dirt on road prosecutions**
				Heavier , bigger machinery		Compaction	Mean bulk density - topsoil or subsoil	Lower yields	Mean gross margins	Increased inputs	Spend on fertilisers and irrigation
								Lower infiltration/greater run-off	% of fields with surface water in winter; mean SPR and/or BFI	Greater spend on flood defence	Spend on flood defence
								Less biodiversity and living biomass	Mean topsoil biomass; mean topsoil biodiversity		
								More difficult cult conditions	**Mean energy consumption for cultivation; mean cultivation costs**	Inc cultivation spend	Spend on cultivation equipment

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
MAFF	Biomass production	Farm profitability								Larger power units	Mean draught BHP of new units
				Use of pesticides	Mean annual application	Altered biology/less biodiversity					
				Use of fertilisers	Mean application rates kg/ha	Higher soil nutrient levels	**Mean topsoil N; P, K**	Increased nutrient leaching/run-off	Freshwater N, P, K concentrations; % of eutrophic freshwaters	Nutrient controls	Length of rivers, no. of lakes with nutrient control plans
								Less biodiversity	Mean topsoil biomass; mean topsoil biodiversity		
						Less biodiversity	Mean topsoil biomass; mean topsoil biodiversity				
				Grazing	**Stock grazing densities; national flock/herd**	Poaching		;Surface sealing and increased run-off			
						De-vegetation		Erosion	**% of land eroding; Mean t/ha soil eroded**	Soil conservation measures	No of farm visits for soil conservation advice
										Set-aside	
										Increased river fish management spend	Salmonid fish stocks; salmonid egg survival rates
										Increased road cleaning spend	**Spend on road drain clearance; dirt on road prosecutions**
				Waste application		Nutrient enrichment	**Mean topsoil N; P, K**	Increased nutrient leaching/run-off	Freshwater N, P, K concentrations; % of eutrophic freshwaters	Nutrient controls	Length of rivers, no. of lakes with nutrient control plans

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
MAFF	Biomass production	Farm profitability						Less biodiversity	Mean topsoil biomass; mean topsoil biodiversity		
						Contamination with vet products		Changes/impoverishment in biota	Mean topsoil biomass		
						Contamination with heavy metals		Changed soil biology	Mean topsoil biomass		
						Contamination with detergent		Changed soil biology	Mean topsoil biomass		
				Drainage	**extent of drained soils**	changed water regime	**mean duration of water logging; extent of soils in different drainage classes**	Less waterlogging in gley soils			
								Shrinkage and oxidation of peat soils	**Extent or volume of peat soils**		
								Drying out of associated wetland wildlife sites	Extent of damage to wetlands	Water table management plans	**Number of WMPs in place**
				GMO introduction		Genetic contamination of soil biota					
		Forest profitability (mainly uplands)		Cultivation		Bare soil surface		Increased erosion		Buffer zones	
						Deep disruption of soil profiles		Destruction of soil horizonation			
						Compaction and structural damage from heavy machinery					
				Land drainage		Deep disruption of soil profiles		Increased erosion		Codes of practice; buffer zones	

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
								Increased sedimentation in rivers		Codes of practice; buffer zones	
						Changed soil hydrology and drainage		Changes to site and river hydrology		Blocking of drains	
								Increased flooding down stream		Increased flood defence spend	
				Fertilisation of nutrient poor soils		Higher nutrient content		Changes to soil biota and biomass			
								Changes to semi-natural vegetation supported by soil			
								Eutrophication of related freshwaters			
				Increased acid deposition and acidity of tree exudates/litter		Lower pH		Greater mobilisation of acid-soluble cations (e.g. Al and heavy metals)		Liming	
								Changes to soil biological activity and biodiversity			
								Damage to stream chemistry and biology		Liming of sites	
				Disturbance by clear felling		Physically disrupted soil profiles		Increased soil erosion		Codes of practice	
								Increased nutrient fluxes			
								Increased sediment in rivers			

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
DTi		Energy policy (biomass cropping)		Heavy harvesting machinery in winter		Compact soil		Depressed coppice yield			
						Surface disruption		Increased erosion			
								Increased sediment in rivers			
								Increased nutrient fluxes to rivers			
				Disposal of metal rich sludges on sites		Higher metal concentrations		Changes to soil biota and living biomass			
DETR	Conserv. of biodiversity	Desire for more extensive sites with high biodiversity; habitat management plans		Reduction of nutrient status & productivity		Lower NPK contents					
				Reversal of land drainage improvements		Wetter soils and more waterlogging		Better habitat for certain birds but not others			
								Change to catchment hydrology			
						Changed soil biology		Better habitat for certain birds but not others			
		Conservation of existing wildlife sites		Maintenance of nutrient regime							
				Maintenance of hydrological regime for wetlands							
		Conservation of individual species									
		Agri-env regulation		Reduction of nutrient status & productivity							

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
				Reduction of land drainage improvements							
				Acidification		Lower pH		Greater mobilisation of acid-soluble cations (e.g. Al and heavy metals)		Liming	
								Changes to soil biological activity and biodiversity			
								Damage to stream chemistry and biology		Liming of sites	
DETR	Filtering etc	Desire for high natural water quality		Nutrient controls							
				Containment of diffuse contaminants in soil							
		Disposal of waste to land.		Disposal of potentially contaminated wastes		Increased contaminant loading		Changes to soil biology			
								Water pollution from leaching or run-off		Increased water treatment costs	
								Soil designated as contaminated		Land taken out of food production	
				Overloading of soil with BOD/COD				Run-off of wastes and soil to rivers		Pollution control action	
				Introduction of alien pathogens		Change to soil biology		Possible contamination of related water resources and supplies		Increased water treatment costs & loss of 'clean water' status	
		Use of polluting chemicals		Accidental release to soil		Contamination of soil		Change in soil biology		Clean up operation	

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
								Leaching or run-off of chemically contaminated soil to water		Site designation and clean up	
		Climate change protocols		Increased C storage in soil							
DETR/ MAFF	Water storage and release	Control of flooding		Use of land for emergency water storage							
				Demand for reduced run-off							
		Maintenance of river flows		Demand for higher summer river flows							
		Water supply		Flooding of reservoir floors		Submerged soil					
				Disturbance associated with pipe network installation		Disrupted soil along trench					
						Compaction along working line for bigger pipes					
DETR	Spatial platform	Demographic trends - more, smaller households; regional shifts.		Domestic & industrial development		Destroyed soil					
				Contamination from industrial use		Contaminated soil		Changed soil biology			
								water contamination from leaching and run-off			
		Transport provision		Land take for roads etc		Destroyed soil					
				Contamination and pollution from vehicles							
		Provision for recreation & sport		Landscaping of parks, pitches and golf courses		Disturbed soils					

StHr	Soil Fn	D	I_D	P	I_P	S	I_S	I	I_I	R	I_R
						Compacted soils					
				Visitor pressure in tourist sites		Bare soil		Increases soil erosion		Hard engineering of footpaths	**Footpath restoration costs**
DETR/ DTi	Raw materials	Demand for minerals		Stripping/loss of productive soil		Complete soil removal					
						Loss of structure in storage					
						Loss of biomass in storage					
						Loss of structure in restored soil					
		Demand for coal		Stripping/loss of productive soil		Complete soil removal					
						Loss of structure in storage					
						Loss of biomass in storage					
						Loss of structure in restored soil					
	Heritage protection	Demand for heritage conservation									

Table 5.2 Application of the DPSIR Framework to Forestry

1) The DPSIR system provided a useful framework within which to structure <u>initial</u> thoughts on the subject of indicators for forest soils. For example, with regard to the <u>s</u>tate of 'soil organic matter', the framework enabled clarification of commonly quoted, yet conflicting, impacts of timber production. Timber production may be expected to increase or decrease organic matter depending on the intensity of management as demonstrated below.

Soil function	Driver	Indicator of driver	Pressure on soil	Indicator of pressure	State of soil
Tree production	Economic demand for timber and woodfuel	Timber production	Increased intensive production forestry (residue removal, burning , windrowing)	Greater timber tonnage per unit land area	***Reduced organic matter content*** and fertility
Tree production	Economic demand for timber and woodfuel	Timber production	Increased area under conventional forest production	Increased woodland cover	Changes in soil morphology, chemistry and physics usually associated with forest growth - including ***increased organic matter.***

2) The most commonly encountered problem with the DPSIR framework was the varying levels of approach adopted for each element within it. Despite prior discussion amongst the group to define the constraints of each of these, different individuals and also often the same individual on different occasions, found it difficult to maintain continuity. Examples include:

- distinguishing between <u>p</u>ressures and <u>d</u>rivers
- the level of detail addressed in the <u>s</u>tates section. This could simply read 'fertility' or alternatively it could read 'extractable P, mineralisable N, base saturation'
- the <u>r</u>esponse section could either be that of the soil/landscape or of the politico-economic system

The consequence of each of these, but particularly the latter point, was that either intentionally or by mistake, the user could move the flow of thought (from left to right across the table) in various directions. **As such the DPSIR tool is vulnerable to manipulation.**

3) The final DPSIR tables for forestry contained much repeated material particularly in the <u>d</u>river, indicator(s) of <u>s</u>tate and indicator(s) of <u>i</u>mpacts sections. It was a common finding of the group that the same indicator would arise on multiple occasions. This has several implications. The most obvious is that the presentation of DPSIR tables as a final product of this exercise would <u>not</u> be valuable. This would provide too much information for any user to interpret effectively. However, as a development tool the tables may be useful, the debate in the following paragraph gives an example.

> The number of occurrences of each indicator could be used as an objective method of weighting their relevant importance. Conversely, it could be argued that the use of indicators occurring frequently on the table leads to a loss of uniqueness; as a result any changes detected through monitoring could not be related to a single cause and would thus be of limited use. There is therefore a

case either for choosing the least common indicators occurring on any DPSIR table, or for selecting the common ones but pairing each of these up with a driver indicator for monitoring purposes. The latter goes part of the way to reducing dependency on ‘post event’ indicators (such as those of state and impact) which only detect change once it has occurred and including predictive indicators which are associated with the drivers.

Regardless of which of the approaches discussed above might finally be adopted, the collation of a DPSIR table at least provides us with a basis from which to select and conceptually test different sets of indicators**. I believe that DPSIR is both a starting point and working tool, but not a final product.**

4) By stacking chains of DPSIR tables end on end positive and negative feedback loops could be identified which often ended with a response of ‘undertake cost-benefit analysis’. For example reduced nitrogen deposition leading to improved biodiversity but also increased fertiliser usage. As noted in 3) above, this provides a useful conceptual test for developing of indicators. The developer can use the stacked tables to visualise how the indicator under consideration would perform in all scenarios. E.g. Would it work during a recovery period or is it unidirectional?

Table 5.3 Application of the DPSIR Framework in a Multiple Land Use Context

Land use	Stakeholder	Soil function	Driver	Id	Pressure	Ip	State	Is	Impact	II	Response	IR
								on the, or of	the soil			
Agriculture	Farmers	1. Crop prod	1a More food	Yield	Nut't load	Nut budget	Fertility	P,K,Mg index	Eutrophicn.	Biodiversity	Reduce inputs	Nut budget
							Acidity	pH	Acidification			
									Water poll	Water chem	NVZs	Leaching
									Air polln.	Emissions	Reduce ems.	Emissions
										Hydrograph	Reduce erosion	Sediment load
					Irrign dem'd	Water use	Aquifer level	Water dem'd	Dry rivers	Hydrograph	Reduce water use	Water use
							Hydrograph	Aquifer level				
					Over cultivn.	Energy use? Passes?	Struc failure	Yield?	Erosion Crop failure	Hydrograph	Reduce cultn.	Energy use Passes
			1b Populn. increasing		Nut't load							
			1c Convert	Org/Conv	Nutrient	Nut budget	Fertility	as in 1a above				
			to organic	food sales	supply							
			(less food, better quality)									
		2. Inheritance	2a Sustain'b'ty	Yield	as 1a above							
				Erosion	Reduce	Yield	Fertility	SOM	continue as	in 1a		
				SOM	demand	Inputs	Acidity	P,K,etc.				
								pH				

Land use	Stakeholder	Soil function	Driver	Id	Pressure	Ip	State	Is	Impact	II	Response	IR
Agriculture	MAFF	Crop prod	Food supply Sustainabty Biodiversity Media	Yield	Continue as	in 1a						
	Envt groups	Biodiv	Biodiversity Landscape	Floral biodiv.	Nutrient load	Continue as	in 1a					
					Pesticide load	Pest. Use	Persistent chemicals in soil	Pest./chem. analyses	Biodiversity	Earthworms SMB	Reduce pest. use	Pest use
									Pest. In waters Fish stocks Invertebrates	Analyses of waters, fish, etc.	"	"
	Consumers	Food	Yield	Continue as 1a								
			Health	Illnesses caused by food	Improved food quality	Contaminants in food	Contaminants in soil	Metals, POPs	Soil qual.	Earthworms Metals POPs	Reduce inputs	Inputs
						Sales					Go organic	Organic area

Table 5.4 Application of the DPSIR Framework to Game Production

Luse	StHr	Soil Fn	D	I_D	P	I_P
Wild game production.	Land owners. CLA. “Hunters” field sports associations conservation bodies	Habitat maintenance. Biomass production. Food source.	Agricultural production. (Food).	Agricultural output/returns. Livestock numbers	Agricultural intensification, drainage, Grazing/trampling	Livestock numbers. Loss of habitat area Fenced areas; quantity of agrochemical inputs, data on drainage schemes Soil loss
			Timber production.	Timber production – type/area	New areas monocultures harvesting, access routes	Bare ground.
			Transport.	Vehicle type+numbers. Age of fleet. Fuel usage.	Traffic increase	Infrastructure area. Loss of habitat area Soil erosion.
			Energy production.	Energy production/consumption	Atmospheric pollution	Deposition levels of N, SO_4, NH_Y, NO_X, metals, PoPs, radionuclides
			Building +Industrial activity.	Industrial output. Fossil fuel consumption.	Infrastructure/Building. Mining/extraction	Infrastructure area. Loss of habitat area Soil loss/erosion Bare ground. Water quality
			Recreational pressures	Visitor numbers. Footpath lengths/usage Vehicle numbers Soil C content	Track/footpath creation. Traffic increase Traffic emissions	Track/footpath length, rate of creation. Loss of habitat area Soil loss Bare ground. Water quality
			Carbon sequestration	Climate change levies? Locally – Land use, livestock numbers, trace gas emissions, Soil carbon content, water quality	Increased CO2, temperature, rainfall	Met data; + soil moisture and temperature. Flooding
			Waste disposal	Type – Amount/unit area	Contamination	Monitoring of pollution levels – air, soil + water
			Conservation issues/ legislation; Agenda 21?	Records of important species	Intro. of pathogens, pests, exotics	Outbreak records, mapping

Table 5.5 Application of the DPSIR Framework to the Maintenance of Soil Biodiversity

Luse	StHr	Soil Fn	D	I_D	P	I_P
Preservation or conservation of biodiversity [Agriculture Forestry Habitats maintenance]	Agencies EA SEPA Landowners DETR Public Local authorities National Parks Authorities Conservation organisations Industry (pharmaceutical esp.)	Biodiversity reservoir	Agricultural production. Timber production. Transport requirements. Energy production. Industrial activity. Recreational pressures Climate change Waste disposal Game production	Agricultural output/returns. Livestock numbers Timber production – type/area Vehicle type+numbers. Age of fleet. Fuel usage. Energy production/consumption Industrial output. Fossil fuel consumption. Visitor numbers. Footpath lengths/usage Vehicle numbers Soil C content Climate change levies? Locally - Land use, livestock numbers, trace gas emissions, Soil carbon content, water quality Type - Amount/unit area Records of important species	Intensification, chemicals, grazing New areas monocultures harvesting, access routes Traffic increase Atmospheric pollution Infrastructure/Building. Mining/extraction Track/footpath creation. Traffic increase Traffic emissions Increased CO2, temperature, rainfall Contamination Intro. of pathogens, pests, exotics	Livestock numbers. Loss of habitat area Fenced areas; quantity of agrochemical inputs Soil loss Bare ground. Infrastructure area. Loss of habitat area Soil erosion. Deposition levels of N, SO_4, NH_Y, NO_X, metals, PoPs, radionuclides Infrastructure area. Loss of habitat area Soil loss/erosion Bare ground. Water quality Track/footpath length, rate of creation. Loss of habitat area Soil loss Bare ground. Water quality Met data; + soil moisture and temperature. Flooding Monitoring of pollution levels – air, soil + water Outbreak records, mapping

Table 5.5 (continued)

S	I_S	I	I_I	R	I_R	Comment
Maintenance of conservation status spp. Maintenance: microbial diversity/activity Maintenance: viable mycorrhizal communities Maintenance: viable invertebrate communities Non-viable pests, pathogens or exotics Maintenance of gene pool Soil stability Soil moisture status Nutrient status. Buffer capacity Acidity Carbon status Low pollutant levels (available vs total?) Mineralisation activity/potential.	Red Data book species Respiration measures; PLFA; ergosterol; microbial counts BIOLOG Bait infection Invertebrate populations. (biomass – key food spp.) Occurrence/counts in soil or soil solution Genomics techniques – gene library Bulk density, structure, porosity, Water holding capacity, Soil moisture content, water retention Hydraulic conductivity, water table depth CEC, Ex. cats/anions, soln. chem. P enzymes. P demand. Av. P., K. N., NH_3 Exch. NH_3 pH , base saturation, Ca:Al. Exchangeable acidity. Soil solution chem C, C:N, labile C Soil solution chem., trace gas fluxes Soil radionucs., metals + organics (bioavail.) soln vs soil; food chain levels Respiration measures - (de) nitrification rates/potential, C:N	Reduction in diversity, abundance, occurrence Change in habitat type or area Contamination in food chain Acidification of surface and ground waters. Eutrophication of surface waters. Sediment transport. Change in habitat Increased DOC, CO_2, N_2O emissions. Transfer to humans/ animals. Water contamination Change in habitat	Change in species composition, or biomass Change in plant species composition, or biomass Health implications for humans and animals Surface water acidity, ANC. Surface water P. Stream sediment levels. Trace gas emissions + DOC in water Water assays. Pollutant levels in plants, animal biomass/ shell thinning Plant community structure	Implementation of Local BAPs, national or regional conservation strategies. Modify land use Environmental health and animal welfare regulations Emission controls. Energy taxes. Energy efficiency measures. Controls on tracks/footpaths/access Emissions control, Energy effic. Etc. Modification of water purification processes Waste disposal regulations Implementation of Local BAPs, national or regional conservation strategies. Modify land use	Monitoring of Indicator species and/or habitats Monitoring of health and disease outbreaks Monitoring Emissions. Energy consumption-transport, house or industrial facility. Taxation Number of new tracks/footpaths. Reduction in vehicle access Planning restrictions/limits Regulator statistics Change in land use Regulator statistics	I_S – could be divided into short, medium and long term indicators. Medium and long term could be measured at a large number of sites in national surveys. Short term – small number of sites or site specific studies.

Table 5.6 Application of the DPSIR Framework to Agricultural Production

Luse	StHr	Soil Fn	D	I_D	P	I_P
Agricultural production (maintenance of agricultural environment?)	Land owners. Farmers. MAFF. Conservation agencies. National Parks Authorities Public – access Agencies	Medium for habitat maintenance Medium for biomass production. Biological reactor (waste disposal).	Demand for food/fibre	Output/returns, Stocking density,	agro-chemicals, grazing, drainage, burning, ploughing, waste spreading, traction, conversions (organic)	Livestock type + numbers, crop type + system, loss of habitat area, fenced areas; drainage schemes, agrochemical inputs, burn freq. + severity, Soil loss, erosion , Bare ground.
			Population density	Census data		
			Agric. Support policies	Support payment data		
			Employment	Employment statistics		
			Animal welfare	Healthy stock, vet. Stats.	Intro. of pathogens, pests, exotics	Outbreak records, mapping Healthy Stock
			Transport requirements.	Road densities Fossil fuel consumption	Traffic increase Local emissions	Loss of soil Pollution levels
			Energy production.	Energy production/consumption	Atmospheric pollution	Deposition levels of N, SO_4, NH_Y, NO_X, metals, PoPs, radionuclides
			Industrial activity.	Industrial output. Fossil fuel consumption.	Infrastructure/Building. Mining/extraction	Area, Loss of habitat area, Soil loss/erosion, Water quality
			Recreational pressures	Visitor numbers. Footpath lengths/usage Vehicle numbers	Track/footpath creation. Traffic increase Traffic emissions	Track/footpath length, density, Loss of habitat area, Soil loss, Bare ground, Water quality
			Climate change	Soil C content Climate change levies? Locally - Land use, livestock numbers, trace gas emissions, Soil C content, water quality, flood occurrence	Increased CO2, temperature, rainfall	Met data; + soil moisture and temperature. Flooding
			Waste disposal	Type + volume	Contamination	Monitoring of pollution levels – air, soil + water
			Game production	Stocking density	Habitat maintenance	Stock numbers Food source Plant community Habitat area
			Biodiversity maintenance	Records of important species, gene pool, diversity.	Habitat maintenance,	Plant community Habitat area Species occurrence

Table 5.6 (continued)

S	I_S	I	I_I	R	I_R	Comment
Soil stability (physical carrying capacity - erodibility) **Soil moisture status**	Bulk density, structure, porosity, Water holding capacity, Soil moisture content, water retention Hydraulic conductivity, water table depth	Water and sediment transport Changes in water transport	Flooding/drought events Stream sediment levels.	Drainage/irrigation strategies. Erosion control measures.	Data on water use; Number of schemes Number of new tracks/ footpaths. ??? Planning restrictions/limits	I_S – could be divided into short, medium and long term indicators. Medium and long term could be measured at a large number of sites in national surveys. Short term – small number of sites or site specific studies.
Buffer capacity	CEC, Ex. cations/ anions, soil sol. chem. P enzymes. P demand. Avail. P., K. N., NH_3	Acidification of surface and ground waters. Eutrophication of surface waters.	Surface water acidity, ANC. Surface water P/N	Emission controls - national to local (Rio to NVZ) Energy taxes - efficiency measures, traffic control	Monitoring emissions. Energy consumption- transport, house or industrial facility. Taxation, traffic numbers	
Acidity	Exch. NH_3 pH , base saturation, Ca:Al. Exchangeable acidity. Soil solution chem					
Carbon status	C, C:N, labile C Soil solution chem., trace gas fluxes	Increased CO_2, N_2O emissions.	Trace gas emissions.	Emission controls - national to local (Rio to NVZ), tax, efficiency measures, traffic control	Monitoring emissions. Energy consumption- Taxation, traffic N	
Low pollutant levels (available vs total?)	Soil radionucs., metals + organics (bioavail.) soln vs soil; food chain levels, growth regs.	Contamination of local biodiversity Contamination of water supplies	Pollutant levels in local biota body tissue/egg shell thinning etc Water assays (POPs, metals, pathogens etc)	Reduce agro-chemical inputs, Modification of water purification processes, Change in waste disposal practices	Water quality stats, chemical use data Monitoring emissions	
Nutrient mineralisation rates.	Respiration measures, (de) nitrification rates/potential, C:N etc	Crop – livestock yield or quality reduced	Yield figures Quality measures Profits margins	Change in farming practice, Reduction in intensification Modify agricultural subsidies	MAFF Farming statistics	
Maintenance of decomposer diversity/activity	Respiration measures; PLFA; ergosterol; microbial counts BIOLOG, SMB etc	Change in habitat type or area Reduction in food/habitat for local biodiversity	Change in plant species composition, or biomass Reduction in N, biomass, community structure	Development of Local BAPs, subsidies for habitat maintenance	Monitoring of soil biodiversity or habitats	
Maintenance of mycorrhizal diversity.	Bait infection					
Maintenance of beneficial invertebrate populations	Populations e.g. worms (N + biomass); food web					
Non-viable levels of pests, pathogens or exotics	Occurrence (nematodes, E. coli 157 etc)	Increased disease; human & stock. Crop – livestock yield or quality reduced	Levels of pathogens + pests in food and water	Environmental health regulations	Human health and animal welfare stats and schemes	

Table 5.7 Application of the DPSIR Framework to Catchments

Luse	StHr	Soil Fn	D	I_D	P	I_P
Water catchment.	Water companies. EA. Water users – public and industrial users Recreational groups	Filter and buffer	Demand for food/fibre Population density Agric. support policies Employment	Output/returns, Stocking density, Census data Support payment data Employment statistics	agro-chemicals, grazing, drainage, burning, ploughing, waste spreading, traction, conversions (organic)	Livestock type + numbers, crop type + system, loss of habitat area, fenced areas; drainage schemes, agrochemical inputs, burn freq. + severity, Soil loss, erosion , Bare ground.
			Animal welfare	Healthy stock, vet. Stats.	Intro. of pathogens, pests, exotics	Outbreak records, mapping Healthy Stock
			Transport requirements. Energy production. Industrial activity. Recreational pressures	Road densities Fossil fuel consumption Energy production/consumption Industrial output. Fossil fuel consumption. Visitor numbers. Footpath lengths/usage Vehicle numbers	Traffic increase Local emissions Atmospheric pollution Infrastructure/Building. Mining/extraction Track/footpath creation. Traffic increase Traffic emissions	Loss of soil Pollution levels Deposition levels of N, SO_4, NH_Y, NO_X, metals, PoPs, radionuclides Area, Loss of habitat area, Soil loss/erosion, Water quality Track/footpath length, density, Loss of habitat area, Soil loss, Bare ground, Water quality
			Carbon sequestration	Soil C content Climate change levies? Locally - Land use, livestock numbers, trace gas emissions, Soil C content, water quality, flood occurrence	Increased CO2, temperature, rainfall	Met data; + soil moisture and temperature. Flooding
			Waste disposal	Type + volume	Contamination	Monitoring of pollution levels – air, soil + water
			Game production	Stocking density	Habitat maintenance	Stock numbers Food source
			Biodiversity maintenance	Records of important species, gene pool, biodiversity.	Habitat maintenance,	Plant community Habitat area Plant community Habitat area Species occurrence

Table 5.7 (continued)

S	I_S	I	I_I	R	I_R	Comment
Soil stability (physical carrying capacity - erodibility) Soil moisture status Buffer capacity Acidity Carbon status Source of pollutants Nutrient mineralisation rates. Maintenance of decomposer diversity/activity Maintenance of mycorrhizal diversity. Maintenance of beneficial invertebrate populations Non-viable levels of pests, pathogens or exotics	Bulk density, structure, porosity, Water retention, Soil moisture content, Hydraulic conductivity, water table depth CEC, Ex. cations/ anions, soil sol. chem. P enzymes. P demand. Avail. P., K. N., NH_3 Exch. NH_3 pH , base saturation, Ca:Al. Exchangeable acidity. Soil solution chem C, C:N, labile C Soil solution chem., trace gas fluxes Soil radionucs., metals + organics (bioavail.) soln vs soil; food chain levels, growth regs. Respiration measures, (de) nitrification rates/potential, C:N etc Respiration measures; PLFA; ergosterol; microbial counts BIOLOG, SMB etc Bait infection Populations e.g. worms (N + biomass); food web Occurrence/counts in soil or soil solution (algae nematodes, whitegrubs, E. coli 157 etc)	Water and sediment transport Changes in water transport Acidification of surface and ground waters. Eutrophication of surface waters. Increased CO_2, N_2O emissions. DOC to water Contamination of local biodiversity Contamination of water supplies Change in habitat type or area Reduction in food/habitat for local biodiversity Contamination in food chain	Flooding/drought events Stream sediment levels. Surface water acidity, ANC. Surface water P/N Trace gas emissions. DOC levels Pollutant levels in water and biota, RIVPACS Change in plant species composition, or biomass Reduction in N, biomass, community structure Health implications for humans and animals	Drainage/irrigation strategies. Erosion control measures. Land use changes Emission controls - national to local (Rio to NVZ) Energy taxes - efficiency measures, traffic control Emission controls - national to local (Rio to NVZ), tax, efficiency measures, traffic control Reduce agro-chemical inputs Modification of water purification processes Change in waste disposal practice Change in farming practice, Reduction in intensification Change in practice Modify agricultural subsidies Development of Local BAPs, subsidies for habitat maintenance Environmental health and animal welfare regulations	Data on water use; Number of schemes Number of new tracks/ footpaths. ??? Planning restrictions/limits Monitoring emissions. Energy consumption- transport, house or industrial facility. Taxation, traffic numbers Monitoring emissions. Energy consumption- Taxation, traffic N Water quality stats, chemical use data MAFF Farming statistics Monitoring of biodiversity or habitats Monitoring of health and disease outbreaks	I_S – could be divided into short, medium and long term indicators. Medium and long term could be measured at a large number of sites in national surveys. Short term – small number of sites or site specific studies.

Table 5.8 Application of the DPSIR Framework to Habitat Maintenance

Luse	StHr	Soil Fn	D	I_D	P	I_P
Habitat maintenance	Agencies NGOs Land owners DETR CPRE Public National Trust CLA Game Conservancy	Growth medium Habitat Food source	Agricultural production.	Agricultural output/returns. Livestock numbers	Agricultural intensification, drainage, Grazing/trampling	Livestock numbers. Loss of habitat area Fenced areas; quantity of agrochemical inputs, data on drainage schemes
			Timber production.	Timber production – type/area	New areas monocultures harvesting, access routes	Soil loss Bare ground.
			Transport.	Vehicle type+numbers. Age of fleet. Fuel usage.	Traffic increase	Infrastructure area. Loss of habitat area Soil erosion.
			Energy production.	Energy production/consumption	Atmospheric pollution	Deposition levels of N, SO_4, NH_Y, NO_X, metals, PoPs, radionuclides
			Building +Industrial activity.	Industrial output. Fossil fuel consumption.	Infrastructure/Building. Mining/extraction	Infrastructure area. Loss of habitat area Soil loss/erosion Bare ground. Water quality
			Recreational pressures	Visitor numbers. Footpath lengths/usage Vehicle numbers Soil C content	Track/footpath creation. Traffic increase Traffic emissions	Track/footpath length, rate of creation. Loss of habitat area Soil loss Bare ground. Water quality
			Carbon sequestration	Climate change levies? Locally - Land use, livestock numbers, trace gas emissions, Soil carbon content, water quality	Increased CO2, temperature, rainfall	Met data; + soil moisture and temperature. Flooding
			Waste disposal	Type - Amount/unit area	Contamination	Monitoring of pollution levels – air, soil + water
			Conservation issues/ legislation; Agenda 21?	Records of important species	Intro. of pathogens, pests, exotics	Outbreak records, mapping

Table 5.8 (continued)

S	I_S	I	I_I	R	I_R	Comment
Maintenance of conservation status spp. Maintenance: microbial diversity/activity	Red Data book species Respiration measures; PLFA; ergosterol; microbial counts BIOLOG	Reduction in diversity, abundance, occurrence Change in habitat type or area	Change in species composition, or biomass Change in plant species composition, or biomass	Implementation of Local BAPs, national or regional conservation strategies. Modify land use	Monitoring of Indicator species and/or habitats	I_S – could be divided into short, medium and long term indicators. Medium and long term could be measured at a large number of sites in national surveys.
Maintenance: viable mycorrhizal communities	Bait infection					
Maintenance: viable invertebrate communities Non-viable pests, pathogens or exotics	Invertebrate populations. (N + biomass – key food spp.) Occurrence/counts in soil or soil solution	Contamination in food chain	Health implications for humans and animals	Environmental health and animal welfare regulations	Monitoring of health and disease outbreaks	Short term – small number of sites or site specific studies.
Maintenance of gene pool Soil stability Soil moisture status Nutrient status. Buffer capacity Acidity	Genomics techniques – gene library Bulk density, structure, porosity, Water holding capacity, Soil moisture content, water retention Hydraulic conductivity, water table depth CEC, Ex. cats/anions, soln. chem. P enzymes. P demand. Av. P., K. N., NH_3 Exch. NH_3 pH , base saturation, Ca:Al. Exchangeable acidity. Soil solution chem	Acidification of surface and ground waters. Eutrophication of surface waters. Flooding Sediment transport. Change in habitat	Surface water acidity, ANC. Surface water P. Water levels Stream sediment levels.	Emission controls. Energy taxes. Energy efficiency measures. Flood controls Controls on tracks/footpaths/access	Monitoring Emissions. Energy consumption-transport, house or industrial facility. Taxation Number of new tracks/footpaths. Reduction in vehicle use Planning restrictions/limits	
Carbon status	C, C:N, labile C Soil solution chem., trace gas fluxes	Increased DOC, CO_2, N_2O emissions.	Trace gas emissions + DOC in water	Emissions control, Energy effic. Etc. Modification of water purification processes	Monitoring Emissions. Energy consumption- Taxation. Reduction in vehicle use	
Low pollutant levels (available vs total?)	Soil radionucs., metals + organics (bioavail.) soln vs soil; food chain levels	Transfer to humans/ animals. Water contamination	Water assays. Pollutant levels in animal biomass/ shell thinning	Waste disposal regulations	Regulator statistics	
Mineralisation activity/potential.	Respiration measures - (de) nitrification rates/potential, C:N	Change in habitat	Plant community structure	Implementation of Local BAPs, national or regional conservation strategies. Modify land use	Change in land use Regulator statistics	

Table 5.9 Application of the DPSIR Framework to Carbon Sequestration

Luse	StHr	Soil Fn	D	I_D	P	I_P
Carbon sequestration	DETR MAFF Land Owners	C reservoir Source of trace gases	Demand for food/fibre Population density Agric. support policies Employment	Output/returns, Stocking density, Census data Support payment data Employment statistics	agro-chemicals, grazing, drainage, burning, ploughing, waste spreading, traction, conversions (organic)	Livestock type + numbers, crop type + system, loss of habitat area, fenced areas; drainage schemes, agrochemical inputs, burn freq. + severity, Soil loss, erosion, Bare ground.
			Animal welfare	Healthy stock, vet. Stats.	Intro. of pathogens, pests, exotics	Outbreak records, mapping Healthy Stock
			Transport requirements.	Road densities Fossil fuel consumption	Traffic increase Local emissions	Loss of soil Pollution levels
			Energy production.	Energy production/consumption	Atmospheric pollution	Deposition levels of N, SO_4, NH_Y, NO_X, metals, PoPs, radionuclides
			Industrial activity.	Industrial output. Fossil fuel consumption.	Infrastructure/Building. Mining/extraction	Area, Loss of habitat area,
			Recreational pressures	Visitor numbers. Footpath lengths/usage Vehicle numbers	Track/footpath creation. Traffic increase Traffic emissions	Soil loss/erosion, Water quality Track/footpath length, density, Loss of habitat area,
			Climate change	Soil C content Climate change levies? Locally - Land use, livestock numbers, trace gas emissions, Soil C content, water quality, flood occurrence	Increased CO2, temperature, rainfall	Soil loss, Bare ground, Water quality Met data; + soil moisture and temperature. Flooding
			Waste disposal	Type + volume	Contamination	Monitoring of pollution levels – air, soil + water
			Game production	Stocking density	Habitat maintenance	Stock numbers Food source Plant community
			Biodiversity maintenance	Records of important species, gene pool, diversity.	Habitat maintenance,	Habitat area Plant community Habitat area Species occurrence

Table 5.9 (continued)

S	I_S	I	I_I	R	I_R	Comment
Maintenance: microbial diversity/activity involved in C cycling	Respiration measures; PLFA; ergosterol; microbial counts BIOLOG	Reduction in diversity, abundance, occurrence	Change in species composition, or biomass	Implementation of Local BAPs, national or regional conservation strategies. Modify land use	Monitoring of Indicator species and/or habitats	I_S – could be divided into short, medium and long term indicators.
Maintenance: viable mycorrhizal communities	Bait infection	Change in habitat type or area	Change in plant species composition, or biomass			Medium and long term could be measured at a large number of sites in national surveys.
Maintenance: viable invertebrate communities involved in C cycling	Invertebrate populations. (N + biomass – key food spp.)	Contamination in food chain	Health implications for humans and animals	Environmental health and animal welfare regulations	Monitoring of health and disease outbreaks	Short term – small number of sites or site specific studies.
Non-viable pests, pathogens or exotics	Occurrence/counts in soil or soil solution	Acidification of surface and ground waters.	Surface water acidity, ANC.	Emission controls. Energy taxes. Energy efficiency measures.		
Soil stability Soil moisture status	Bulk density, structure, porosity, Water holding capacity, Soil moisture content, water retention Hydraulic conductivity, water table depth	Eutrophication of surface waters. Flooding Sediment transport.	Surface water P. Water levels Stream sediment levels.	Flood controls Controls on tracks/footpaths/access	Monitoring Emissions. Energy consumption- transport, house or industrial facility. Taxation Number of new tracks/footpaths. Reduction in vehicle use Planning restrictions/limits	
Nutrient status. Buffer capacity Acidity	CEC, Ex. cats/anions, soln. chem. P enzymes. P demand. Av. P., K. N., NH_3 Exch. NH_3 pH , base saturation, Ca:Al. Exchangeable acidity. Soil solution chem	Change in habitat DOC, CO_2, N_2O emissions… soil properties … habitat	Trace gas emissions + DOC in water …soil properties… plant species	Climate change levies Emissions control, Energy effic. Etc. Modify land use Modification of water purification processes	Monitoring Emissions. Energy consumption- Taxation. Reduction in vehicle use, land use stats. Regulator statistics	
Carbon status	C, C:N, labile C Soil solution chem., trace gas fluxes, respiration measures					
Low pollutant levels (available vs total?)	Soil radionucs., metals + organics (bioavail.) soln vs soil; food chain levels	Transfer to humans/ animals. Water contamination Change in habitat	Water assays. Pollutant levels in animal biomass/ shell thinning Plant community structure	Waste disposal regulations Implementation of Local BAPs, national or regional conservation strategies. Modify land use	Change in land use Regulator statistics	
Mineralisation activity/potential.	Respiration measures - (de) nitrification rates/potential, C:N					

Table 5.10 Application of the DPSIR Framework to Waste Disposal

Luse	StHr	Soil Fn	D	I_D	P	I_P
Disposal of waste to land	EA DETR Industry Waste disposal companies Local authorities NRPB?	Filter and buffer Biological reactor	Demand for food/fibre Population density Agric. support policies Employment Animal welfare Transport requirements. Energy production. Industrial activity. Recreational pressures Climate change Waste disposal Game production Biodiversity maintenance	Output/returns, Stocking density, Census data Support payment data Employment statistics Healthy stock, vet. Stats. Road densities Fossil fuel consumption Energy production/consumption Industrial output. Fossil fuel consumption. Visitor numbers. Footpath lengths/usage Vehicle numbers Soil C content Climate change levies? Locally - Land use, livestock numbers, trace gas emissions, Soil C content, water quality, flood occurrence Type + volume Stocking density Records of important species, gene pool, diversity.	agro-chemicals, grazing, drainage, burning, ploughing, waste spreading, traction, conversions (organic) Intro. of pathogens, pests, exotics Traffic increase Local emissions Atmospheric pollution Infrastructure/Building. Mining/extraction Track/footpath creation. Traffic increase Traffic emissions Increased CO2, temperature, rainfall Contamination Habitat maintenance Habitat maintenance,	Livestock type + numbers, crop type + system, loss of habitat area, fenced areas; drainage schemes, agrochemical inputs, burn freq. + severity, Soil loss, erosion, Bare ground. Outbreak records, mapping Healthy Stock Loss of soil Pollution levels Deposition levels of N, SO_4, NH_Y, NO_X, metals, PoPs, radionuclides Area, Loss of habitat area, Soil loss/erosion, Water quality Track/footpath length, density, Loss of habitat area, Soil loss, Bare ground, Water quality Met data; + soil moisture and temperature. Flooding Monitoring of pollution levels – air, soil + water Stock numbers Food source Plant community Habitat area Plant community Habitat area Species occurrence

Table 5.10 (continued)

S	I_S	I	I_I	R	I_R	Comment
Maintenance: microbial diversity/activity involved in nutrient cycling	Respiration measures; PLFA; ergosterol; microbial counts BIOLOG	Reduction in diversity, abundance, occurrence	Change in species composition, or biomass	Implementation of Local BAPs, national or regional conservation strategies. Modify land use	Monitoring of Indicator species and/or habitats	I_S – could be divided into short, medium and long term indicators.
Maintenance: viable mycorrhizal communities	Bait infection	Change in habitat type or area	Change in plant species composition, or biomass			Medium and long term could be measured at a large number of sites in national surveys.
Maintenance: viable invertebrate communities involved in nutrient cycling	Invertebrate populations. (N + biomass – key food spp.)	Contamination in food chain	Health implications for humans and animals	Environmental health and animal welfare regulations	Monitoring of health and disease outbreaks	Short term – small number of sites or site specific studies.
Non-viable pests, pathogens or exotics	Occurrence/counts in soil or soil solution	Acidification of surface and ground waters.	Surface water acidity, ANC.	Emission controls. Energy taxes. Energy efficiency measures.		
Soil stability Soil moisture status	Bulk density, structure, porosity, Water holding capacity, Soil moisture content, water retention Hydraulic conductivity, water table depth	Eutrophication of surface waters. Flooding Sediment transport.	Surface water P. Water levels Stream sediment levels.	Flood controls Controls on tracks/footpaths/access	Monitoring Emissions. Energy consumption- transport, house or industrial facility. Taxation Number of new tracks/footpaths. Reduction in vehicle use Planning restrictions/limits	
Nutrient status. Buffer capacity Acidity	CEC, Ex. cats/anions, soln. chem. P enzymes. P demand. Av. P., K. N., NH_3 Exch. NH_3 pH , base saturation, Ca:Al. Exchangeable acidity. Soil solution chem	Change in habitat				
Carbon status	C, C:N, labile C Soil solution chem., trace gas fluxes, respiration measures	DOC, CO_2, N_2O emissions… soil properties … habitat	Trace gas emissions + DOC in water …soil properties… plant species	Climate change levies Emissions control, Energy effic. Etc. Modification of water purification processes	Monitoring Emissions. Energy consumption- Taxation. Reduction in vehicle use Regulator statistics	
Low pollutant levels (available vs total?)	Soil radionucs., metals + organics (bioavail.) soln vs soil; food chain levels	Transfer to humans/ animals. Water contamination Change in habitat	Water assays. Pollutant levels in animal biomass/ shell thinning Plant community structure	Waste disposal regulations Implementation of Local BAPs, national or regional conservation strategies. Modify land use	Change in land use Regulator statistics	
Mineralisation activity/potential.	Respiration measures - (de) nitrification rates/potential, C:N					

6. CONCEPTUAL FRAMEWORK FOR SOIL MONITORING AND THE IDENTIFICATION OF INDICATORS OF SOIL QUALITY

6.1 Guiding principles

The principal purpose of defining and populating indicators of soil quality is the Government's commitment to sustainable development and environmental protection. A concept or definition of what is meant by soil quality is a pre-requisite, but this is made difficult by the multi-functional nature of soil and its inseparability from land, i.e. space that is subject to rights of ownership. Thus, in attempting to identify a suite of indicators, it seems sensible to set down a number of guiding principles.

1. the choice of indicators needs to be viewed against the backdrop of the overall policy aim of meeting and safeguarding the land-based needs of current and future communities, as set out in plans for areas of land, and of conserving sufficient soil diversity to protect the environment and natural biodiversity. For any given area of land, there is a bewildering number of plans (Figure 6.1). Soil indicators should **inform** the objectives of these plans, although they might not ultimately determine them.

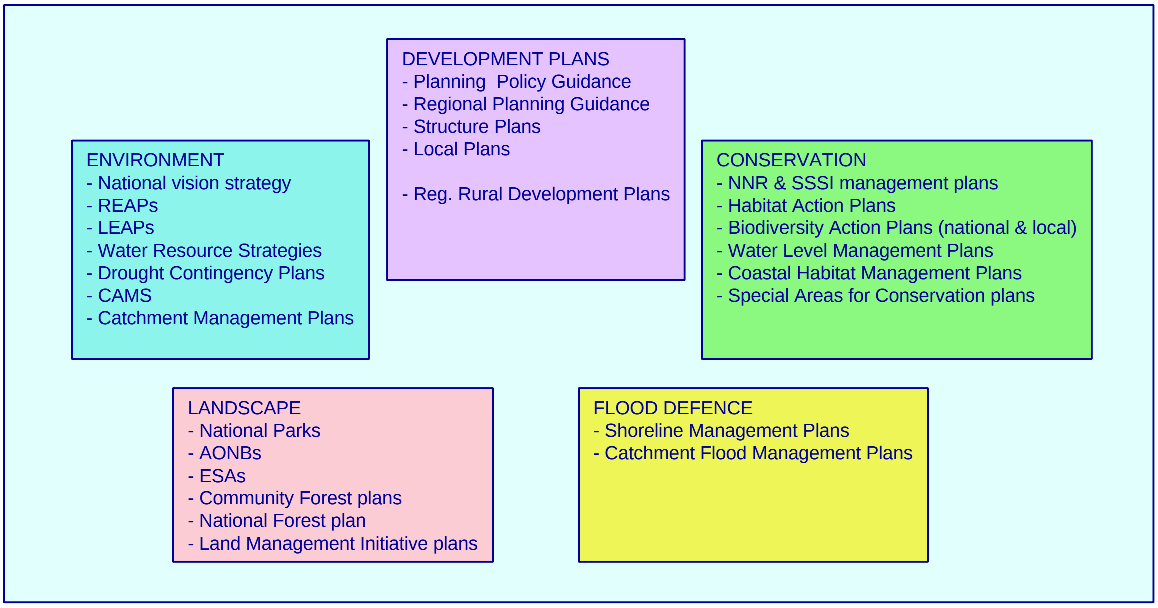


Figure 6.1 Land (and therefore soil) related plans and strategies

2. on that basis, indicators will need to be chosen to a) guide policy, use, management and/or conservation of **areas of soil** supporting a suite of land uses (plus the wider environment), **as well as** b) to indicate the quality of **individual soils**.
3. indicators have to be of practical use to groups who are developing or implementing policy on land use and management, or managing land for the following primary uses:
   - agriculture
   - forestry
   - development
   - highways and other forms of construction/infrastructure /soil sterilisation (i.e. development planning)
   - nature and heritage conservation

waste recycling to land
mineral extraction

4. at the same time, the approach taken should recognise the full range of goods and services that an area of land or individual soil is required to provide while being used and managed for delivery of one or more of the above primary forms of land use that can be associated with given policy fields.
5. indicators should fit into a hierarchy of soil monitoring objectives. Headline indicators, if they can be established, will be at the highest level of this hierarchy, while a wide range of monitored variables that do not all feed into indicators of soil quality will form the lowest level.
6. an arbitrary decision is taken with regard to the DPSIR model, namely that **Drivers** are socio-economic factors and **Pressures** are physical/environmental/natural factors.

6.2 User relevance - indicators and the planning/management process

Soil indicators need to meet the requirements of the user and be policy- or management-relevant. Users will range from the manager of an individual unit of land (e.g. a farmer), through planners, regulators, and agencies up to national Government, at which level policy makers are concerned with the adequacy of the finite resources of the nation. Without exception, the decision making process and the role of soil indicators at each of these levels can be represented by the plan-implement-monitor-evaluate cycle (Figure 6.2). In the second and subsequent planning cycles, the process is responsive rather than pro-active in nature (i.e. the R of the DPSIR model). The DPSIR model is used as a logical framework for analysing the relationship between drivers and pressures (agents of change), the response of the soil (change of state) and the actions of policy-makers/managers (responses). It can be used to characterise indicators, but is problematic for a number of reasons that are elaborated elsewhere in this report. However, it is worth re-iterating that it does offer a useful and pragmatic mechanism whereby thinking can be focused on four questions:

a) what is this soil doing at the moment and why is it doing it = current function(s) ?
b) what could this soil do = potential function(s) ?
c) what do we want this soil to do = desired function(s) ?
d) is this the best use of this soil, and why = optimum functions(s)?

It is obvious that indicators of function are required to help answer these questions (see more, below). Note, however, that although the questions are simple enough, we do not pretend that it is necessarily easy to answer them, and we well recognise that these questions might be even more difficult for the non-specialist to deal with.

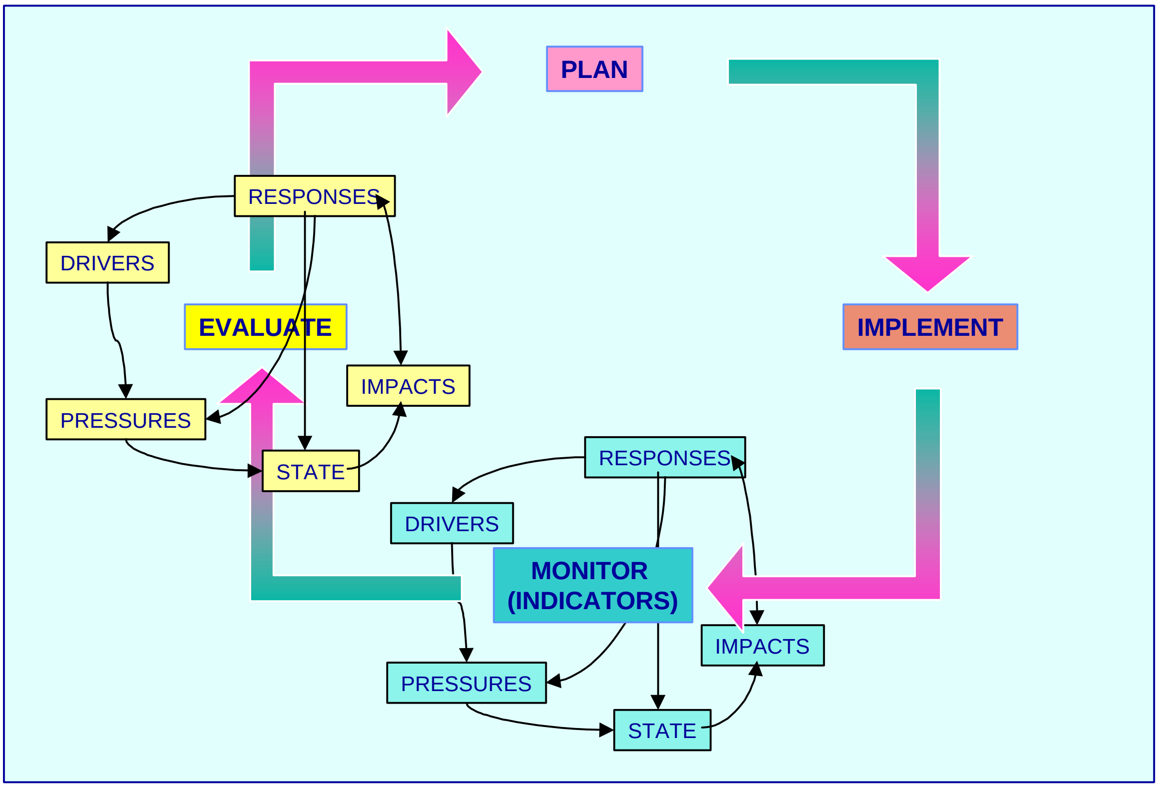
6.3 Soil multi-functionality

Within this cyclic process, indicators are used to measure performance, i.e. the degree to which stated objectives are being attained or not attained; this is impact-response. In terms of soil, these objectives relate to one or more soil functions. Soil multi-functionality is widely accepted, but there are numerous functional models and lists. This document identifies **a seven-function model**. Some doubt is expressed over the conventional function relating to the provision of raw materials, as this is not perceived to be a function of soil that is in any way influenced by soil as an organo-mineral, living resource. It is, however, included due to its influence over land use in areas of mineral wealth.

- Biomass production
- Filtering, buffering and transforming substances

- Supporting biodiversity
- Catching and releasing water to surface and groundwater
- Providing a sound platform for development and human activity
- Preserving heritage
- (Supplying raw materials)

Figure 6.2 The PLAN/IMPLEMENT/MONITOR/EVALUATE cycle and its relationship to the DPSIR model



Land use can be regarded as an expression of the dominance of one of these functions through targeted management. Thus, for agricultural soils, biomass is the adopted primary function. However, the wider community still relies on agricultural soils to deliver a range of other 'goods and services' that are traceable back to the above functions.

It is proposed, as the first building block of the framework, that a number of simple functional models be identified that define the goods and services to be supplied by soils under the principal forms of land use. Table 6.1 is such a model for agricultural soil that identifies the **primary function,** which drives most soil and land management decisions, and a list of **secondary or ancillary functions,** which may or may not be the focus of current or future management.

The value of this approach is that it defines the soil protection objectives for each policy or market sector. The links between soil and other resources such as air and water are clearly and specifically defined and this should discourage the marginalisation of soil protection that has characterised the past decades.

Table 6.1 Functions of a Soil used for Agricultural Production

1. Production of crop/animal biomass *while also being a*
2. Medium for the degradation of xenobiotics used in crop/animal protection and production
3. Controlled sink/source for nutrients
4. Source of food for farmland birds, mammals and arthropods
5. Carbon sink
6. Controlled sink/source of water from precipitation (flood defence/water resources)
7. Bio-digestor of organic wastes and associated contaminants
8. Controlled source/sink for inorganic contaminants/trace elements/atmospheric pollutants
9. Controlled medium for physical erosion and chemical weathering.
10. Habitat for farmland plants and animals

6.4 Classification of Soil Indicators

Indicators of sustainable development are required to inform a range of policy and management decisions centred on the following forms of question:

- is the resource stock in decline ?
- will the resource meet supply demand on a sustainable/acceptable basis ?
- is the resource functioning sustainably or is functional performance/capacity in decline ?
- how much does it matter if resource capacity or functional performance is declining ?

Based on the above analysis, **it is recommended** that three categories of soil quality indicator be adopted in order to allow for the full range of questions that will be asked of the soil indicator framework:

- **FUNCTIONAL PERFORMANCE INDICATORS** address questions of how capable a body of soil is of performing:

a) its primary function, and
b) b) its ancillary functions

- **RESOURCE CAPITAL INDICATORS** address questions relating to the aggregated effective soil resource and rate of loss or gain of capacity for an administrative area (regional / national / continental / global).

- **AWARENESS INDICATORS** address questions relating to public and professional awareness of, and concern for, soil. To some degree, they are a surrogate indicator of the significance and importance of soil degradation and/or depletion.

The three categories of indicators are outlined in Figure 6.3, which also indicates the likely geographical scale of application and DPSIR indicator types that are most likely under each category. Note that indicators can, indeed *must*, show both positive and negative aspects of soil state or function(s). A system will soon fall into disuse if it delivers only negative messages.

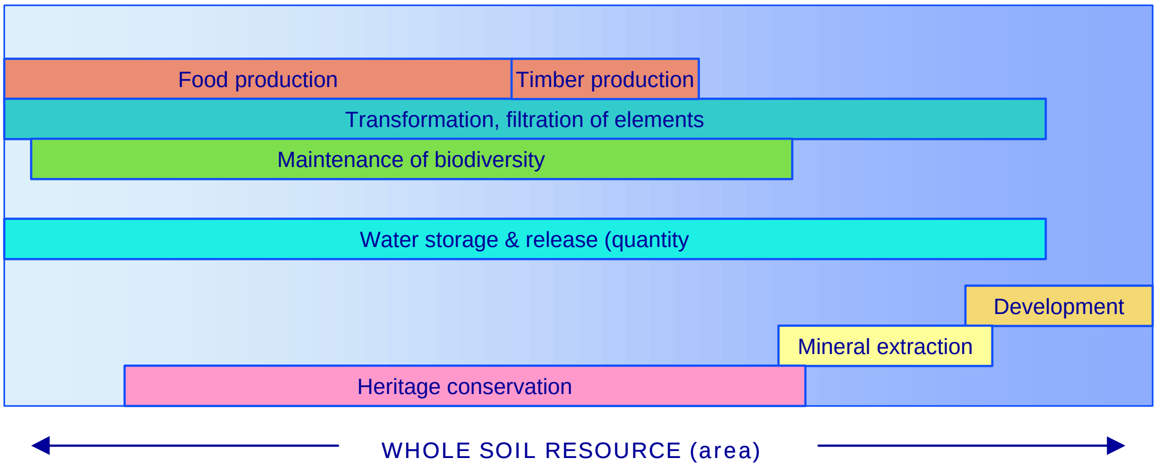
Category 1 indicators are perceived as national inventory indicators and will be relevant to land resource policy making - how much high quality agricultural land, how much land has valuable mineral resources beneath it, how much land is and will be used for housing and industrial development, how many contaminated land sites are there ?

Figure 6.3 Soil indicator categories

CATEGORY	TITLE	APPLICATION SCALE	MAIN INDICATOR TYPES
1	RESOURCE CAPITAL	NATIONAL OR ADMINISTRATIVE REGION	D P S I R eg farmland, lowland peat soils
3	FUNCTIONAL PERFORMANCE	NATIONAL THROUGH TO MANAGEMENT UNIT	D P S I R eg forest productivity, NO3 concn in groudnwater, river sediment; G/W NO_3
4	AWARENESS	ASPATIAL/NATIONAL	D P S I R eg public, officer awareness Newspaper coverage data

These indicators will be predominantly measurable by area (Figure 6.4). However, given the overall national objective of maintaining diversity of soil conditions, one indicator at least could usefully be an aggregate measure of the diversity of the national or regional soil resource.

Figure 6.4 Soil resource capital (capacity and consumption) indicators (category 1)



Category 2 indicators cater for the functional performance and capacity of a soil or area of land for primary and/or ancillary functions.

Managers of land and policymakers in primary production sectors need information on changes in the state of the soil that impact on its usefulness and primary functionality. Factors affecting the primary productivity of land for crops are an obvious example.

Where the chosen indicator is a state indicator, an understanding of the factors influencing fitness for purpose or productivity (Figure 6.5) is required to give meaning to the indicator. The debate over soil organic matter as an indicator of soil quality for agricultural production indicates that there are still gaps in knowledge that require to be filled. Rather like a set of sound quality slides in a sound studio, the optimum value and acceptable ranges of values for each of the properties will vary according to the target use. Desired nutrient levels, acidity and depth/frequency of waterlogging for agricultural crops as opposed to semi-natural habitats are the obvious example. This mirrors the SINDI model from New Zealand (Schipper and Sparling, 2000) but, unlike that model we propose that the concept is not confined to agriculture, but is open-ended. Indicators can be added at will and, when they are no longer useful, they can be removed without damaging the basis of the approach. The Soil State Model concept is the second building block of the proposed framework for indicators of soil quality and is described in more detail in a subsequent section.

With respect to the ancillary functions of soils, Category 2 indicators inform the user about impacts of soil management and external pressures on ancillary functional performance. Nitrate leaching from soils employed in agricultural production, sediment in rivers from agricultural and recreation land, or the acidification of rivers resulting from industrial and transport emissions are all examples. Figure 6.6 represents the relationship between land use (i.e. exploitation of the primary soil function) and the other (ancillary) functions.

Category 3 indicators are measures of the importance given to soil by Government and of how widely appreciated the role and importance of soil is within the general public and perhaps certain key professional groups. The possession and uptake of advice from the Code of Good Agricultural Practice for Soil is an example. The number of land owners employing soil maps and soil conservation practices is another.

Figure 6.5 Fitness for purpose framework (soil state model) for agricultural soils

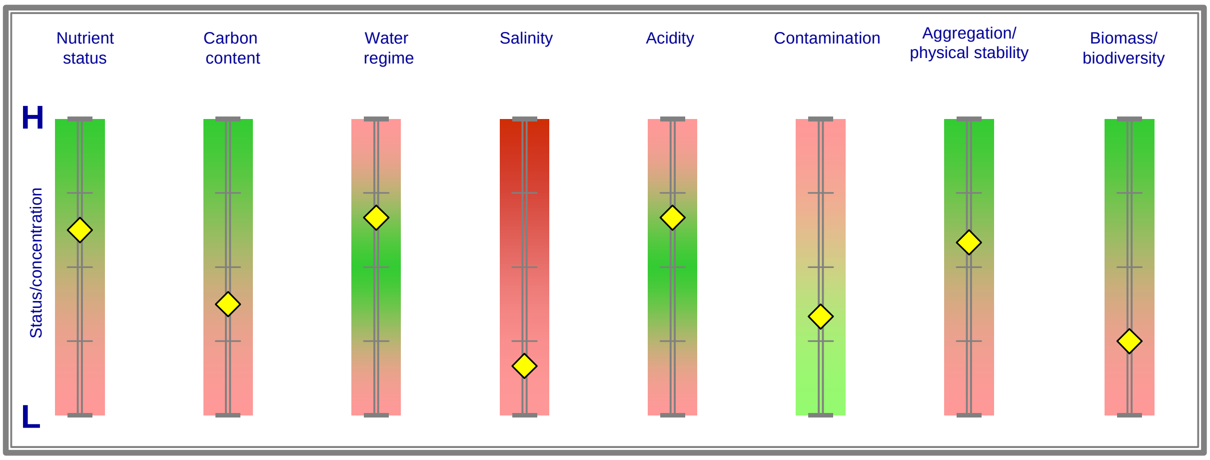
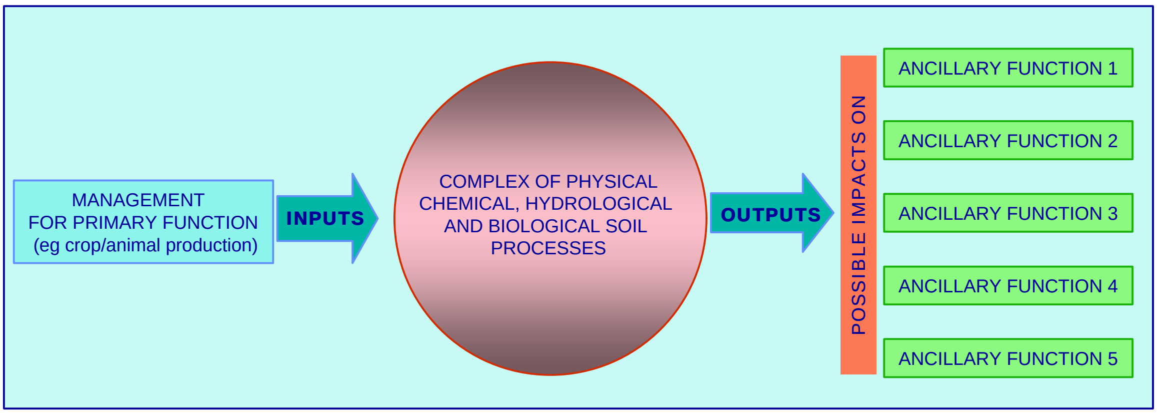


Figure 6.6 Soil Processes and Functional Interaction



Organisations and groups with a potential use for soil indicators have widely varying interests and needs (Figure 6.7). The three category framework is designed to meet these different demands.

In terms of the specific scientific issues that indicators should address, Figure 6.8 represents an attempts to highlight some of the current sustainable development issues that are present in the fields of soil-based land and environmental management. The diagram is a schematic representation of the environment, with processes that link soil to economic activity and the other natural resources identified in light blue. The policy issues are identified in purple.

6.5 Overall Framework

Two initial building blocks for the overall framework have been identified so far.

- Soil functional models
- Soil state models

Figure 6.9 illustrates a framework into which each of these building blocks could be fitted. Acceptance and further development of this overall framework would enable:

1. the DPSIR model to be adopted as a conceptual framework for managing soil quality and as one dimension in the categorisation of indicators;
2. soil multi-functionality to be represented conceptually and incorporated into land use policy and management decisions (via the *soil functional models*);
3. a model of soil functional capacity (*soil state models*) and a related suite of indicators to be developed within a policy and regulatory framework. This offers a practical solution to the sustainable management of the soil resource and wider terrestrial and freshwater environments.

Figure 6.7 Indicator categories and user groups

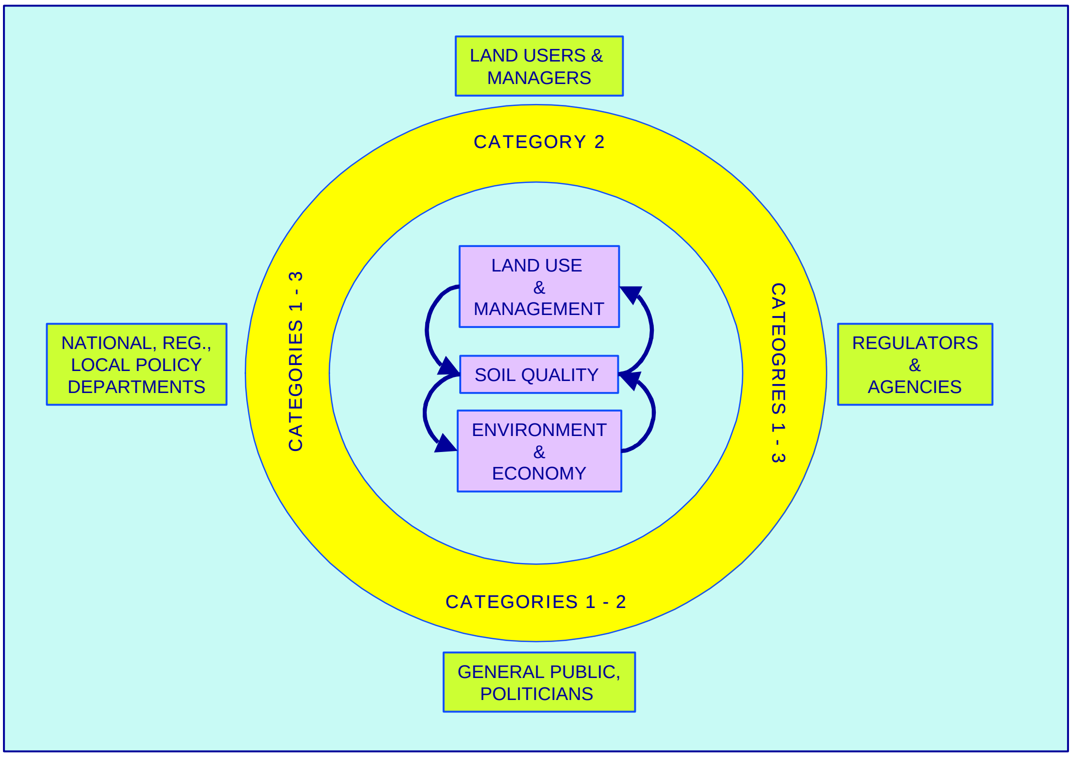


Figure 6.8 Sustainable development themes related to soil quality

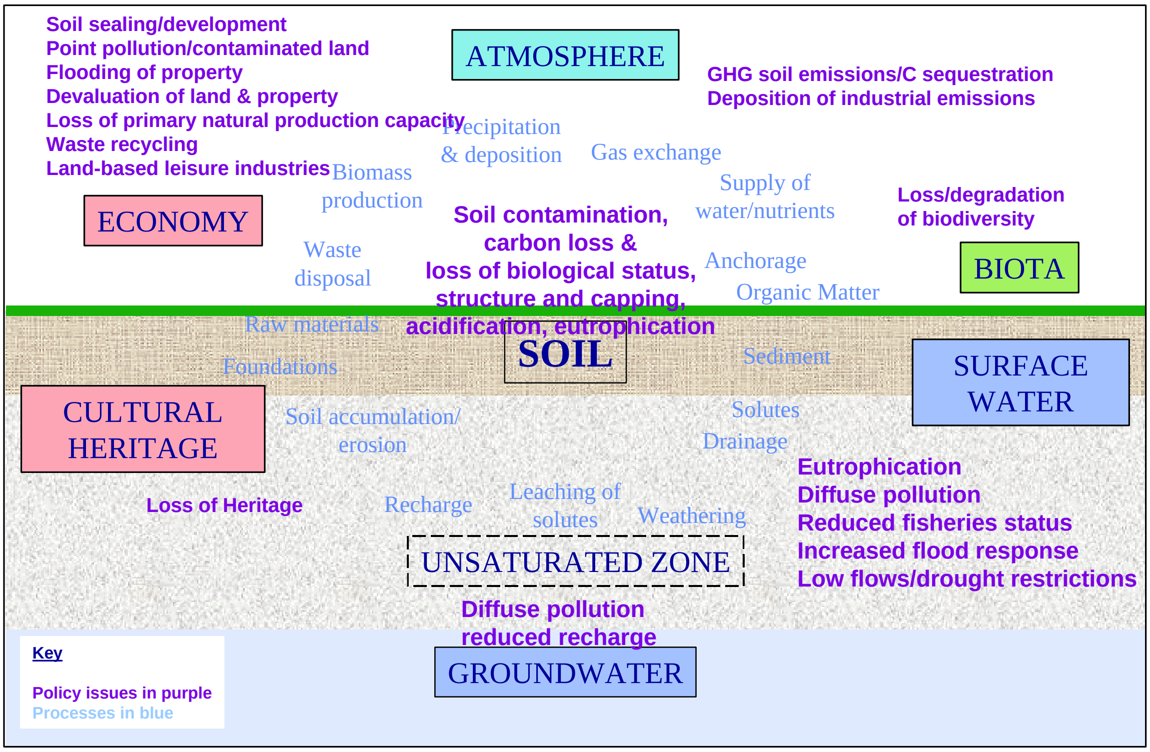
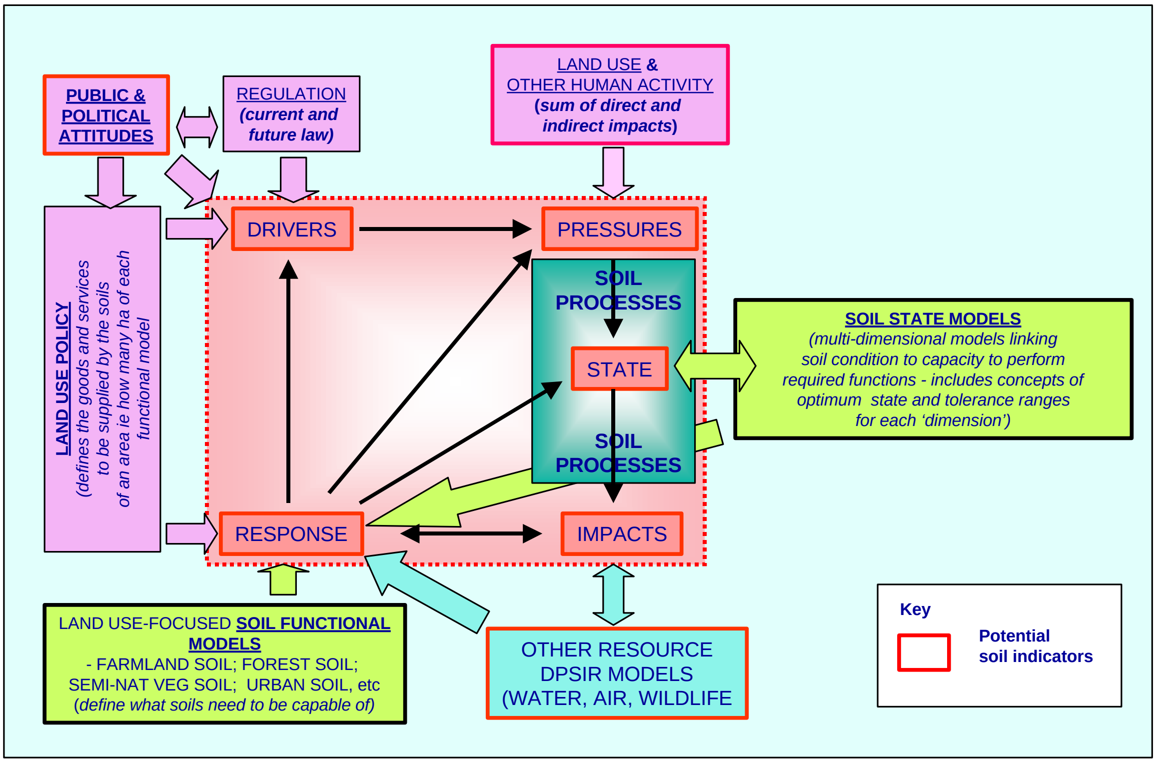


Figure 6.9 Overall framework for monitoring and sustainable management of soil quality



7. THE BACKGROUND TO MONITORING.

7.1 Introduction

Recommendation 8 of report on the Sustainable Use of Soil (RCEP, 1996) recommended the '*setting-up of a national soil quality monitoring scheme, the responsibility for which should lie with central government*…'. This concept is embedded in the consultation paper *'The draft soil strategy for England'* (DETR/MAFF, 2001) as: '*Effective soil monitoring will provide the information we need to understand the extent, diversity and quality of our current soil resource and how it is changing*.' Soil monitoring thus needs to function effectively in space and time as it is the mechanism by which most indicators will be populated by quantitatve values.

7.2 The Audience for Soil Monitoring

A number of reasons can be identified for monitoring soil.

1. To comply with the law, a code of practice, a quality target and/or policy;
2. To achieve a policy, quality or management objective;
3. To inform policy development (including the population of chosen indicators of soil quality), land or environmental management;
4. To understand the role of the soil within natural and human systems.

The population of indicators of soil quality is therefore only one of a number of reasons for monitoring soil and non-soil properties. Customers for soil monitoring range in their geographical scope and in the nature of their interest. Table 7.1 identifies broad classes of customers for a UK soil monitoring activity and classifies these into those with a strong interest in indicators of soil quality, those with a lesser interest and the remaining group with no interest in indicators data.

Within the UK, there are five national soil monitoring schemes, each with its own purpose:

- the Representative Soil Sampling Scheme (RSSS) (Skinner and Todd, 1998);
- the National Soil Inventory (NSI) (Loveland, 1990);
- the Countryside Survey (CS);
- ICP Forests (e.g. Lorenz *et al*., 2000) and
- the Environmental Change Network (ECN) (Sykes and Lane, 1996).

However, the basis on which soil samples are collected within theses surveys, and the analyses performed on the soils obtained differ greatly. The Representative Soil Sampling Scheme (RSSS) takes a sub-set of *c*. 900 of farms, derived from the Survey of Fertiliser Practice, and measures pH and the amount of nutrient in the soil by sampling them according to a rolling 5-year programme. Soil samples are taken from a depth of 25 cm. The National Soil Inventory (NSI) is based on a fixed 5 km grid of sites, which yielded 5692 sites, but they have been sampled less frequently, and only to a fixed depth of 15 cm or less. In Scotland, the NSI has also been assembled from a 5 km grid, but only alternate grid points were analysed for a range of properties. Thus for each 5 km point there exist data on site and profile characteristics while for the 10 km points these are supplemented by analytical data. In addition, it is important to note that in Scotland the different nature of the soil resource, with a much higher proportion of uncultivated soils, led to a horizon-based sampling strategy rather than a depth based one. In 1978, the Countryside Survey (CS) took samples from soil profiles at 5 locations within each of 254 1 km x 1 km squares representative of the range of landscapes in the UK. In 1998, the number of squares has risen to 569, but included re-sampling of the original 5 points within the original 254 1 km x 1 km squares. The Environmental Change Network (ECN) has a more intensive sampling regime than either the RSSS, NSI or CS, but there are only 8 sites in England and Wales and samples are taken at depth intervals inconsistent with other schemes.

Table 7.1 Customers for a soil monitoring network

Customers for soil monitoring	Customers for indicators-driven monitoring
<u>Supra-national</u> United Nations, OECD, European Commission <u>National</u> UK Government departments Executive agencies and other organisations NGOs <u>Sub-national</u> Regional offices of Government Local authorities Land managers Land users Industry	

This diversity of approach is meant to serve different functions and all the schemes have their strengths and weaknesses. However, it does illustrate the need to focus on factors such as:

- what is the purpose of monitoring;
- which ecosystems are of interest;
- where and how should the data collection sites be located;
- how many sites would give the maximum information for the minimum cost and effort;
- how can the robustness and integrity of the monitoring system be maintained;
- is there a need to detect change in the spatial structure of the data;
- over what time interval is the detection of change required;
- which indicators choose the stated purpose(s) best;
- which organisation becomes custodian of the data and how shall these be maintained and made available.

Any soil monitoring scheme would lose much of its value if the structure and protocols are not robust. It must be designed to withstand changes of technique, staff and government, with few operating procedures left to subjective judgements, as the information gathered will increase in value with the length of the monitoring period.

7.3 Choosing Sites

The purpose of a soil monitoring network (SMN) is to provide reliable data used to populate indicators. The data themselves will demonstrate whether any changes have occurred in given soil properties over time. The presence or absence of such change (whether it is an increase in or decrease in a property) may be used to demonstrate or predict a change in soil quality. It is also possible that the data may be used to derive, model or predict a property that is difficult to measure directly. The establishment of a SMN implies that choices have to be made about:

i) The soils themselves, which can be differentiated at several levels of complexity, such as:

- spatial extent, i.e. those soils which occupy the greatest area of land;
- a suite of soils which together represent the full range of properties/attributes likely to encountered;
- frequency of occurrence; it may be necessary to deliberately include sites representative of unusual conditions;
- soils representing environments under stress, e.g. subject to potentially large inputs of pollutants;
- soils which might be expected to respond rapidly to a change in environmental conditions, e.g. organic soils;
- whether understanding is required of the spatial structure within the data.

ii) Soil-land use combinations. The matrix representing this aspect could, again, be very large. Soil-land use combinations could be confined to major systems, e.g. urban vs non-urban soils; soils representatives of intensive agriculture, long-term grassland, and forest; landscape units. There are several ‘types’ within each of these categories which may need to be addressed in more detail. Experience of this approach in Scotland, using a combination of soil / land cover / climate is that the size of the matrix is largely dependent on the classifications used for the component parts. Using data in the NSI for Scotland, there are 132 vegetation classes, 69 climate classes and 32 major soil groups and major soil sub-groups. This results in 1750 unique combinations over 3090 sites. However, considerable simplification is possible using expert judgement.

A more difficult question is whether monitoring sites should be representative of normal land use practice, or whether sites should be ‘preserved’ under one particular system of land use. The latter may be acceptable for forestry, which has a long land use cycle, but could rapidly become atypical for, e.g. land under cereal cultivation.

iii) The density of observations. A soil monitoring network should be robust. This means that the data collected for particular sites should be demonstrably representative of the system that site represents. This has implications for the number of sites that should form part of the network. Is it better to choose a number of sites representative of a (relatively?) small number of environments, but for which we can expect reasonable statistics for assessing variability, or a larger number of sites which have fewer representatives in each class ? MAFF Project SP0124 showed, for example, that much of the spatial structure could still be discerned in the NSI data if only 25 per cent of the 5692 sites were used. The magnitude of the change which can be detected is influenced by the absolute values themselves, the range of the values, the magnitude of change that one wises to detect, and the statistical confidence with which one wishes to detect that amount of change.

iv) The following methods for selecting sites are widely considered:

- a regular net such as a grid (the shape of which could be the subject of much discussion). This approach has the advantage of simplicity, but the number of nodes to the grid, each of which could be a sampling point, needs to be large if the variation within the countryside is to be taken into account adequately (see point about the NSI data, above);
- a geostatistical approach, which would attempt to establish the variability of the landscape to be monitored. Whilst this might be the most attractive from a rigorously scientific point of view, it has large implications for the cost of preliminary work before a network could be established. It may be necessary to carry out a geostatistically-based investigation of a site before making a final choice as to its suitability;
- an expert judgement. This is popular in that it combines elements of the first two approaches. However, there has to be strong statistical control if serious bias is to be avoided;
- nested sampling, i.e. a number of sites within a landscape unit or within an area affected by an environmental pressure. The site locations within each unit could themselves be chosen by one of the methods mentioned above.

7.4 Choosing variables

Clearly there is a very large number of variables which could be monitored. These could be grouped as shown below, although we recognise that there are numerous systems for doing this, and one may have little advantage against another. Some of the variables listed are not necessarily obvious monitoring variables. They could, however, be necessary for site characterisation, and could be used in the formulation of pedo-transfer rules for the purposes of data extrapolation.

- relatively stable variables, e.g. particle size distribution, bulk density, soil water release characteristics; cation exchange capacity; soil mineralogy;
- potential pollutants, e.g. the common heavy metals (Cd, Cr, Cu, Pb, Ni, Zn), organic chemicals (of which pesticides are an obvious example, but the potential list is very large); other elements, of which As, Se, Hg, F, are obvious examples;
- ‘intensive’ variables, i.e. those which might change quite rapidly, e.g. organic carbon content, salinity; aggregate stability;
- special cases, the most obvious of which is that of radionuclides;
- biological variables, e.g. indicator species
- physical variables, e.g. structural features, run-off potential;
- the chemistry of the soil solution, which could be important, for example, in the determination of water quality.

Some of these variables might best be judged against the ability of a soil to buffer against them. There is also the need to consider surrogate measurements, i.e. the use of one measured variable to derive another, e.g. erosivity - from a combination of particle size distribution, organic carbon, salinity etc. Whether this should be regarded as monitoring in the strictest sense, is open to discussion, but we should not lose sight of the opportunity of adding value to measured data in this way. Some variables might also be useful as model parameters.

Not all variables will need to be monitored with the same intensity in space or time, and local circumstances will dictate that different sampling regimes might be appropriate for the same variable under different conditions. Measurement of soil solution chemistry could be necessary at intervals as frequent as every week, whereas background metal contamination might be measured only every 10 to 15 years. This has to be set against the need for a monitoring network which detects a relatively sudden change, so that we do not design a system which is monitored so rarely that it detects an important change 5 or 10 years after it has begun. In some cases, an alternative approach to measuring soil concentration, especially where one can be looking for small differences between large values, is to determine inputs *via* principal routes, and thereby make an assessment of (maximum) likely change. A nested sampling might then be enough to guard against missing a major change.

This highlights the very real problem of the precision to which a measurement of an indicator is required or sensible. It might be highly desirable or necessary to know of quite small changes in the concentration of a very toxic substance, e.g. a member of the dioxin family, but a much greater change in another variable might be of less concern. Again, this leads back to the need for some assessment of hazard and risk. Mention has already been made of pedo-transfer functions, and these are a common means of deriving properties for which there are few or no measured data. However, all the studies which have derived or used pedo-transfer functions have shown that their precision is often not good as expressed, for example, by the amount of variance explained. Thus, the use of such functions to derive indicators might be severely limited, as the output will simply not be considered good enough. This could be especially true in situations where regulatory values are concerned or where the derived values are used to indicate an increase or decrease in risk.

7.5 Quality Assurance and Harmonisation

Environmental data should be both representative and comparable. The first point is inherent in the points made above, i.e. what do you measure and where, and the second point raises a number of questions, not all of which relate to analytical methodology:

- geo-referencing (system, accuracy (+/- X metres);
- site layout - agreed protocol;
- site and soil description - standard system;
- sampling protocols;
- sampling frequency - variable dependent;
- sample treatment and storage (who keeps them, who pays for this, who has access to them and under what conditions ?)
- analytical methods - BSI, ISO ;
- analytical QA - participation in National and/or International validation programmes; limited number of laboratories; ring tests, use of some SMN sites to act as QA controls etc.;
- reporting and storage of data;
- who ‘owns’ the data, who has access to them, and by what mechanism;
- the need for links to international networks;
- who ‘owns’ the intellectual property inherent in derived data.

The aim of the SMN is to monitor soil properties (variables) over a period of time (not necessarily defined) in order to measure changes and identify trends. The properties can be indicators themselves, or they can be used to derive indicators. However, the indicators can be expected to change at different rates, some of which may be almost imperceptible. It will therefore be necessary design a monitoring schedule for each variable. Some might require annual sampling, others require medium-term sampling, and still others will only change very slowly, if at all, and may only require sampling once a decade or more.

Most existing SMNs include a common set of basic variables (particle size analysis, total organic carbon, pH, and main nutrients), but many of the detailed variables are only measured in a smaller proportion of sites, if at all.

It is suggested, therefore, that there could be three basic sets of variables (Tables 7.2 to 7.4):

- **Minimum data set (MDS)**: variables to be monitored at all sites to which they sensibly apply; this could mean grouping site-types, e.g. organic soils vs. mineral soils, acid soils vs. calcareous soils etc.;
- **Regional data set RDS)**: variables to be monitored at some sites in addition to MDS, according to local or regional concerns;
- **Non-site variables**: information to be collected from non-site sources, *e.g.* centrally held census data, remote sensing data.

Table 7.2. Examples of Minimum Data Set variables

Family	Variables
Site characteristics	Elevation, slope, meteorological data
Soil type	classification, particle size analysis, soil profile description
Vegetative Cover	vegetation class (Corine biotope ?) or broad (agricultural) land use
Nutrients	macronutrients (total and available), selected micronutrients
Organic carbon	total, fractions - more or less 'active'
Soil chemistry	pH, cation exchange capacity, base saturation, 'reactive' forms of Al, Fe, Mn, lime requirement (or a measure of buffering capacity), adsorption indices
Soil water characteristics	complete retention curve, air capacity, plant available water capacity, infiltration rate, hydraulic properties
Soil structure	shear strength, compaction, aggregate stability, erosivity, capping, porosity, bulk density
Soil biology	biodiversity, respiration activity, key species (earthworms)
Contamination	heavy metals, organo-chemicals, radio-nuclides, other toxic elements
Soil management	none, fertiliser/manure, tillage, burning, chemicals, livestock

In some systems, the Regional and Non-site variables / indicators would be regarded as 'high-level' or *headline* indicators, i.e. overall assessments of soil quality, that might not depend directly on measurements made of the soil or soils themselves. One example could be the suspended sediment load in surface waters, which would be a headline indicator of the amount of run-off / erosion within a catchment. An increase in the value of the indicator could be a warning of soil quality deterioration, leading to more detailed investigation of the cause. However, some caution is required before taking this approach. It could easily fall into the 'all eggs I one basket' system. One needs to be very certain that the desired objectives are being fulfilled. For example, stream turbidity might be a very good indicator of run-off, erosion etc., in circumstances where it can be reasonably certain that such change in water quality is due to these factors and only these. If not, then it could be positively misleading.

Table 7.3. Examples of Regional Data Set variables

Family	Variables
Erodibility	rain aggresivity, evapotranspiration, slope, vegetation cover & biomass
Acidification	acid deposition (wet and dry), soil parent material, mobile Al, pH, key species
Salinisation	irrigation, evapotranspiration, saline and sodic development, water retention, electrical conductivity
Eutrophication	N deposition (wet and dry), available soil N; key species

Table 7.4. Examples of non-site indicators

Non-site indicators	
Indicator	**Variables**
Contaminated land	total area of contaminated sites
Greenfield development	total area of new greenfield development ratio of greenfield : brownfield development
Conservation	total area protected under conservation agreements
General land use	total areas under arable / grassland / forestry/ amenity / unmanaged / residential / industrial use

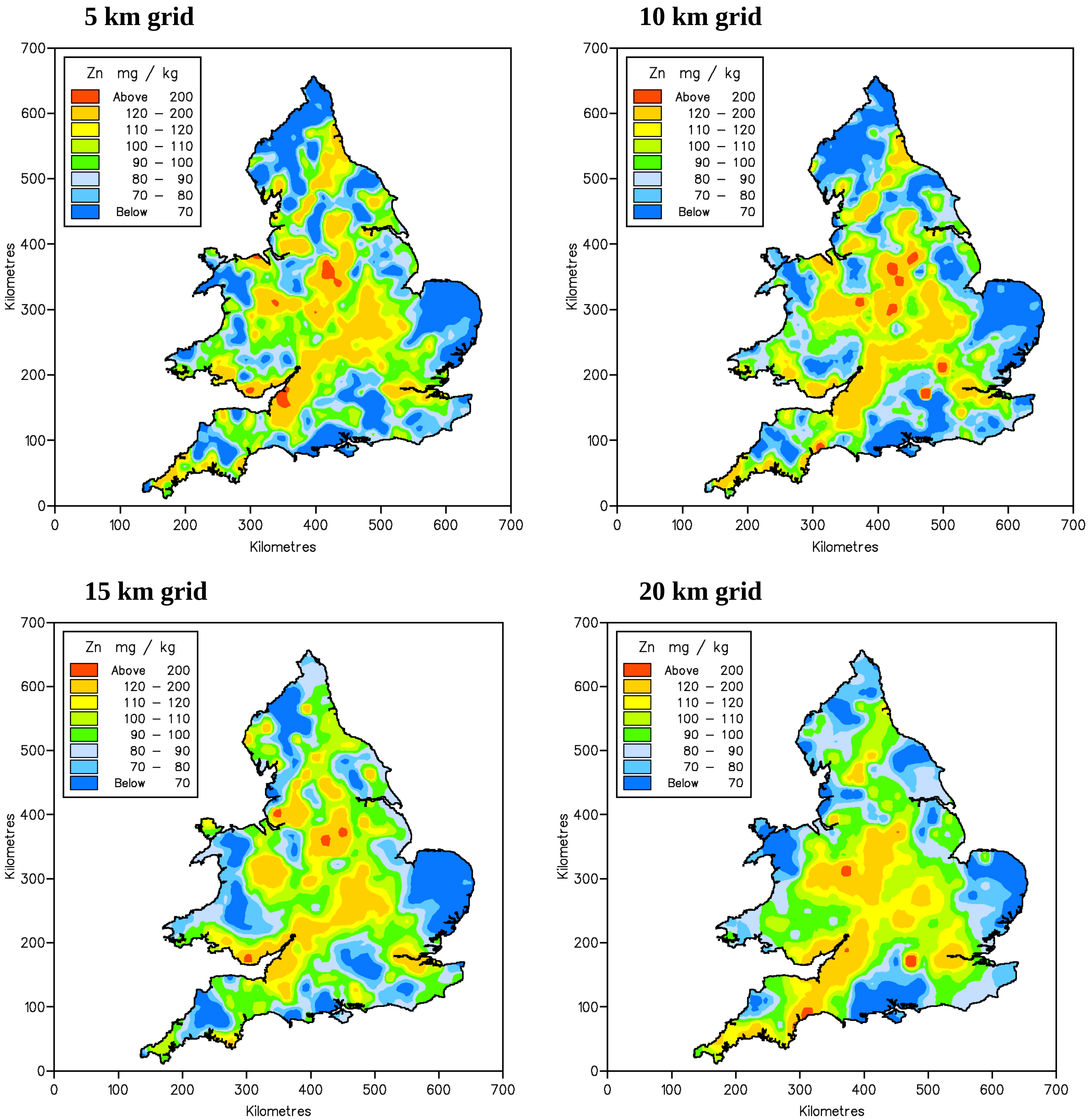
7.6 Some practical aspects of monitoring

Whatever system of soil monitoring is chosen and whichever variables are measured, two fundamental questions will need to be answered:

a) is the monitoring network expected to show the spatial variation of the indicator(s) across the country ?
b) what level of precision is expected in the detection of change in a variable ?

These two questions can determine the density of the sampling network. For example, earlier work on the National Soil Inventory showed that a reasonable description of spatial structure (variability) in the data could be obtained for a number of measurements made at the intersects of a 10 km, or possibly 15 km, regular grid. Figure 7.1 shows the situation for zinc, although it is similar for many other elements.

Figure 7.1 The spatial structure of zinc in topsoils (0 - 15 cm) at different sampling densities



It is clear that much of the structure is retained at an acceptable level at 10 km resolution, but is beginning to break up at 15 km resolution. At 20 km the pattern is demonstrably different. These findings are demonstrated in the statistics for a number of variables in Table 7.5.

Table 7.5 Summary statistics for the sub-sampled Cd, Cr, Cu, Ni, Pb, and Zn data for England and Wales (mg kg^{-1}).

Variable	Subset	*n*	Mean	Minimum*	Maximum	Variance	Standard deviation	Skewness
Cd	10-km	1433	0.8203	0.0	10.5	0.4400	0.6633	4.983
	15-km	637	0.8234	0.0	5.8	0.3852	0.6206	2.953
	20-km	358	0.8464	0.0	10.5	0.5964	0.7723	6.515
Cr	10-km	1433	40.80	0.6	353.1	634.2	25.18	4.161
	15-km	637	41.65	0.2	692.9	1142.7	33.80	11.82
	20-km	358	40.70	0.6	348.3	656.8	25.63	5.111
Cu	10-km	1433	23.35	1.9	1507.7	2054.1	45.32	25.97
	15-km	637	22.44	2.0	182.4	335.2	18.31	3.785
	20-km	358	27.50	2.4	1507.7	7129.5	84.44	15.76
Ni	10-km	1433	24.58	0.8	298.8	300.1	17.32	4.775
	15-km	637	24.15	0.8	123.9	204.1	14.29	1.428
	20-km	358	25.18	0.8	136.9	221.6	14.89	1.747
Pb	10-km	1433	68.98	3.0	1647.0	13208.0	114.9	7.995
	15-km	637	64.45	3.0	929.0	6327.5	79.55	4.656
	20-km	358	65.17	3.0	1026.0	7741.4	87.99	6.507
Zn	10-km	1433	94.99	7.0	1985.0	7996.0	89.42	9.941
	15-km	637	93.64	6.0	830.0	4485.3	66.97	4.450
	20-km	358	100.4	8.0	1985.0	15993.6	126.5	10.57

* a value of zero for Cd means that it was <detection limit (0.2 mg kg^{-1})

These data are based on regular grids, but nested sampling is also a possibility. This can be represented by sampling the National Soil Inventory using a randomising technique and comparing the data for the same (approximately) number of samples taken from regular grids of increasing interval between sample points. Table 7.6 shows the statistics of the sampling regimes. It is clear that, if the interest is in the mean or median value, then sampling at 10 to 20 km (regular grid) or at between about 1400 and 350 points will yield a representative value. At coarser grids or fewer randomly selected points, then the quality of the data deteriorates. This is especially true if one is interested in the range of values.

Table 7.6 Some statistical variables for organic carbon from the National Soil Inventory dataset, with the grid-points sampled at different densities and in different ways.

No of samples	Grid (spacing for regular grid in km)	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Std. Dev.
5667	Regular (5)	6.66	3.60	0.10	65.9	2.30	5.90	9.89
1431	Regular (10)	6.78	3.60	0.20	65.9	2.30	5.90	10.31
1435	Random	6.73	3.70	0.50	65.9	2.20	5.80	9.94
362	Regular (20)	6.99	3.50	0.60	65.9	2.30	6.00	10.65
366	Random	6.37	3.7	0.60	56.4	2.20	5.90	9.15
94	Regular (40)	6.67	3.25	0.70	48.8	2.20	4.70	10.73
96	Random	6.38	3.8	0.6	47.9	2.15	6.05	9.15
15	Regular (100)	8.49	3.40	1.30	48.8	2.00	12.10	12.62
17	Random	3.55	2.60	0.9	10.9	1.50	5.50	2.77

The effect of the difference in sampling strategy can be clearly seen in a 'box-plot' diagram (Figures 7.2 and 7.3) but, interestingly, is not so well seen in the presentation of the data through a conventional cumulative distribution curve (Figures 7.4 and 7.5).

Figure 7.2 Box-plot of soil organic carbon data from samplings of increasingly coarse regular grids.

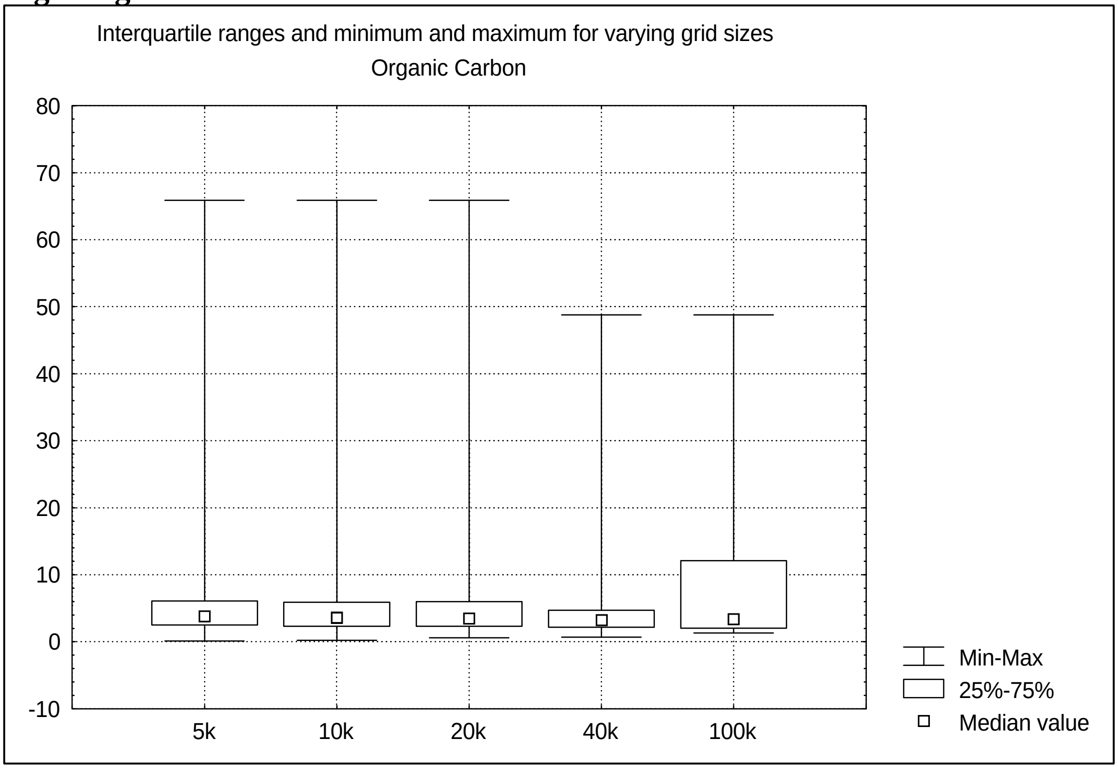


Figure 7.3 Box-plot of soil organic carbon data from increasingly sparse random sampling of the regular 5 km grid data.

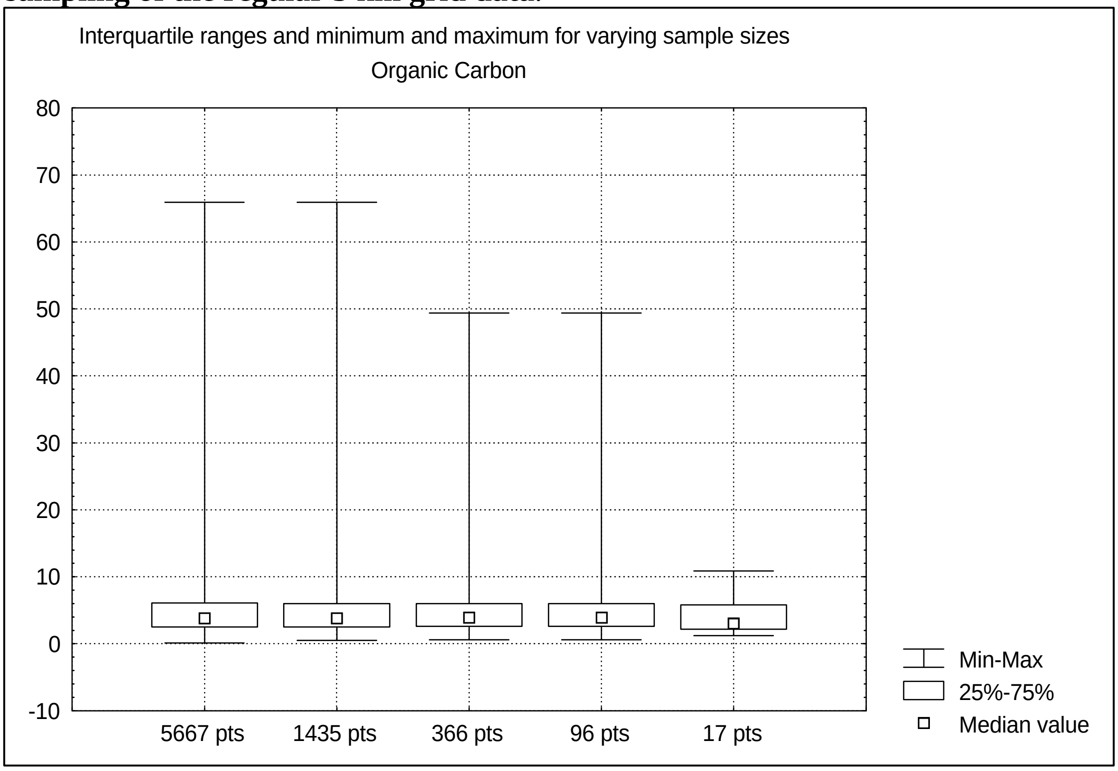


Figure 7.4 Cumulative distribution curve of soil organic carbon data from increasingly coarse regular grids

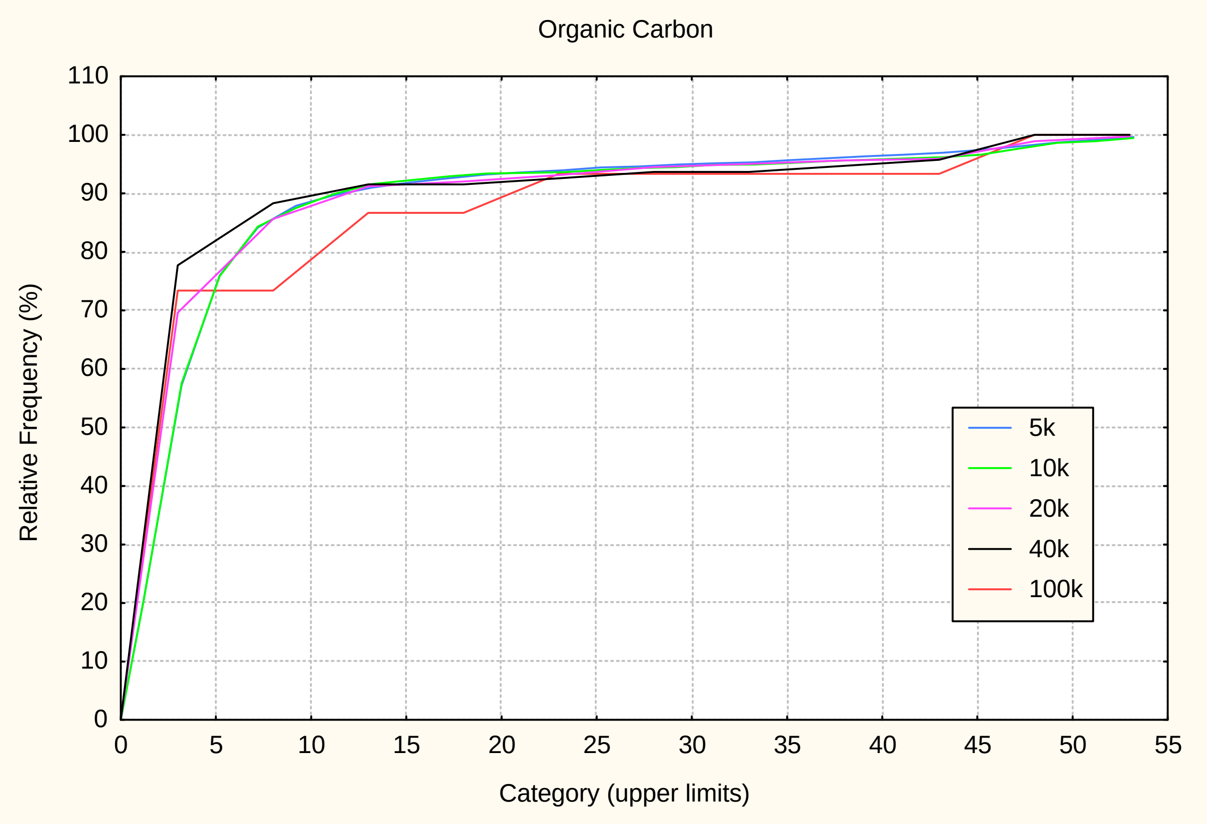
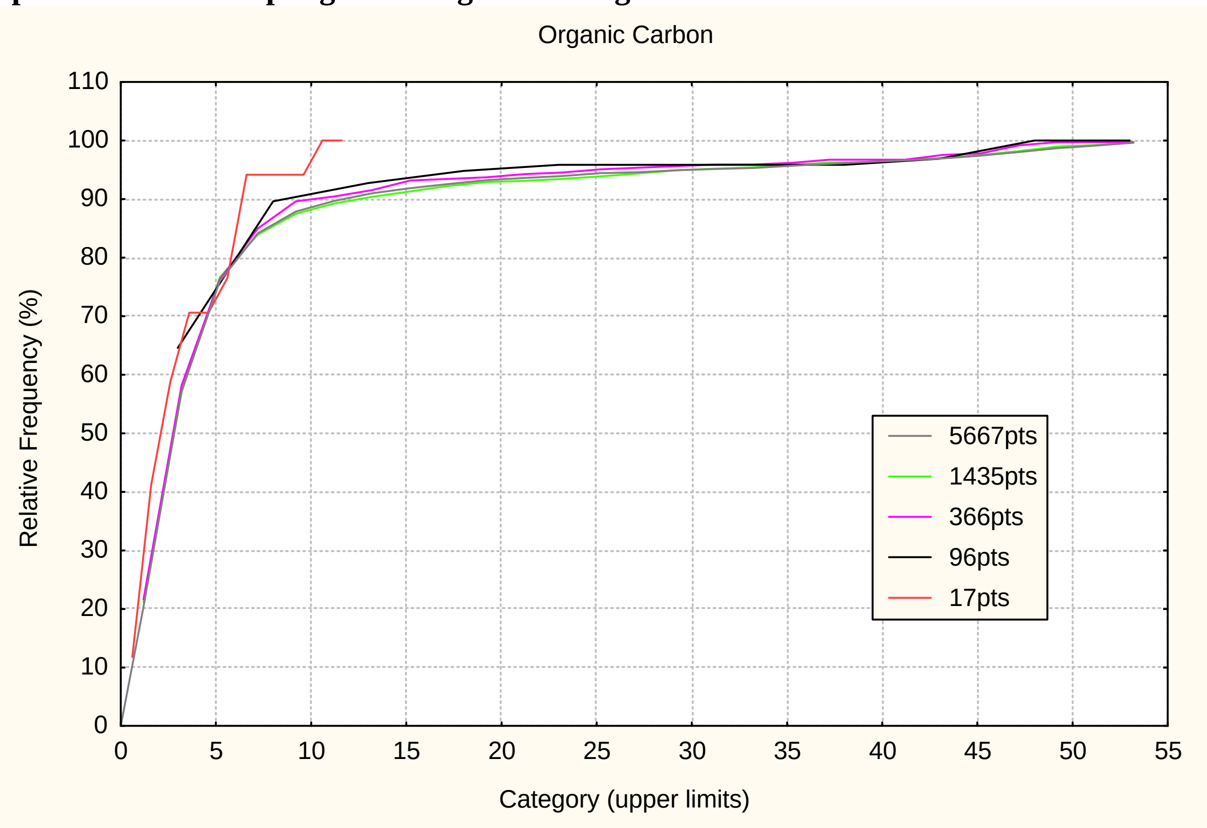


Figure 7.5 Cumulative distribution curves of soil organic carbon data from increasingly sparse random sampling of the regular 5 km grid data.



Finally, it is worth examining briefly the concept of an envelope of values of a variable, within which the desirable value is indicated and any deviation from this can be given a positive or negative rating. Such a procedure has been advocated strongly in the United States by, for example, Glover *et al*. (2000) and Reganold *et al*. (2001) in order to arrive at ratings for soil quality functions. Thus, a value below the optimum would receive a negative score and thus lower the soil quality rating, whilst a value above the optimum would have the opposite effect. In practice, the envelope that encompasses the acceptable range is commonly set at the upper and lower quartile values of the property. If the property lies outside the envelope then the soil function is deemed to be impaired and cannot contribute to the overall rating of the soil or ecosystem. Figures 7.6 and 7.7 show the appropriate envelope for soil bulk density in terms of two land uses within three broad soil textural groupings for England and Wales (LandIS data). The points to note are that there are distinct differences between the values in some of the different classes, but the range is large in all cases. Thus, there would be considerable overlap between any 'envelopes' set as a measure of this particular variable. However, so long as the monitoring sites were chosen to be fully representative of the range of cultivation and grassland management practices, it would certainly be possible to say whether such soils were becoming more or less compacted over time. No doubt, ways could be found of presenting the results in terms of proportions of given land areas for the major soils, i.e. where there are enough points to give a meaningful distribution. It also has to be remembered that these median values are not necessarily the optimum values. The latter could be set from some other basis and it would be possible to say whether soils were moving towards them, or away from them.

Figure 7.6 Upper and lower quartile and median values for A horizon bulk density (Mg m^{-3}) under arable cultivation in three broad soil particle size groupings (SSLRC data from LandIS).

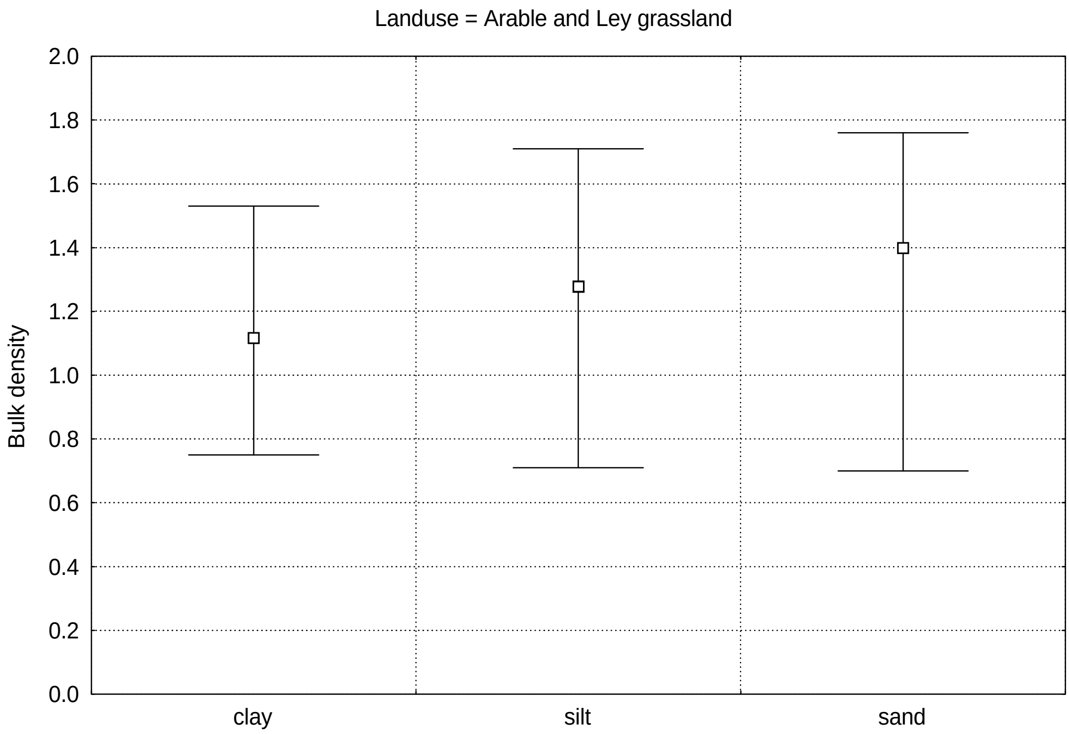
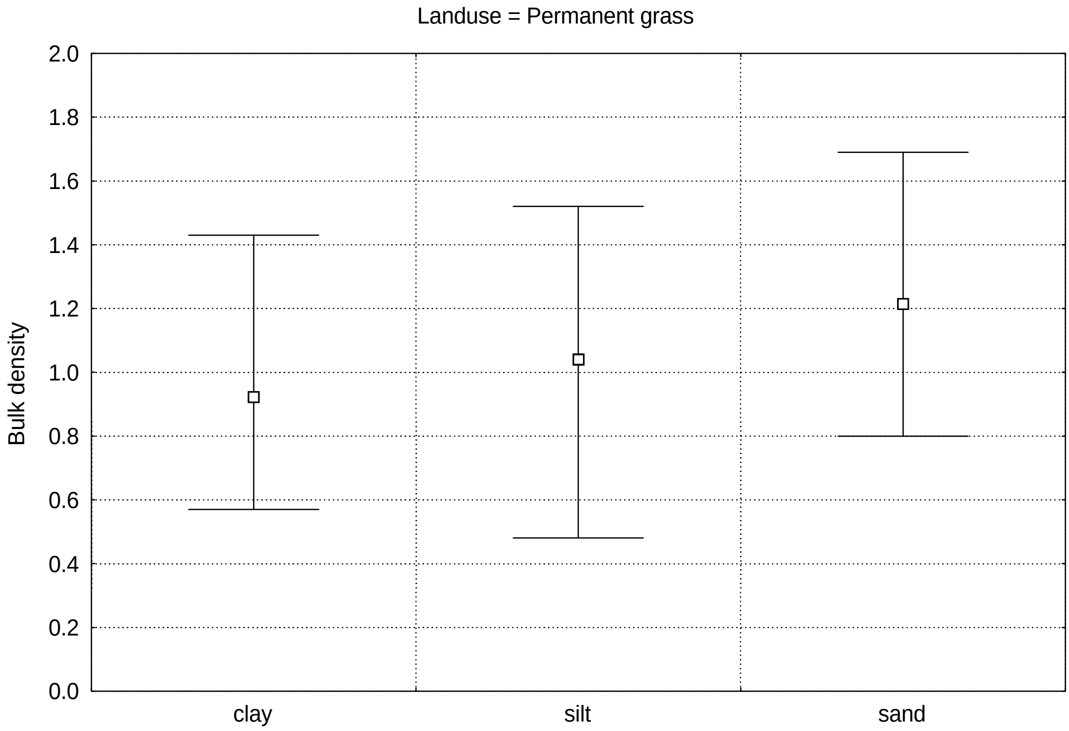


Figure 7.7 Upper and lower quartile and median values for A horizon bulk density (Mg m^{-3}) under permanent (managed) grass in three broad soil particle size groupings (Soil Survey data from LandIS).



8. INDICATORS OF SOIL QUALITY FOR UK FORESTRY

A J Moffat and F M Kennedy (Environmental Research Branch, Forest Research)

8.1 Summary

This report reviews briefly the pressures on forest soils and the services expected of them. It reports the use of soil quality indicators in plantation forestry world-wide, and makes recommendations for the utilisation of direct and indirect (headline/surrogate) measures of soil or site quality suitable for use in a forestry context in the UK. It reviews the degree of forest soil monitoring in Great Britain, and the problems posed by spatial and temporal variation associated with this activity. It identifies research needed to increase the ability to use more direct measures of soil function in the future.

8.2 Introduction

Much of the foregoing report reflects the fact that the bulk of the work on soil quality indicators to date has been written with agriculture in mind. In order to address the specific concerns of the forestry industry in the UK, it was thought essential to give this aspect of soil use a specific section in this report. ‘Sustainable Forestry – the UK Programme’ (1994), published by the government after the Earth Summit in Rio in 1992 and the Helsinki agreement in 1993, makes it clear that soil is a vital element to the forest ecosystem, and its protection and enhancement is essential if forestry is to be practiced sustainably. Considerable guidance is available to encourage forest managers towards a responsible attitude in forest soil management. Nevertheless, such soils can also be affected by influences external to the forest such as atmospheric pollution and climate change.

Despite a developing culture which acknowledges the importance of soil in the forest industry, it has been recognised that there is a responsibility for all (forest manager and Forestry Department) to monitor the state of the soil so that forest practices can be modified should negative (and irreversible) impacts occur. The concept of ‘soil quality indicator’ has been put forward as an appropriate means to establish a baseline of soil quality and / or functional ability, and from which changes can be observed as a result of pressures exerted on the soil.

8.3 Functions of forest soils

8.3.1 Biomass production

The four functions below relate primarily to the function of soil to promote biomass production, in particular the growth of stemwood for economic exploitation. Of course, this outcome is also necessary for most other recognised services that woodlands provide, for example recreation, sport, biodiversity and employment. Forest soil properties differ in many respects from those under agriculture or non-woody vegetation (Box 8.1). In a similar way, the functions of forest soils differ from those supporting agricultural uses. Of course, basic biological functions are similar, but there are some important differences, which in turn influence the way that pressures on the soil are experienced, and how forest soils respond.

8.3.2 Water supply

Forest soils supply water for tree metabolism and transpiration. In common with most other plants, water needs in summer months are supplied mostly from that stored in the soil pore system. However, trees are generally able to withdraw water from deeper in the soil profile than, say, grasses, and the magnitude of seasonal soil drying may also be greater. Root mycorrhizas also help tree roots extract water when soil moisture content is small.

8.3.3 Nutrient supply

Forest soils supply trees with most nutrients needed for health and growth. Essential nutrients and elements are the same as those required for agricultural crops, though production of non-food chain products reduces concerns about sufficiency of some such as selenium. Other important differences include:

- Absorption of nutrients, notably nitrogen and sulphur, by the tree canopy directly from atmospheric sources (Broadmeadow and Freer-Smith, 1996),
- Nutrient supply from organic soil layers above mineral horizons (the forest floor).

Agricultural soil	**Forest soil**
Topsoil often affected by cultivation; Ap horizon common	More diverse humus forms; commonly well developed horizonation in topsoil
pH usually >5.5	pH often <5.5
Small organic matter content	Large organic matter content
Moderate macroporosity	Large macroporosity
Relatively small spatial variability in many soil properties	Large spatial variability in many soil properties
Biological disturbance dominated by earthworms	Biological disturbance dominated by arthropods
Microbial biomass dominated by bacteria	Microbial biomass dominated by fungi
Relatively fertile	Relatively infertile
Relatively large diurnal variation in soil temperature	Smaller diurnal variation in soil temperature
Soils exploited by plant roots to moderate depth; soil drying accordingly	Soils exploited by tree roots to depth; soils maintained in drier state for longer period of year

Box 8.1 Differences between agricultural and forest soils

8.3.4 Anchorage

Trees depend on the support provided by roots. Most (up to 90%) tree roots are located in the upper 100 cm of soil (Perry, 1989), though some roots will penetrate deeper if soil conditions allow. Shallow and poorly drained soils can pose problems for tree stability against wind, and machinery-induced soil compaction may also contribute to instability where it occurs.

8.3.5 Oxygen supply

Roots require oxygen for respiration, and most tree species require an aerobic soil substrate to permit proper root extension during the growing season. However, some species are reasonably tolerant of soil waterlogging because they can transport oxygen down from aerial parts of the plant. Such species include some Salix (Armstrong, 1968), pines (Philipson and Coutts, 1980), poplars (Chirkova, 1968), and alders (Westra, 1959; Diaconu *et al*., 1971).

8.3.6 Filtration of atmospheric pollution

Woodland is more effective than ground vegetation types at intercepting atmospheric pollution (Broadmeadow and Freer-Smith, 1996). Pollutants which trees take up include oxides of nitrogen and sulphur, ozone and ammonia. Most are assimilated and broken down within the tree. Trees also intercept heavy metals and airborne dusts. Soil acidification usually accompanies pollution capture.

8.3.7 Preservation of historical past

Much archaeological heritage is preserved beneath and within British forests (Yarnell, 1999). Indeed, the presence of trees may do much to help in its preservation (Crow and Moffat, in press). Forestry Commission policy is for forest operations to take account of the need to preserve all sites of archaeological importance (Forestry Commission, 1995). Several soil quality headline indicators can take account of this function.

8.3.8 Carbon sequestration

About 80% of the carbon in British vegetation is in forests and woodlands (Cannell and Milne, 1995). Forest soils also contain considerable amounts of organic matter, and are important world-wide as global carbon sinks. Coniferous forests hold most of the organic carbon in litter or peaty organic horizons. Nevertheless, there is currently no policy in the UK to plant or manage woodland specifically for carbon sequestration.

8.4 Pressures and their impacts on forest soil quality

This section describes the principal pressures on forest soils. They are discussed principally in the context of the primary role for forest soils as promoting the growth of trees. Other benefits and services provided by forests, and thus reliant on forest soils will also be discussed at the end of this section. For convenience, pressures are classified into ‘physical’ and ‘chemical’ and discussed individually, but it is recognised that many inter-relate with each other. Good reviews on the influence of forest operations on forest soils are given by Worrell and Hampson (1997) and Forestry Commission (1998). General reviews on UK forest soil sustainability include Moffat (1991) and Malcolm and Moffat (1996).

8.4.1 Physical pressures

<u>8.4.1.1 Forest establishment</u>

Historically, forest plantations have tended to be located on comparatively infertile, poorly drained or thin soils in Britain. At a national scale a disproportionate amount are found on gleys and peats, but locally, individual forests tend to occur on the poorest soils in the region. In addition, many soils presented pedological impediments to deep rooting, such as ironpan and fragipan soils.

A consequence of this soil geography is that twentieth century forest establishment was dominated by the need to conquer the ground and bring it into a state fit for forest establishment, and promote economically satisfactory growth. Drainage was achieved principally by forming an open ditch network, and soil cultivation took place mainly by ploughing. Deep subsoiling was used to break up ironpans where necessary.

The effects of these practices on the water environment were appreciated in the 1980s and current guidance (Box 8.2) is far more restrictive in advocating minimal and shallow cultivation wherever possible.

Cultivate only those parts of a site where it is necessary. For new planting in the uplands, the use of scarifiers for dry soils and the use of continuous-acting mounders – preferably fitted with a moling or ripping attachment – for wet soils, is recommended for all soils except the wettest peaty gleys and peats. On peaty soils, spaced furrow ploughing should be as shallow as possible (e.g. 30 cm) aiming to expose mineral soil as little as possible. In the lowlands, cultivation is unlikely to be necessary, except, perhaps, for weed control.

Box 8.2 Guidance on soil cultivation. (From Forestry Commission Forests & Water Guidelines (2000))

Nevertheless, all types of cultivation affect soil conditions and functions, including the minimal types described above. Paterson and Mason (1999) have recently summarised the main effects for forest soils. They include effects on soil and air temperature, soil moisture, nutrients and bulk density. The effects above are regarded by foresters as beneficial and likely to improve tree survival, growth and stability. Table 8.1 summarises these effects, but also highlights the potential for cultivation to promote obvious negative effects such as erosion and nutrient loss. The soil's ability to sequester carbon may also be compromised.

Table 8.1 Effects of cultivation (from Paterson and Mason (1999))

Potential physical effects	**Potential biological effects**	**Potential environmental effects**
Altering the surface configuration of the site	Increase in rate of nutrient release from decomposing organic matter to the planted or regenerating trees	Greater sediment loss and altered pattern of water flow, especially during and after storms
Removal of physical obstructions such as brash	Alteration to the amount of vegetation cover and type of plant community	An increase in nutrient losses
Breaking up humus and mixing it with other soil horizons	Increase in activity of soil fauna, fungi, and microbes resulting from improved aeration	Alteration to the visual texture of the landscape
Increasing pore space and breaking up compaction Changing soil and air temperatures near the soil surface Amending soil moisture conditions	Decrease in organic carbon	Damage to archaeological remains

8.4.1.2 Harvesting

In contrast to forest establishment, when purposeful, hopefully beneficial, intervention is made to the soil, harvesting operations are considered those with the most potential for inadvertent degrading effects on forest soils. In the UK, harvesting is increasingly mechanised and now involves large machinery in the cutting and transporting of timber products from the forest site. Most activity takes place on the forest soil – forest roads are used to transport collected timber once it has been removed from the growing area. Much research from overseas suggests that the soil is at risk from rutting, compaction and erosion during harvesting. These will have concomitant effects on other soil properties and functions. Limited research in the UK has confirmed that on sensitive soils (principally gleys and peats), forest soils are prone to these forms of damage, and surveys have confirmed that it can take place. Nevertheless, significant protection to the soil is provided by harvesting residues which are laid out as continuous brash mats on which harvesting equipment and extraction vehicles travel across the felling coupe. Recent research has shown the effectiveness of this methodology (Hutchings *et al*., in press; Wood *et al*., 2001).

Felling and harvesting operations are usually subject to considerable planning. In the private forestry sector operations are also subject to the award of a felling licence from the Forestry Commission. This procedure enables good practice guidance to be taken up by the applicant, and the Forestry Commission has a supervisory and policing role, especially if the felling is also part of a Woodland Grant Scheme. There are additional means of scrutiny if the woodland or forest is registered under the UK Woodland Assurance Scheme (Section 8.5.5).

8.4.1.3 Road construction

The major pressure on forest soils from road construction is one of simple substitution: roads are built over soil, and prevent its use for other purposes. The width and specification of forest roads depends on required use, topography, terrain, underlying formation and availability of local road-making material (Hart, 1991). Low specification roads are normally about 3 m wide, involving excavation to hard formation level followed by laying of 15-40 cm crushed stone which is then blinded and rolled. Roads normally have drainage ditches running parallel to them. High specification roads capable of carrying heavy vehicles and machinery are normally 3.2 m wide. Adequate side drainage is essential. The ground is excavated to hard formation level, and stone laid 30-50 cm thick. The surface is then blinded and rolled to a camber of 7-9 cm. Road width may increase up to 6 m at sharp curves.
The density of roads is dependent on forest production, and will vary with size of woodland and species planted. In small woods, a density of 20 or more metres per hectare may be appropriate. Road location is greatly affected by surface drainage, topography and terrain, but soil type probably plays a small part in choice of location.

8.4.1.4 Tree growth and woodland development

Changes to soil properties and functioning are also caused by the growth of trees themselves, notably if land-use changes from agriculture to forestry. Box 8.1 summarises the principal differences between soils under these two land-uses. Interception of precipitation by the woodland canopy is much larger than grass and most other agricultural crops. Thus, woodland soils tend to be at field capacity for a shorter time than those under agriculture. In peat soils and some gleys, tree crops may cause *irreversible* shrinkage and cracking, leading to altered hydrological behaviour (King *et al*., 1986).

8.4.2 Chemical pressures

8.4.2.1 Atmospheric pollution

Concern that atmospheric pollution could adversely affect forest soils was first raised in the 1980’s. The initial dominant issue was ecosystem acidification as exemplified by many Scandinavian soils and lakes. This was attributed to the acid anion effect caused by sulphur emissions from coal fired power stations throughout Western Europe. Soil acidification demonstrably causes soil nutrient depletion and increased concentrations of aluminium in soil solution which can result in toxicity. The chemistry of the soil acidification process is now well understood and this is an area where debate regarding indicators of acidification is advanced. Cronan and Grigal (1995) wrote an authoritative review paper on the subject confirming that percent base saturation and then the molar Ca:Al or base cation:Al in the soil solution are acceptable indicators of soil acidification.

Due to the successful implementation of international abatement protocols, sulphur deposition is now showing signs of falling. Acidification is, however, still perceived as a current threat because it also arises when nitrogen deposition is in excess of ecosystem demand. The elevated deposition of nitrogen (particularly in the form of reduced nitrogen), which is predominantly a consequence of vehicle exhaust fumes, as yet shows no signs of declining. The impacts of nitrogen pollution are slightly more complex than those of sulphur. Nitrogen pollution is a 'double-edged sword'; in the medium term the so called 'fertilisation effect' is expected to enhance growth, but with emissions left unchecked in the long term acidification occurs. The result is a system in which other macro nutrients quickly become limiting, a situation exacerbated by the fertilisation effect of the nitrogen and rising CO_2 (see Section 8.3.2.2).

Both foliar nitrogen and the C:N ratio of the forest floor have been successfully used to predict the onset of nitrogen saturation (i.e. supply in excess of demand) for conifers. The use of different forms of soil nitrogen as indicators would more than likely be flawed for forest ecosystems. A recent unpublished literature review has shown that while forms of nitrogen may vary considerably throughout the life cycle of a managed stand, the total nitrogen shows little variation.

The atmospheric deposition of heavy metals and POPs (persistent organic pollutants) also deserve comment.

Although heavy metals exist naturally as products of mineral weathering in many forest soils, potential anthropogenic sources include atmospheric pollution (mainly as a result of industrial activity during the 20th Century) and organic fertiliser application, such as sewage sludge and wood ash. The metals can become tightly bound, particularly to organic exchange sites in the soil and there is some concern that a reduced supply of essential exchangeable nutrients will ensue. More common though are reports of negative correlations between heavy metal concentrations and soil flora and fauna populations (Kowalski *et al*., 1998) and the possible implications of these on soil functioning. The development of critical loads for heavy metals is a relatively young subject that should be closely monitored so that compatible indicators can be selected.

Mayer (1993) highlights the potential for the build up of organic pollutants in highly organic forest soils. He quotes the work of Matzner *et al*. (1981) in Germany, which found polycyclic aromatic carbohydrates in beech and spruce to be up to just under 90 times higher in Of/Oh layers than the mineral soil directly beneath them. The concern here and with heavy metals is that forest management practice and/or atmospherically derived soil acidification may lead to mobilisation of these compounds rendering them 'ecologically active' and free to enter living cells and water supplies.

8.4.2.2 Climate change

Predictions of the nature of climate change in the UK are uncertain. As the emissions of green house gases, such as CO_2, impact upon temperature which in turn effects precipitation levels, wind speed and potential evapotranspiration a chain of dependency with increasing uncertainty is created.

Current scenarios for the UK suggest that average temperatures will increase by approximately 1 to 1.5°C by 2010 to 2039, with larger increases in the winter and in the south. An increase in evapotranspiration is expected to be associated with this temperature rise which, combined with a reduction in summer rainfall in the south (3% by 2010 to 2039), could lead to longer periods of summer drought with higher frequency. Summer rainfall is expected to increase slightly in the north and winter rainfall to increase throughout the country (6 to 11% in the same time period). (DoE, 1996a).

Predicting the impacts of climate change on soils introduces yet more uncertainty as these form a link on the end of the chain of dependency. Initially, based on increases in temperature alone, studies speculated that mineralisation and CO_2 release from soils would increase leading to a depletion in soil C stocks. However, soil temperatures do not readily follow changes in air temperature meaning the temperatures used in these studies may be erroneous and, furthermore, the short term nature of the experiments meant that C released was from the labile pool only. To add to this, it can be hypothesised that increases in forest growth as a direct response to elevated CO_2 conditions (the so called "CO_2 fertilisation effect") will sequester more carbon into the forest ecosystem. Perhaps the resultant of these two effects will be no change at all ?

It is not the aim here to predict what will happen; it is not essential for the identification of soil indicators to know the direction of a change, only to anticipate a change. Possible, primary, soil related changes are as follows:

- soil carbon dynamics;
- increased nutrient demand as rising CO_2 drives growth rates;
- soil moisture deficits also exacerbated by increased growth rates;
- build-up of the products of mineralisation during extended periods of drought, with subsequent heavy flushes during precipitation events.

and some more tenuous secondary effects are:

- higher wood densities may affect decomposition;
- introduction of new provenances altering soil chemistry and water demand;
- improved growth results in reduced rotation length and an increased frequency of trafficking.

8.4.2.3 Fertiliser application

Fertilisation in forestry is usually limited to phosphorus and potassium and is not as common as it is in agricultural systems. The interpretation of fertilisation as a threat is therefore debatable. For example, the fertilisation of successful establishment of healthy first rotation stands on previously degraded agricultural land has been perceived as soil quality improvement (Fox, 2000). Prolonged fertilisation on agricultural land is known to cause soil acidification and can be a source of metals such as cadmium. Therefore fertilisation in forestry should only be perceived as a pressure if it is occurring with increasing frequency on second and later rotation crops. Such a scenario would suggest that its use is to counter unsustainable biomass removal; thus in forestry fertiliser usage is more likely to be symptomatic of another more important threat than a pressure in itself and may provide a useful indicator in this context.

8.4.2.4 Pesticide use

Pesticides are used in forestry primarily to prevent weed competition (during establishment phase only). Improvements in pesticide legislation mean that the chemicals of the organo-chlorine group, which remain in the soil for several years (and thus build up with successive applications) are no longer in use. However, there are justified concerns that modern pesticides, or their breakdown products, may still have long enough durability and/or low enough adsorption capacities to affect non-target organisms and biological processes in the soil, particularly nitrogen cycling.

To monitor these chemicals and their breakdown products by means of soil sampling and analysis requires specialised equipment and is likely to be costly. As with so many other indicators, a more realistic approach would be to use a surrogate such as a record of the nature and amount of chemicals that are purchased per annum.

8.4.2.5 Brash management

Brash is the residue of branches, needles and stem tops left on a site after conventional harvesting. There is no doubt that on certain sites the fate of this residue may be critical to the subsequent soil nutrient resource. Where brash is used to construct protective mats (Section 8.4.1.2), mounded or removed entirely from the site (whole tree harvesting) the potential is created for nutrient depletion and concern about Ca, P and K particularly have been voiced (Dutch, 1993). Conversely whole tree harvesting can be useful in areas showing visible signs of nitrogen saturation thus it is not necessarily the case that residue removal is ‘bad’. The pressure is thus specific at the compartment level and reinforces the need for some indicator of soil fertility whether it be a direct measurement performed on the soil or a surrogate such as foliar chemistry.

8.4.3 Conclusions concerning Pressures

Forest soils experience a range of pressures, some due to forestry operations and the growth of trees themselves, others outside the control of the forest manager. Changes in the functioning and properties of forest soils are inevitable, but not all changes are commensurate with degradation. The most recent assessments of UK forest soil quality give it a reasonably good state of health (Moffat, 1991; Malcolm and Moffat, 1996; Worrell and Hampson, 1997; Moffat, 1997; Moffat *et al.*, 1997). Of the threats to soil chemistry, eutrophification and acidification are probably those considered by many to be the most serious, and worthy of monitoring. The main physical effects are due to harvesting operations, and result in rutting, soil disturbance and possible soil compaction.

8.5 The International and National Policy Perspective

8.5.1 The Montreal Process

The 1992 Earth Summit, or United Nations Conference on Environment and Development (UNCED), called upon all nations to ensure sustainable development, including the management of all types of forests. The summit produced a Statement of Forest Principles, conventions on biodiversity, climate change and desertification, and a plan of action for the 21st century called Agenda 21, all of which have implications for forest management.

Following UNCED, Canada convened an International Seminar of Experts on Sustainable Development of Boreal and Temperate Forests. This seminar, held in Montréal in 1993 and sponsored by the Conference on Security and Cooperation in Europe (CSCE), focused specifically on criteria and indicators and how they can help define and measure progress towards sustainable development of forests. European countries decided to work as a region under the framework of the Ministerial Conference on the Protection of Forests in Europe.

The Montréal Process is the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests. It was formed in Geneva, Switzerland, in June 1994 to develop and implement internationally agreed criteria and indicators for conservation and sustainable management of temperate and boreal forests.

Membership in the Working Group is voluntary and currently includes from both hemispheres, having a wide range in natural and conditions. The member countries represent about 90 per cent the world's temperate and boreal forests in the northern and southern hemispheres. This amounts to 60 per cent of all of the forests of the world. Europe's forests are not included - they are addressed by the Helsinki or Pan-European Process.

At their Sixth Meeting as the Montréal Process Working Group in Santiago, Chile, February 1995, ten nations agreed to a comprehensive set of *criteria* and *indicators* (Box 8.3) for forest conservation and sustainable management. This statement of endorsement is referred to as the "Santiago Declaration". They were joined in October 1995 by two more nations, Argentina and Uruguay, completing the current group of twelve member countries.

Criterion: A category of conditions or processes, by which sustainable forest management may be assessed. A Criterion is characterised by a set of related indicators, which are monitored periodically to assess change.

Indicator: A measure (measurement) of an aspect of the criterion. A quantitative or qualitative variable which can be measured or described and which, when observed periodically, demonstrates trends.

Box 8.3 Definition of criteria and indicators used in the Montréal Process

8.5.2 Montréal Process Criteria

The Montréal Process Working Group agreed on a framework of criteria and indicators that provide member countries with a common definition of what characterises sustainable management of temperate and boreal forests. The framework identifies seven criteria that are further defined by 67 associated indicators, which are aspects of the criteria that can be identified or described. There is one Criterion and four indicators specifically relating to the conservation and maintenance of soil resources.

- Area and percent of forest land with significant soil erosion;
- Area and percent of forest land with significantly diminished soil organic matter and/or changes in other soil chemical properties;
- Area and percent of forest land with significant compaction or change in soil physical properties resulting from human activities;
- Area and percent of forest land experiencing an accumulation of persistent toxic substances.

Individual member countries of the Montréal process have taken forward their own thinking on how these indicators can be applied. Australia has published useful guidance (Anon, 1998;

Rab, 1999) where lack of systematic data has led to a number of interim indicators and approaches (Box 8.4).

8.5.3 The European dimension

The "Ministerial Conference on the Protection of Forests in Europe" is an ongoing initiative for co-operation between around 40 European countries to address common threats and opportunities related to forests and forestry. This process consists of a chain of political level conferences and mechanisms for the follow-up work. The signatory states and the European Community are responsible for the national and regional implementation of the decisions taken at the conferences. The discussion and work between the conferences is called the "Pan-European Process", which is characterised by a dynamic joint approach with a strong political commitment.

The First Ministerial Conference on the Protection of Forests in Europe took place in 1990. Under the impression of dying forests, cross-border protection of the European forests was discussed for the first time at ministerial level. The Ministers responsible for forestry and the European Community signed six resolutions and committed themselves to technical and scientific co-operation and common measures for the protection of the European forests.

The intention to implement the forest related results of the United Nations Conference on Environment and Development (UNCED), which took place in 1992 in Rio de Janeiro, led to the Second Ministerial Conference, held in 1993 in Helsinki. There the international debate on forests was continued, bringing together not only the countries and their respective ministries responsible for forestry affairs but also the private sector, international forest community and environmental NGOs. Thirty-seven states and the European Community signed four resolutions, and for the first time a common definition of Sustainable Forest Management was agreed upon (Box 8.5):

> "Sustainable management means the stewardship and use of forests and forest lands in such a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems."

Area and per cent forest land with significant soil erosion

Issues

- Difficult to calculate areal extent of erosion
- Methods for measuring erosion can only be practically applied at research scales
- Case studies involving measurements of erosion/forest operations interactions should be expanded
- R & D development of methods for defining erosion risk
- R & D development of relationships between erosion quantity and environmental effects

Interim indicator:

Area and per cent of forest land systematically assessed for soil erosion hazard, and for which site-varying scientifically-based measures to protect soil and water values are implemented. Erosion hazard is based on: soil erodibility, rainfall erosivity, slope and degree of soil or forest floor disturbance. Data is derived from management and operational plans.

Other options for indicators include:

The areas for which Codes of Practice have been adopted and applied

The period the ground is left bare

The proportion of activity (e.g. harvesting) that occurs in periods of high rainfall intensity.

Area and per cent of forest land with significantly diminished soil organic matter and/or changes in other soil chemical properties

Issues

- Establishing the quantitative relationship between SOM and soil fertility. Relationships are better developed for agriculture than forestry. Relationships will vary with soil and forest type
- Spatial and temporal variation
- Methodological issues including depth of soil to be sampled, forest floor and timing of measurements
- Limited data, mainly confined to research studies
- R & D needs to establish relationships between SOM and other ecosystem processes
- R & D to explore the utility of SOM as a surrogate for other forest values

Interim indicator:

The total quantity of organic carbon in the forest floor (< 25 mm diameter components) and the surface 30 cm of soil. Monitoring is only practical in case studies or at reference sites. Timing of measurements must be considered in relation to operations.

Area and per cent of forest land with significant compaction or change in soil physical properties resulting from human activities

Issues

- Critical link with traffic and harvesting system and thus potential to reduce impact with better harvesting planning
- Soil strength a function of soil water, so damage can be minimised by avoiding traffic on wet soils
- Soil physical change may occur without obvious rut formation
- Soil displacement may require measurement
- R & D needs to establish the relationship between soil physical change and local scale forest productivity
- R & D need to examine potential to use rut characteristics or remotely-sensed data as surrogates for soil physical change

Interim indicator:

Proportion of harvested forest area with significant change in bulk density of any horizon of the surface (0-30 cm) soil. Data to be collated from case studies and from representative operational coupes.

Area and per cent of forest land experiencing an accumulation of persistent toxic substances

Issues

- Use of pesticides in plantations; biosolid/effluent application
- Data from amount and extent of pesticide application
- Some reference sites to indicate accumulation in the soil
- Biosolid/effluent data from licence monitoring
- R & D needs low compared with other indicators

Box 8.4 Examples of indicators used in Australia to conform to the requirements of the Montreal process

Third Ministerial Conference on the Protection of Forests in Europe
Pan-European Criteria and Indicators for Sustainable Forest Management which relate to soil
CRITERION 2: Maintenance of Forest Ecosystem Health and Vitality
Quantitative indicators
Changes in nutrient balance and acidity over the past 10 years (pH and CEC); level of saturation of CEC on the plots of the European network or of an equivalent national network.
Descriptive indicators
2.4. Existence of informational means to implement the policy framework, and the capacity to:
Strengthen regular field monitoring on forest health status and inventories of soil acidification
Prevent serious damage caused by machinery and forestry operations: compaction of soil, injuries into standing trees, etc.
CRITERION 5: Maintenance and Appropriate Enhancement of Protective Functions in Forest Management (notably soil and water)
*CONCEPT AREA**: Soil erosion***
Quantitative indicator
Proportion of forest area managed primarily for soil protection
Descriptive indicators
Existence of informational means to implement the policy framework, and the capacity to:
Conduct inventories and research on soil erosion
CONCEPT AREA: *Water Conservation in Forests*
Quantitative Indicators
Proportion of forest area managed primarily for water protection
Descriptive Indicators
Existence of informational means to implement the policy framework, and the capacity to:
Conduct inventories and research on water quality and flow characteristics in relation to land use practices / forest management
CRITERION 6: Maintenance of other Socio-Economic Functions and Conditions
CONCEPT AREA*: Cultural Values*
Descriptive Indicators
Existence of informational means to implement the policy framework, and the capacity to:
Conduct studies on proportion of culturally valuable sites and sites with special visual value

Box 8.5 Criteria and indicators relevant to soil protection in the pan-European Process

8.5.4 The UK position

The UK Forestry Standard was published in 1998. It sets out standards for managing UK woodlands and forests, and includes Criteria and Indicators to be used in monitoring forests to ensure that they are being managed sustainably. The UK Forestry Standard is compatible with the Pan European system described above, but Criteria and Indicators have been interpreted to put them into a UK context. Those that deal specifically with soil are shown in Table 8.2.

The forest management plan is the basic reference for monitoring assessment at the forest management unit scale. Note that little thought has been given, as yet, to evaluation of any soil changes detected in the EU long-term monitoring plots.

Table 8.2 Criteria and indicators relevant to soil in the UK Forestry Standard

Criteria for Sustainable Forest Management (SFM)	**Source of National-Level Indicators** ***National SFM requirements***	**Forest Management Unit Indicators**
Forest soil condition	• Soil changes in EU long-term monitoring plots • Annual statistics for afforestation of restored land *Forest soil condition is stable or improving towards a more stable condition*	Evidence that: • The use of cultivation, drainage, herbicides and fertilisers is selective with potential impacts taken into account • Anti-erosion precautions are planned and carried out in vulnerable situations • Pollution of soils is avoided by correct procedures for handling and disposal of substances and containers • Establishment, maintenance, harvesting and roading methods are chosen to minimise soil damage • Silviculture complements other measures designed to improve soils of damaged or reclaimed sites

At the forest scale, maintenance of soil quality is mainly exercised by adherence to forestry practices recommended as suitable by the Forestry Commission. Publications which relate specifically to soil are listed in Section 8.16.

Since 1998, further development of the UK indicators has taken place, and a draft set has recently been published for consultation. It is anticipated that the next set will be published at the end of 2001 (Forestry Commission Economics & Statistics Unit, 2001).

8.5.5 The UK Woodland Assurance Scheme

The international forest products market is increasingly demanding assurance about the quality and environmental impacts of forest management. One way to provide this assurance is through independent verification against a published standard, which defines appropriate and effective management. In forestry, this process is widely known as forest certification. The UKWAS certification standard sets out the requirements that woodland and forest owners and managers and forest certification bodies can use to certify woodland and forest management under the United Kingdom Woodland Assurance Scheme. The standard is the product of an inclusive and transparent process, which has involved a balanced representation from the UK forestry and environmental community. It has been designed to ensure that it reflects the requirements of both the Government's UK Forestry Standard - and through this the guidelines adopted by European Forestry Ministers at Helsinki in 1993 - and the Forest Stewardship Council's (FSC's) GB Standard.

8.6 Previous proposals for forest soil quality indices

One of the earliest soil quality standards and guidelines was developed by the US Forest Service (Griffith *et al*., 1992). Table 8.3 summarises these guidelines for the Northwest USA (Page-Dumroese *et al*., 2000) which is an area similar to the UK in terms of species and climate. The threshold values were set on the assumption that site quality will be maintained if <15% of an area is detrimentally impacted after disturbance. The guidelines are applied uniformly across each USFS Region regardless of soil or ecosystem properties.

Another comparatively early attempt to produce an integrated index of forest soil quality was by Burger and Kelting (1998). This incorporates measures of soil physical and chemical properties related to root growth (Gale *et al*., 1991), and attempts to compare these properties with those for an 'ideal' soil. This method seems arbitrary and poorly founded. These authors also derived a forest soil quality (FSQ) multiplicative model, based on several soil quality attributes that influence forest productivity. However, the model has been condemned as overly complex and expensive to use (Fox, 2000).

Powers *et al*. (1998) proposed a series of three soil quality indexes:

(a) a physical index based on soil strength, that integrates soil density, structure and moisture content;
(b) a nutritional index based on laboratory analyses of soil mineralizable nitrogen, that integrates soil organic matter quality, content and microbial activity, and
(c) a biological index based on soil macrofauna, that integrates the activity of soil organisms relative to physical and chemical properties.

However, thresholds for these indexes have not been developed, and these would be dependent on forest ecosystem and forest soil type. Fox (2000) concluded that considerable research would be needed to establish that these indices form the basis of a realistic system for monitoring soil quality that is also simple and economic.

Adams *et al*. (2000) have recently proposed two sustainability criteria for Appalachian hardwood forests under threat from atmospheric pollution. These were (1) maintenance of nutrient balances adequate for forest composition and productivity commensurate with historical levels, and (2) maintenance of a soil acidity/alkalinity balance commensurate with natural levels. For the first criterion, the authors suggested that CEC, base saturation, buffering capacity, measures of sulphate steady-state and N-saturation, and foliar nutrient levels. For the second they suggested pH, base neutralising capacity, base saturation, Ca/Al in soil solution and the ratio of base cations to acid cations in fine roots and humus. Some examples of thresholds have been proposed by Meiwes *et al*. (1986). However, Adams *et al. (loc. cit.)* concluded that further work was necessary to establish this kind of system across the range of forest types in eastern US.

The main conclusions to be drawn from the review of research pioneering the development and use of soil quality indicators in forestry are:

- Most effort has been expended in conceptual development, with much less spent on evaluating how such systems might work in practice.
- Little or no consideration of cost-benefit for soil quality monitoring has been undertaken.
- Thresholds used are largely deductive, and there has been little research to link them to productivity. It is also clear that 'blanket threshold values are not the optimum solution' (Page-Rimroese *et al*., 2000), and that site-specific information is important.
- Considerable research is necessary before meaningful thresholds can be erected, and it is debatable whether this should form the basis of a research campaign, given the high cost and risk involved.

Table 8.3 USFS soil quality standards for the Northwest USA. 1: Northern Region; 4: Intermountain Region; 6: Pacific Northwest Region (from Page-Dumroese *et al*., 2000)

Disturbance variable	USFS region	Thresholds
Soil displacement	1	Loss of 2.5 cm of any surface horizon, usually the A horizon
	4	Loss of either 5 cm or 0.5 of the humus-enriched topsoil, whichever is less
	6	Loss of 50% of the A horizon
Compaction	1	Bulk density increase of 15%, usually in the A horizon
	4	Reduction of >10% soil porosity or a doubling of soil strength
	6	15% bulk density increase (Volcanic soils: 20%)
Rutting and puddling	1	Wheel ruts at least 5 cm deep
	4	Ruts or hoof prints in mineral soil or Oa horizon
	6	Ruts to at least 15 cm depth
Erosion (surface)	1	Visual evidence of detrimental soil loss and maintenance of minimum ground cover based on local conditions (soil loss should be <2-4 t/ha/year)
	4	Establish local minimum ground cover guidelines to limit erosion (not to exceed the natural rate of soil formation)
	6	Visual evidence of detrimental soil loss and maintenance of minimum ground cover based on erosion hazard class (not to exceed the soil formation rate)
Soil cover	1	Enough cover to prevent erosion from exceeding natural rates of formation
	4	Too little to prevent erosion from exceeding natural rates of formation
	6	Less than 20% cover on sites with low erosion hazard ratings, 30% for moderate, 45% for high, and 60% for very high (for year 1 after disturbance)
Organic matter	1	Local guidelines developed based on ecological type
	4	Local guidelines developed based on ecological type
	6	Local guidelines developed based on ecological type
Burned conditions	1	Forest floor lost and A horizon has intense heating
	4	Loss of either 5 cm or 0.5 of litter layer, whichever is less
	6	Mineral soil oxidised and next 1.5 cm blackened due to charring of organic matter

8.7 Forest soil chemical indicators

Although there might be a *prima facie* case for choosing soil chemical indicators that are similar across land uses (e.g. for agriculture and forestry), there are significant differences as far as their use and assessment are concerned. Powers *et al*. (1998) pointed out that many analytical soil testing methods frequently used in agriculture have proved much less useful in predicting tree and forest growth. Lack of long-term correlative data on forest soil properties and crop performance makes assessments of many soil properties rather inductive (Schoenhotlz *et al*., 2000). Inclusion and evaluation of soil properties in soil quality assessment is largely based on inference regarding their role in critical soil functions (e.g. soil organic matter) rather than being based on concrete data. Critical threshold values are seldom available. Inductive ratings are only as good as our understanding of the underlying mechanisms (Henderson *et al*., 1990). Furthermore, forest ecosystems encompass a wide spectrum of structural complexity, management intensity and societal function, which does not lend itself to simple one-size-fits-all soil property ratings. Changes in soil quality indicators cannot be easily interpreted unless their relationship is known to important ecosystem processes (Smith and Raison, 1995) and ultimately productivity (Richardson *et al*., 1999).

The following are examples of differences between agriculture and forestry:

1. The importance of *soil organic carbon* as a structural and functional component of soil productive capacity and in providing the critical linkage between management and productivity is widely recognised for forest soils (Henderson *et al*., 1990, Henderson, 1995; Burger, 1997, Nambiar, 1996). However, no quantitative relationships (deductive or inductive) between this critical parameter and soil quality or forest productivity have yet to be established (Nambiar, 1996). Indeed, there are clear cases of reduction in forest productivity associated with accumulation of soil organic matter (Grigal, 2000).

2. Because *pH* influences so many biological and chemical relationships simultaneously, soil pH in itself provides little direct information as to which soil process is critically affected by it and in turn critically affects the productive capacity of the soil. Rather, pH is simply a surrogate for this complex of potentially nutrient-limiting processes (Schoenhotlz *et al*., 2000). In forestry, UK research shows that the more simple relationship between pH and yield found in agriculture is not borne out (Freer-Smith and Read, 1995; Moffat *et al*., 1997).

Site/yield studies are valuable in identifying important soil factors determining tree growth (forest productivity), and constraints to it. Table 8.4 reviews a selection. These studies differ in the breadth of climatic, site and soil variables chosen, and this will affect the variable(s) that emerge as the most important to explain tree growth. Species may also differ in their response to different soil factors. Nevertheless, the results suggest that there are no *consistent s*oil variables which relate to tree growth. Soil fertility, notably, has not materialised as a frequent explanatory factor, perhaps in contrast to agricultural studies of a similar kind. This may be for several reasons:

(a) total soil elemental measures such as N or P do not correlate with the plant available fraction;
(b) many tree species are conservative in their nutrient requirements, and are satisfied by supply;
(c) uptake from atmospheric sources confounds the relationship between soil supply and tree growth;

(d) depletion of nutrients by removal in woody biomass is rare.

Forest soil science has yet to identify generally useful measures of soil fertility which relate to tree response (Fisher and Binkley, 2000), and evaluation of nutrient content in soil *solution* is probably best related to nutrient uptake and physiological response. Alternatively, analysis of foliar samples to identify nutrient status of tree crops has been undertaken traditionally in UK forestry, and these data may serve as sensible surrogates for soil measures. Foliar analyses reflect uptake and integrate across soil horizons which, in forest soils, may be starkly contrasting (*c.f.* agricultural soils). They avoid difficulties of establishing the depth of soil required for evaluation, which partly depends on rooting depth.

Table 8.4 Site/yield studies in forestry

Author(s)	**Soil variables important for explaining growth/productivity**	**Significance**
Zutter *et al*. 1997	Organic matter (up to age 3)	SOM useful as an index of site fertility for establishing sweetgum and loblolly pine
Worrell and Malcolm 1990	Soil type (major soil group)	Only explained 2-4% of variation in Sitka spruce growth
Tyler *et al*. 1995	Drainage class	Soil variables less important than climatic and topographic ones for Douglas fir
Shrivastava 1982	Available water capacity	Useful for explaining variation in height of Norway spruce
O'Carroll and Farrell 1993	C:N, air porosity and pH	Explained 73% of variation in Norway spruce yield class
Macmillan 1991	Drainage class	Soil variables less important than climatic and topographic ones for Sitka spruce
Jokela *et al*. 1988	Texture, pH, exchangeable cations, organic C, CEC	Soil and topographic variables explained 53-82% of variation in Norway spruce growth
Johnson *et al*.1987	Parent material, drainage class, nutrient content	Complicated relationships between Red maple growth and soil and site factors.
Fourt *et al*. 1971	Phosphate and pH	Variables explaining growth of Corsican pine. Water variables unrelated to growth differences
Corona *et al*. 1998	Calcium and clay content	Climatic factors relating to water balance most important for Douglas fir growth
Blyth and MacLeod 1981	Total N, total P; drainage	Complex interactions between soil variables depending on other soil and site factors
Day 1947	Depth of freely drained soil	Not specified

In addition, concerns about declines in soil fertility are probably less founded in UK forestry than in agriculture. Use of fertilisers to remediate infertility in UK forestry is very small (Moffat and Williamson, 1991), and atmospheric inputs represent a large proportion of uptake and consequent removal from site at harvest. Forest soils are generally hold on to plant nutrients, and losses from leaching, denitrification and volatilisation are generally small, localised or infrequent when taking a forest stand and a rotation length into consideration (Moffat, 1991). Table 8.5 summarises the chemical indicators most commonly encountered in the scientific literature along with comments on their general suitability for forest soils.

Table 8.5 Common soil chemical quality indicators, and comments on value for forest soils

Soil chemical property	Comments
Carbon	
Organic C and organic matter, O layer depth	Pivotal role in many soil functions which may be its downfall – it is unclear what any detected changes would inform the user. For example, supporting indicators reflecting climate change and acidity status would also need to be erected.
Nutrient availability	
N: total, organic, mineralisable (potential or actual), extractable NH_4, NO_3, C:N ratio	Total N and C:N are probably the most useful. *Potential* mineralisable N requires further investigation. The different forms of N vary too much naturally over a rotation.
P: Mineral, extractable, Bray, P sorption	As macro nutrients some measure of these is logically useful though experimentation has generally failed to find links between P or K and forest growth in the UK. However, the potential increased growth associated with climate change may mean these become increasingly limited and could be of more value for the future.
K: Exchangeable and extractable	
CEC	A useful general indicator of the soil's capacity to supply nutrients (excepting N).
Nutrient balances	Although a valuable concept, these sorts of calculations usually require more measurements than anticipated at the outset. In this sense they move away from the definition of an indicator as a *simple*, measurable warning signal and their cost effectiveness is questionable at a large number of sites.
Soil Acidity	
pH	Although a measure of state rather than capacity this is frequently suggested due to the ease of measurement. Known changes through a forest growth cycle and time lags in soil response to afforestation of agricultural land make its value questionable.
ANC (Acid Neutralising Capacity)	More valuable than pH in terms of interpretation, but requires analysis of full suite of acids and bases in the soil.
Base saturation and Ca:Al	Fairly established indicators for which limits have been extensively debated.

8.8 Forest soil physical indicators

Measures of physical soil quality used by soil researchers have been reviewed recently for their applicability in forestry by Schoenholtz *et al*. (2000). Some important physical properties are static in time, but are valuable for soil characterisation. These include soil texture or particle size distribution and soil depth. Other properties are more dynamic. Some properties are resistant to change by management practices while others are changed easily. Changes can be both positive and negative, reversible and irreversible.

The following soil physical properties seem to be most important for further consideration as forest soil indicators. Comments are given on their likely utility (Table 8.6):

Table 8.6 Common soil physical quality indicators, and comments on value for forest soils

Soil physical property	Comments
Soil depth/ depth to permanent waterlogging	Unlikely to change dynamically; important baseline characterisation
Particle size distribution	Important for characterising forest soil type; useful in pedotransfer functions
Bulk density	Useful for conversion of soil chemical concentrations to mass per unit area; a useful measure of soil compaction due to mismanagement; some correlation with rooting ability (e.g. Dobson, 1995)
Surface topography/rutting	Invaluable indicator of soil damage by poor husbandry, and susceptible to routine monitoring
Available water capacity	Important measure of plant available water; likely to be affected by malpractices such as untimely trafficking
Soil strength	Related to rootability (Dobson and Moffat, 1993), but dependent on soil water content, making variable difficult to use for monitoring purposes
Erosion/deposition	Very site/time-specific and incapable of inserting into a rigid (e.g. grid) monitoring system; comparatively rare in UK forestry. Surrogate indicator of surface water turbidity may offer more effective measure of this phenomenon
Aggregate stability	Not important in forest soil quality
Infiltration capacity	Valuable for assessing water access into soil, but unimportant in a forestry context (unlikely to be useful as indicator of soil quality); forest cultivation, drainage and rotation stage much more important in determining surface water characteristics

8.9 Forest soil biological indicators

The inadequacy of soil chemical properties in explaining tree growth or response to fertiliser application has led to evaluation of indicators which have a biological basis. Advocates of this type of indicator point to the inability of so-called conventional indicators such as compaction or loss of organic matter to predict soil degradation before it occurs. They claim that indicators 'should deal with the ecological processes that control ecosystem health rather than the end result of ecosystem degradation' (Staddon *et al*. (1999). Biological indicators examined in a forestry context include:

- Fine root biomass and chemistry (Bakker, 1999);
- Microbial indicators (Staddon *et al*., 1999);
- Earthworms (Muys and Granval, 1997);
- Mites (Ruf, 1998).

In general, these methodologies are at the early stages of development. Bakker (1999) studied fine root biomass in oak. He found relationships between total fine root biomass and chemistry and lime treatment to the soil, and considered that the technique showed promise as an indicator of forest ecosystem sustainability. However, he acknowledged that the technique of fine root quantification is laborious, and suggested that further research was required if the technique was to be used to 'complement soil and foliar indicators'. Staddon *et al*. (1999) proposed that microbiological processes are central to forest growth and therefore worthy of monitoring. They reviewed a range of possible indicators (Table 8.7).

Table 8.7 Potential biological indicators for forest soil quality monitoring (from Staddon *et al*. (1999))

Category	**Potential microbial indicators of soil quality**
Microbial biomass	Direct counts; Muramic acid; Ergosterol; Fumigation – incubation; Substrate-induced respiration; Phospholipids; C and N; Biomass C/total organic carbon
Soil enzymes	Dehydrogenase; Phosphatase; Arylsulfatase; Arginine
Activity measurements	Respiration; qCO_2
Microbial community structure	Sole-carbon source utilisation; Phospholipids; Nucleic acids: • Whole population DNA • Amplification of specific genes by PCR
Indicator organisms/process	Nitrifying bacteria/nitrification

They identified four critical barriers to the development and use of suitable indicators:

(1) indicators must have ecological relevance;
(2) indicators should be properly documented across various ecosystems;
(3) ease of use and
(4) the use of indicators must evolve with new scientific knowledge. In general microbial indicators failed one or more of these ‘tests’, and the authors concluded that none of the indicators proposed in Table 8.7 could be used because of ‘our lack of understanding of their ecological variability’.

Muys and Granval (1997) examined the role of earthworms as indicators of forest soil quality, in a study of 180 plots in Belgium. They found that earthworm biomass could be related to soil pH, organic matter content, water content and humus quality. However, they concluded that earthworms were less precise indicators of site quality than many plant species. In addition, earthworm taxa are too restricted in forest soils for a reliable set of indicators to be put forward. Ruf (1998) examined a soil mite maturity index, which expresses the proportion of species in a community with certain maturity traits to the proportion of other species with other traits assigned by the author. Although Ruf considered that predatory soil mite fauna represent a good indicator of environmental quality in forest soils, when their life history traits are taken into account, the study did not attempt to evaluate the method against more established indices of soil quality. It seems a long way from a workable method at present.

In conclusion, a start has been made in the investigation of suitability of biological indicators for forest soil quality. However, studies demonstrate that these indicators are still at the experimental stage and not ready for consideration as indicators today.

8.10 Forest soil variability in time and space

Compared to soils under agriculture, forest soils are notorious for their spatial variability (Quesnel and Lavkulich, 1980; Arp and Krause, 1984; Riha et al. 1986; Mader, 1963; McFee and Stone, 1965; Blyth and MacLeod, 1978). The influence of stemflow and tree crown and root architecture are the main reasons. In addition, soils may carry influence of *previous* tree crops or individuals. Wildfire and windthrow are other factors which leads to uneven soil disturbance, and woodland animals, especially badgers and wood mice, also disturb the soil by excavating it. Finally, cultivation may increase or decrease soil homogeneity, depending on scale and frequency.

The reality, that forests are dynamic ecosystems, cannot be overlooked in the debate on indicators. Plantation forests are not climax communities - they are usually planted on ex agricultural or marginal land unfit for agriculture. Most are monocultures; thus the age structure of the stand does not remain stable but progresses with time. This in turn influences the nature of forest soils, which change through out a rotation as the crop moves through distinct stages of nutritional demand and light, water and pollutant interception capacities.

Miller (1981) hypothesised three distinct stages in the life cycle of a forest stand (Figure 8.1). Stage one finishes at canopy closure. Prior to this, foliage forms a large proportion of the total biomass and the crop has a high demand for nutrients, which must be supplied by the soil reserve as litter fall, nutrient cycling and the interception of atmospheric nutrients and water are not yet fully functional. After canopy closure, during the second stage, nutrients for new foliage can be supplied to some extent by deployment from older, dying foliage. Nutrients are also supplied through the recycling of litterfall, decaying, out-competed ground vegetation, and atmospheric interception (dry deposition velocities to closed canopy woodlands can be double those of other landuses and, more crucially, those of very young stands). In this second stage there is little appreciable increase in foliage biomass and woody parts form an increasing proportion of the trees. Finally, in the third stage, nitrogen may become immobilised in the deepening litter layer and the onset of nitrogen deficiency may occur if rotations are long enough to reach it.

These hypothesised stages are reflected in the few chronosequence studies of forest soil chemistry that exist. Both Paré and Bergeron (1996) and Fons and Klinka (1998) found decreasing pH and N mineralisation rates and rising C:N ratios with age. Fons and Klinka also noted the significant increase in fungal biomass with age (which they suggested was associated with a build up of litter) and a slight decrease in the depth of the H horizon during the most demanding period of Miller's curve in Figure 8.1. These studies were in temperate climates on first and second rotation sites respectively. Some changes, such as the decline in pH, may be expected to stabilise in the long term if the land remains under forestry whereas we might anticipate others, e.g. C, N and organic matter volume, to move in similar, repeated cycles with each rotation. With so few studies addressing this subject, it is difficult to predict these changes and more research must be directed towards improving this understanding if the realistic interpretation of soil chemistry indicators is to be achieved. For example, nitrogen mineralisation potential has been suggested as a possible indicator of soil fertility. It is not known if and by how much this might change over a growth cycle. The differences between agricultural and forest soils have already been highlighted in Box 8.1 and demonstrate that a young forested stand planted on ex-agricultural land cannot be expected to conform to any indicator threshold considered 'typical' for forestry.

The potential for the use of foliar chemistry, as a surrogate indicator for soil nutrient status, is slightly more promising. Again, few long term chronosequence studies in temperate climates have been carried out, but in Lodgepole pine stands, Binkley *et al.* (1995) did find that, whereas stand scale parameters such as leaf area and specific photosynthetic rate declined with age, needle weights, and N and P foliar concentrations remained unchanged. Only Ca increased with age.

These growth cycle changes, which will be further compounded by the effects of management, such as thinning, lead us to conclude that realistic sampling intervals for forestry cannot be aligned to those for agriculture. Annual measurements are not sensible; five or ten yearly sampling points are realistic and interpretation of time trends must be undertaken with a clear understanding of the expected underlying growth cycle changes outlined above.

Establishing temporal changes in forest soil properties demands that, on every occasion soils are measured *in situ* or sampled for analysis, sufficient samples are taken to quantify the mean value for the properties under scrutiny with adequate confidence. The number of samples or sampling points needed will vary with (a) the soil property measured, and (b) the degree of change likely to be found in the allotted period between sampling occasions. In addition, the methodology for soil sampling must not lead to bias, for example by including a disproportionate element of samples taken from close to tree stems. Furthermore, sampling must accommodate short-term seasonal variation in soil properties. For example, seasonal changes in soil temperature and water content, supply of organic litter (especially under deciduous species) and cation uptake may all affect important soil properties such as pH (Skyllberg, 1991), nitrogen mineralisation (Eichhorn *et al.,* 1999), biological activity (Callaham *et al.*, 1997) and some physical properties (Wairiu *et al.*, 1993). Finally, the methodology should be adequate to permit a monitoring period of decades rather than years, while preventing damage to the trees or running the risk of contamination of remaining soil in the monitoring site. These demands are complex, sometimes counteractive and usually time consuming and costly.

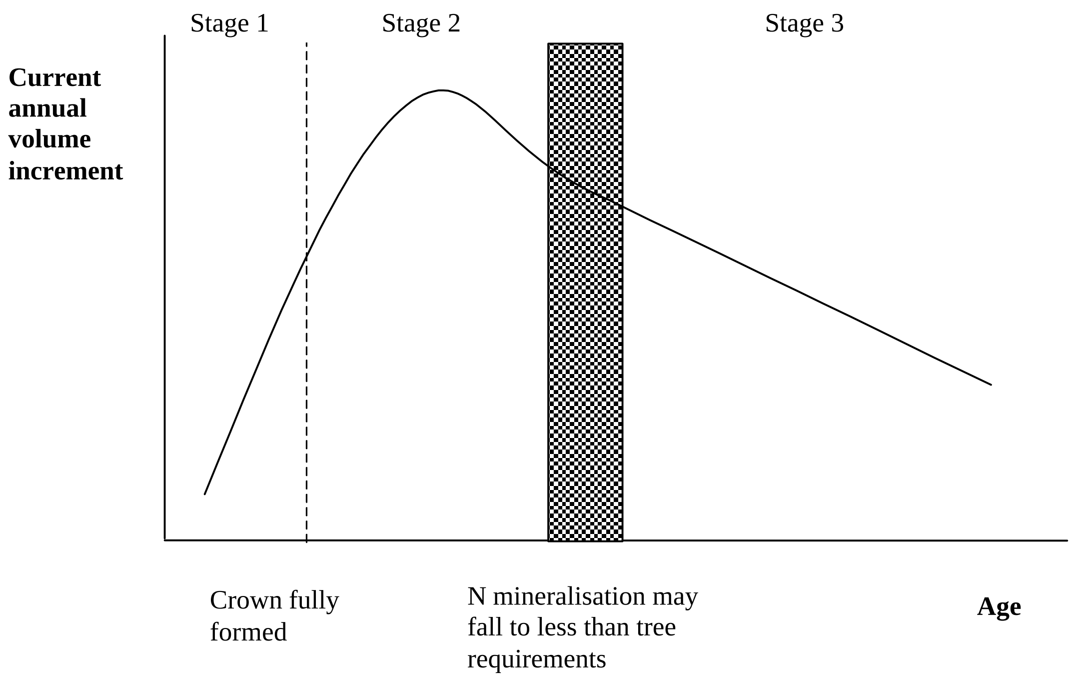


Figure 8.1 The three distinct nutritional stages in the life of a forest stand, as hypothesised by Miller (1981)

8.11 Forest soil monitoring in Great Britain

Until recently there has been little systematic and specific soil monitoring under forests in Great Britain. An early, limited, study examined plots established in four locations in England and Wales by Ovington (1953, 1954, 1956, 1958a; 1958b). These were revisited in the 1970's and 80's (Howard and Howard, 1984, Anderson, 1987). A fortuitous opportunity to study soil change under forests was taken by Billett *et al.* (1988; 1990a; 1990b; 1991; 1993) under coniferous forest in north east Scotland. The Park Grass and Broadbalk Wilderness plots at Rothamsted Experimental Station in Hertfordshire have also been very important for study of soil change (e.g. Johnson *et al*., 1986; Goulding *et al.*, 1988; Blake *et al*., 1999). Smaller studies have been undertaken by Moffat and Boswell (1990) and Wilson *et al.* (1997).

Systematic study of soil change has been facilitated in three main ways:

- Study of the National Soil Inventory dataset (McGrath and Loveland, 1992). A subset has been re-examined recently for arable and grass uses, but a similar study for woodland soils could be undertaken.
- Establishment of the Environmental Change Network (ECN). Two of the sites are under woodland, at Alice Holt Forest in Hampshire and Wytham Wood in Oxfordshire. Soils have been sampled and analysed twice, in 1994 and 1999. Soil solution is monitored every two weeks at Alice Holt Forest. The methodologies for sampling and analysis of soil materials are carefully defined (Sykes and Lane, 1996).
- Establishment of the Level I and II pan-European forest ecosystem monitoring systems. In Britain, there are 10 intensive 'Level II' sites where solid soil chemistry is monitored every 10 years, and soil solution chemistry every two weeks (Durrant, 2000). In addition, soil from 67 Level I plots was sampled and analysed in 1994 (Moffat *et al*., 1997), and it

is anticipated that a repeat exercise will be undertaken in 2004. The methodologies for sampling and analysis of soil materials are carefully defined in the ICP Forests Manual (1998). Quality assurance is an essential part of the ICP Forests Programme.

It is clear that existing monitoring networks have the capability to support soil *chemical* monitoring. However, soil physical monitoring is not part of the protocols for the sites, and they have not been set up to encompass this type. The sites cannot be regarded as part of a statistically valid sample of the total UK forest population; rather they have been established to examine the most important woodland types. Nevertheless, they offer very good prospects for building on in the context of a national system for soil quality monitoring.

Monitoring of soil physical properties and functions probably requires a different approach. In forestry, it is most meaningful to measure the net effect of forest management activities over an entire site or the landscape of many sites. Disturbance (e.g. through harvesting) is usually measured over an entire site, and its effect on productivity is similarly integrated (Grigal, 2000). Hence a monitoring system fixed by grid co-ordinates is inappropriate to measure many forest soil physical and morphological indicators. Instead, these properties are best assessed by a stratified system of periodic surveys after harvesting at coupe scale. Such a system has already been envisaged by the Forestry Commission for assessing soil damage during harvesting operations (Technical Development Branch, 2000).

8.12 Surrogates for soil indicators

Primarily due to the high degree of localised variability in forest soils, the use of surrogate indicators (i.e. measurements which are not made on the soil but can be used to make inferences about its status) has been referred to several times in the preceding text. In this Section these potential surrogate indicators are brought together and discussed. Generally speaking they have the benefit of being less costly than direct soil measurements and often they are more comprehensible to the general public.

8.12.1 Forest Productivity

Forest productivity from a site is affected by other factors than soil, and particularly by management practices (e.g. stocking, fertiliser, weed control, establishment techniques, silvicultural management, species genotype) (Figure 8.2) (Richardson *et al*., 1999). ‘Forest productivity is not a good indicator of soil sustainability unless the contribution of management to productivity can be accounted for’ (Morris and Miller, 1994).

Estimates of biomass could be derived from the Forest Enterprise ‘Subcompartment Database’. However, the data are severely confounded by changes in silviculture, forest age structure, climate and atmospheric chemistry (including [CO_2]). Long lived perennial crops must not be treated in same way as annuals.

In the longer term, remote sensing may provide a means of estimating net primary productivity (Law and Waring, 1994).

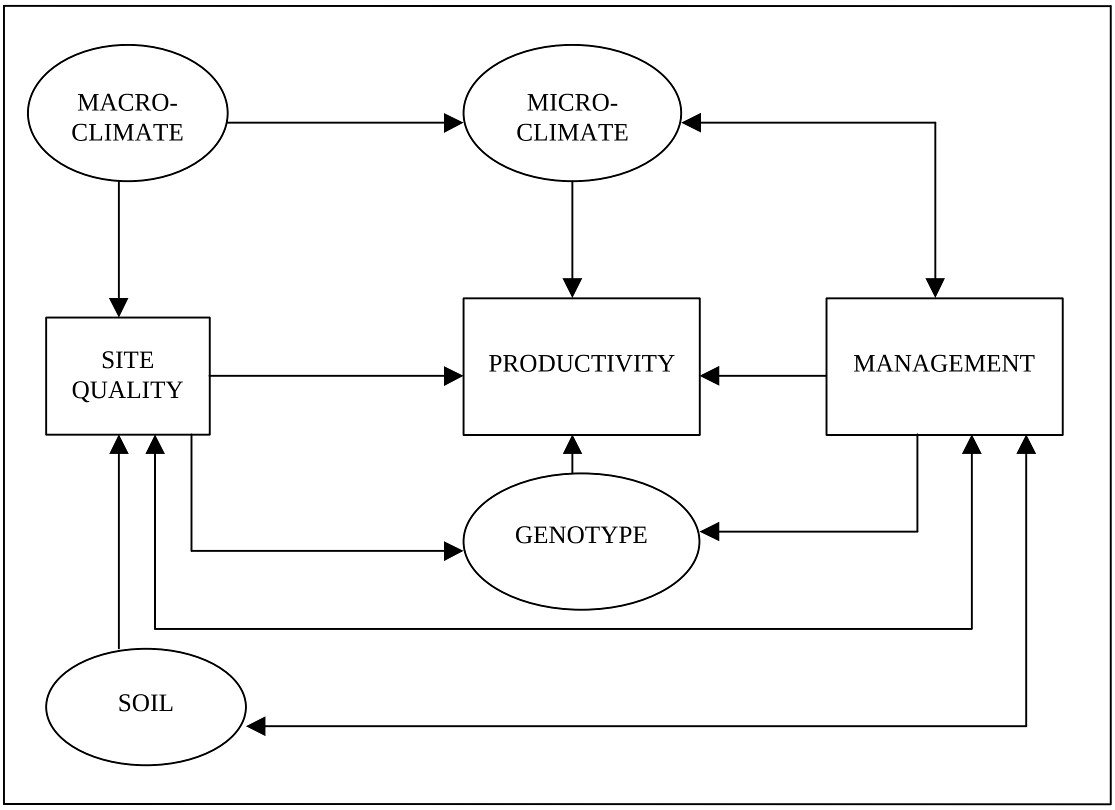


Figure 8.2 Relationship between crop productivity, site quality and management practices (derived from Richardson *et al*., 1999; Dyck and Cole, 1990)

8.12.2 Foliar chemistry

The difficulties of working with soil indicators to give meaningful indicators of soil fertility quality have been discussed earlier. While foliar analysis does not provide a perfect surrogate, it could be used in an interim period. Foliar analyses are taken every year at the ten Level II sites, and every 10 years at about 70 Level I sites. Samples are also taken at numerous forest experiments according to the experimental plan. A few Forest Districts have begun to monitor foliar chemistry as part of their fulfilment of monitoring activities for UKWAS. It is possible to consider that this process might, in time, provide for a reasonably complete coverage of British forests, especially if foliar chemistry was built into the revised Indicators of Sustainable Forestry currently being considered by the Forestry Commission.

8.12.3 Suspended sediment and stream chemistry in upland catchments

No systematic survey of soil erosion has taken place in British forests, nor could one be imagined as cost-effective given the site-specific and circumstantial nature of this form of soil degradation. Monitoring of suspended sediment in streams draining forested catchments may be a useful substitute for direct methods of measuring soil loss. Measurements could include turbidity and colour, routinely undertaken in a range of catchments currently being studied for the effect of forest operations on water quality. Similarly, measurements of streamwater chemistry (cations, anions, DOC, DON) could be useful for expressing loss of nutrients from the forest soil at a catchment scale. Again, many data exist, and continued to be collected, for a range of catchments in upland Britain. However, it should be appreciated that nutrient losses in runoff following harvest do not appear to be important in affecting productivity (Grigal, 2000). Water monitoring will only be useful if performed over a long time period, in order to integrate the short-term effects of particular forest operations.

8.12.4 Input – output nutrient budgets

Input-output nutrient budgets have been an important tool in the understanding of forest ecosystem functioning (Likens *et al*., 1977; Ulrich *et al*., 1979). Recently Ranger and Turpault (1999) have suggested this methodology as a diagnostic tool to assess the sustainable management of forest ecosystems. Ranger and Turpault suggest that budgets calculated for a specific stage of development of a stand cannot be extrapolated to the whole rotation. Thus, it is important to monitor over a substantial time frame, and preferably over the whole rotation. As well as atmospheric inputs (including direct foliar absorption of nitrogen), cations supplied from mineral weathering need to be quantified. The method is difficult to deploy on sloping sites where inputs and outputs can be affected by lateral drainage.

In the UK, the ten Level II plots provide the means to examine this approach. The most important fluxes are measured at these sites, though several are on sloping land. Nitrogen gaseous losses are also unmeasured. Nevertheless, the method is expensive, laborious and expensive. It is recommended that further testing take place.

8.12. 5 Fertiliser and Pesticide use

These data are available for each Forest Enterprise Forest District. In addition, chemical use will be recorded for all woodlands accredited under the UK Woodland Assurance Scheme (UKWAS).

8.13 Headline soil indicators for forestry

Box 8.6 contains proposals for so-called headline indicators which relate to the use and protection of forest soils. Many headline statistics are available from the Forestry Commission Economics & Statistics Unit, Edinburgh. Others can be derived from information from FE Districts, FC Conservancies or UKWAS invigilators.

8.14 Conclusions and Recommendations

- UK forestry has needs for soil quality indicators driven by external policy initiatives such as the Montréal Process and the Pan-European Ministerial Conference for the Protection of Sustainable Forests. The UK Department of Forestry (Forestry Commission in GB) is intent on producing a list of criteria and indicators under the umbrella of continual development of the UK Forestry Standard. These will be relevant both to the national and forest scale.
- Some useful guidance on applicability of soil quality indicators for forestry already exists, as a result of countries working to apply them in their respective circumstances.
- Existing information systems in the UK (mainly but not exclusively from the Forestry Commission) can provide the basis for several headline and / or surrogate indicators of forest soil quality, and / or its sustainable management.
- There are several monitoring networks for forestry needs, which are already used to inform on the sustainable use of forest soils. These could be utilised in a wider programme, though many of the measurements currently taken are controlled by strict protocols.
- Proposals for identification, development and implementation of soil quality indicators for England and Wales should be compatible with the requirements identified above.

- The pressures on UK forest soils are reasonably well understood. The threats to soil functioning posed by these pressures is considered small. Current management is considered to be broadly sustainable.
- Interim indicators, based on the availability of information from monitoring and research plots in the scientific community, may be useful in the period before more robust indicators can be developed.
- It is not yet possible to suggest direct soil quality indicators that can operate at the Forest Management Unit level in the UK. In the interim, before such indicators are ready to be deployed, maintenance and enhancement of soil quality is best achieved by seeking compliance with best practice guidance, in accordance with principles enunciated in the UK Forestry Standard and UKWAS.

1. ***Area under forest/woodland***

1.1. Area of forest/woodland on specific soil types
(reliant on 1:250,000 soil maps – not yet able to use FE GIS)
1.2. Area of forest/woodland on brownfield land (monitored via WGS/LRU data)
1.3. New planting (ex agricultural land)
1.4. General yield class by subcompartment

2. Area of forest/woodland managed to specified standard – possible indicators

2.1. Area with UKWAS accreditation
2.2. Area under WGS
2.3. Areas of ancient and semi-natural woodland categories
2.4. Area with biodiversity/conservation management plans
2.5. Area with archaeological management plans
2.6. Area managed by 'Continuous Cover Forestry'

3. Surrogate indicators

3.1. Foliar analysis (for soil fertility)
3.2. Stream sediment via colour/turbidity (for soil erosion)
3.3. Stream chemistry (for soil loss)
3.4. Input – output nutrient budgets (Ranger and Turpault, 1999)
3.5. Forest industry fertiliser and pesticide use

4. ***Awareness indicators***

4.1. Uptake of '*Forests and Soil Conservation Guidelines*' and other soil-related Forestry Commission publications
4.2. Number of hits/downloads to/from the FC website on soil-related material

Box 8.6 Headline and surrogate indicators for soil quality

8.15 Recommendations for further research

- Forest ecosystems are complex. The dynamics and properties of forest soils differ in many respects from those under agriculture, and these differences must be understood before the development of a national system for monitoring soil quality.
- More chronosequence studies to develop our understanding natural growth cycle changes are essential to enable the interpretation of any soil quality indicators.
- Forest soil science is not ready to erect thresholds for common soil properties considered as candidates for soil quality indicators. 'Arbitrary imposition on managers of poorly validated soil quality criteria for regulating forest management practices would be a retrograde step in achieving wise use of forests' (Nambiar, 1996). Considerable research would be necessary to provide such information, and in many cases a judgement must be made as to whether this research would be cost effective.

- This report has identified some direct and surrogate soil parameters, which may currently have potential as indicators. For these, the undertaking of costings and feasibility studies is the logical next step.
- Biological indicators have considerable potential due to their predictive (rather than responsive) capacity, but much further research in this area in general is necessary before these indicators can become useable.
- Progress on the development of critical loads for heavy metals should be monitored.
- Our understanding of the anticipated impacts of climate change on soil quality needs improving.
- Links between soil *solution* nutrients and woodland productivity may be worthy of investigation to develop future indicators.

8.16 Forestry Commission documents containing soil guidance

Forestry Commission: Forest Nature Conservation Guidelines, 1990.
Forestry Commission: Forest Recreation Guidelines, 1992.
Forestry Commission: Forests & Archaeology Guidelines, 1995.
Forestry Commission: Forests and Soil Conservation Guidelines, 1998.
Forestry Commission: Forests & Water Guidelines, 3rd edn, 2000.
Forestry Commission: Forestry Practice Guide 11 Whole-tree harvesting, 1997
Forestry Commission: Handbook 6, Forestry practice. B. G. Hibberd (ed.), 1991.
Forestry Commission: Bulletin 95, Forest fertilisation in Britain. C. M. A. Taylor, 1991.
Forestry Commission: Bulletin 107, A manual of good practice for the use of sewage sludge in forestry, R. Wolstenholme, J. Dutch, A. J. Moffat, C. D. Bayes and C. M. A. Taylor, 1992.
Forestry Commission: Bulletin 110, Reclaiming disturbed land for forestry, A. J. Moffat and J. D. McNeill, 1994.
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Forestry Commission: Field Book 8, The use of herbicides in the forest. I. Willoughby and J. Dewar, 1995.
Forestry Commission: Technical Paper 20, An ecological site classification for forestry in Great Britain with special reference to Grampian, Scotland. D.G. Pyatt, 1997.
Forestry Commission: Research Information Note 196, Forest drainage. D. G. Pyatt, 1990.
Forestry Commission: Forestry Authority Technical Development Branch Report, Oil and chemical spillages, J. A. Dewar, 1993.
Forestry Commission: RIN 288, Cultivation of lowland sites for new woodland establishment, I. Willoughby and A.J. Moffat, 1996.

9. INDICATORS FOR SEMI-NATURAL SOILS AND THE NATURAL HERITAGE

M. Hornung and HIJ Black, CEH Merlewood

9.1 Introduction

The soils associated with natural heritage cover almost the full spectrum of soil groups and most sub-groups found in Great Britain. They represent, therefore, a wide variation in soil properties: chemical, physical and biological. They range from circum-neutral, nutrient rich soils to extremely acidic, from freely drained to waterlogged, from soils with surface accumulations of organic matter to others with mull humus, from soils dominated by earthworms to those with few subterranean macro-invertebrates, from soils dominated by bacteria to those dominated by fungi.

The soils of semi-natural habitats also perform a series of key functions in parallel. This is true of almost all soils, but the relative importance of the functions varies with the prime land use and the geographical location. In the case of the soils associated with semi-natural habitats, the key functions are habitat maintenance, reservoir of biodiversity, carbon store, filter/buffer and water supply.

It is important to remember, however, that most semi-natural habitats are part of an agricultural system, with many used for low intensity grazing. The production of biomass is therefore important in this context. The soils also have an important role in preservation of cultural heritage and can become the foundation for infrastructure. Indicators related to these functions are not considered in detail in the text below, but are considered in Table 9.1 and elsewhere in the report.

Any series of indicators aimed at the assessment of the status (health) of soils in semi-natural habitats has to be applicable across the wide range of soil types and habitats, be relevant to the key functions these soils perform and address the key pressures/threats. Table 9.1 summarises current key pressures on semi-natural habitats, their relative impacts on soil functions and potential headline indicators.

Table 9.1 Pressures (threats) on semi-natural habitats, their relative impacts on individual soil functions and potential headline indicators of these pressures. xxx (major impact), xxx (intermediate, may increase with time), x (minor impact, may increase with time)

PRESSURE CATEGORY	SPECIFIC PRESSURES	Habitat maintenance	Filter, buffer, transform	Soil biodiversity	Water supply	Human infrastructure	Cultural heritage	Raw materials	HEADLINE INDICATORS
ENVIRONMENTAL CHANGE	Climate change	xx	xxx	xxx	xx	x	xx	x	national monitoring (temperature and rainfall), climate predictions, water quality/flow monitoring
ATMOSPHERIC DEPOSITION	Acidification, trophospheric ozone and nitrogen enrichment	xxx	xxx	xxx	xxx	x	xx	x	national air monitoring, locality of point sources, critical load exceedances, water quality/flow monitoring
	POPs and heavy metal pollutants	x	xxx	xx	xxx	x	x	x	national air monitoring, locality of point sources, critical load exceedances, water quality/flow monitoring
LAND USE CHANGE	Afforestation (mainly by non-native conifers)	xxx	xxx	xxx	xxx	x	xxx	xx	Area of priority habitat, Forestry Commission statistics
	Conversion to pasture/grasslands	xxx	xx	xxx	xx	x	xx	x	Area of priority habitat, Agricultural area statistics
	Industrial and urban development	xxx	xxx	xxx	xx	xxx	xxx	xxx	Area of priority habitat, Planning and Development statistics (applications/approvals)
	In-filling of abandoned chalk and limestone quarries	xxx	xxx	xxx	xx	x	xxx	x	Area of priority habitat, Planning and Development statistics (applications/approvals)
	Recreational uses	xxx	x	x	x	x	xx	x	Area of priority habitat, Visitor numbers
	Localised military use	xxx	xx	xx	xx	xx	xx	xx	Area of priority habitat, MOD statistics
	Peat extraction.	xxx	xxx	xxx	xxx	x	xxx	xxx	Area of priority habitat, industrial/agricultural statistics, Planning/development statistics (applications/approvals)
	Land developments; quarries, windfarms, communication masts, access tracks etc .	xxx	xxx	xxx	xx	xx	xxx	x	Area of priority habitat, industrial statistics, Planning/development statistics (applications/approvals)
MANAGEMENT PRACTICES	Drift of aerial application of fertilisers and pesticides.	xx	xxx	xx	xx	x	x	x	Agricultural statistics, land management records, water quality monitoring, wildlife statistics
	Fertiliser application	xx	xxx	xx	xx	x	xxx	x	Agricultural statistics, land management records, water quality monitoring, wildlife statistics
	Herbicide application,	xxx	xxx	xx	xx	x	xx	x	Agricultural statistics, land management records, water quality monitoring, wildlife statistics
	Liming	xx	xxx	xxx	xx	x	xx	x	Agricultural statistics, land management records, water quality monitoring, wildlife statistics
	Pesticide applications	xx	xxx	xxx	xx	x	xx	x	Agricultural statistics, land management records, water quality monitoring, wildlife statistics
	Burning - scale, poorly managed/accidental	xxx	xxx	xxx	xxx	x	xxx	xx	Area of priority habitat, agricultural statistics, land management records, water quality monitoring, wildlife statistics
	Drainage (moorland 'gripping', forestry impacts adjacent areas)	xxx	xx	xx	xxx	x	xx	xx	Water quality/flow monitoring, agricultural statistics, land management records
	Agricultural intensification - crop type	xxx	xxx	xxx	xxx	x	xxx	x	Area of priority habitat, agricultural statistics, land management records
	Management cessed/bracken encroachment	xx	xx	xxx	xx	x	xx	x	Area of priority habitat, agricultural statistics, land management records
	Fragmentation/isolation	xxx	xx	xxx	xx	x	x	x	Area of priority habitat, agricultural statistics, land management records, wildlife statistics
	Reseeding	xxx	x	xx	x	x	x	x	Agricultural statistics, land management records
	Paths + track management	xxx	xx	xxx	xx	xx	xx	x	Area of priority habitat, visitor numbers, remote sensing of erosional features
	Heavy grazing/high stocking levels (sheep, cattle or deer)	xxx	xxx	xxx	xxx	x	xx	x	Area of priority habitat, agricultural statistics, land management records, remote sensing of erosional features, farmer subsidies
	Under/Lack of grazing	xx	xxx	xxx	xxx	x	xx	x	Area of priority habitat, agricultural statistics, land management records, remote sensing of erosional features
	Ploughing	xxx	xxx	xxx	xxx	xx	xxx	xx	Area of priority habitat, agricultural statistics, land management records,wildlife statistics
INTERACTIONS	Interaction factors may increase impact	xxx	xxx	xxx	xxx	xxx	xxx	xxx	Multiple indicators to address all potential threats e.g. poorly managed burning + heavy grazing = more rapid loss of dwarf shrubs

9.2 The characteristics of soils in semi-natural habitats

In undisturbed systems, there is parallel evolution of vegetation communities and associated soils, changes in one will produce feedbacks leading to changes in the other (Brussaard, 1997). The vegetation adapts to and, in turn, influences the characteristics and properties of the soils. Thus, in broad terms there is a relationship between soils with given characteristics, in terms of physical, chemical and biological properties, and habitat type as defined by vegetation cover and plant species assemblages.

While the natural heritage of Britain has been greatly affected by man, there has still been a parallel development of soils and vegetation in our semi-natural habitats. A key difference between natural systems and many of the semi-natural ones which dominate in the UK, is that the latter systems are often maintained by a particular land management. For example, grazing in the lower areas of the uplands prevents development of woodland, which could lead to changes in the associated soils. It is important to stress that almost all semi-natural habitats are within an agricultural system, albeit with low levels of management. Equally, changes in the land management regime can influence the balance between the above and below ground systems, with consequent changes in the habitat.

Many semi-natural vegetation habitats have adapted to conditions of low nutrient availability. Because of the latter, a key feature of many natural and semi-natural habitats is the tight cycling of nutrient elements in the soil-plant system. This cycling is dependant on complex food-webs within the soil which can vary significantly between habitats and rely upon close associations between plants and the below-ground biodiversity (e.g. mycorrhizal symbionts). A change in the structure of the food web can lead to changes in the rate of nutrient cycling, with consequent impacts on plant competition and species composition of the vegetation. Changes in the vegetation, for example through grazing can lead to changes in the food-web (Bardgett *et al*., 1999; Yeates *et al*., 1997; Brussaard *et al*., 1990).

Although there is a broad relationship between vegetation and soils, the soils of semi-natural habitats show considerable small-scale variation in properties, which are associated with the patchiness inherent, and in some case characteristic of, many of these habitats. This contrasts with intensively managed systems, where the management evens out the small-scale variations.

Any suite of indicators should reflect the close coupling between the above and below ground systems, the link between habitat maintenance and management regime, the importance of within system nutrient cycling and the characteristic food web for the habitat, and the spatial variation in the soils at a variety of scales.

9.3 Functions of soils associated with natural heritage.

The full range of soil functions are listed in Table 9.2 with a summary of specific requirements and threats for the semi-natural environment. The following text focuses on a key sub-set of these functions.

9.3.1 Habitat maintenance

As can be seen from the above, the mosaic of semi-natural vegetation and habitats seen in the landscape reflects a mosaic of underlying soils. Thus, for example, lowland dry shrub heath is generally associated with acid, nutrient-poor podzols; upland bogs are often associated with peat soils or stagnohumic gleys, chalk grassland is associated with calcareous, rendzina or calcareous brown soils.

The maintenance of the semi-natural habitats requires the maintenance of the whole plant-soil system. The soils will have characteristic physical, chemical and biological properties, including soil biota, food web and organic matter type. The habitat is at risk from any external factor which produces changes in these soil characteristics or in the above ground vegetation complex.

Although relationship have been discussed above in terms of soil types, it is important to note that significant changes in vegetation and in the biota of a given habitat can take place before changes are seem in the horizonation of the associated soil.

9.3.2 Reservoir of biodiversity

Soils form a major reservoir of biodiversity, but the magnitude of that diversity has not been characterised and quantified fully for even a single site. However, an undisturbed soil is likely to contain many tens of thousands of species of bacteria, viruses, fungi, and invertebrates (Brussaard, 1998). There is a variation in biota between habitats and this is understood in broad terms. Thus, for example, the decomposer system in acid and woodland soils is likely to be dominated by fungi, while more fertile, improved, grassland soils generally have a bacterially-dominated system (Bardgett and Cook, 1998). Similarly, *Enchytraeid* worms are key components of food webs in acid, upland soils while earthworms dominate in more fertile, less acidic, soils. Although studies have shown changes in the balance of the bacterial population of soils with land management and vegetation type, much less is known about the variation in microbial populations between habitats (Weeks *et al.*, 1996). Available data do not allow a reliable assessment of the total biodiversity of the soils of semi-natural systems as opposed to, for example, arable soils, or of undisturbed acidic grassland versus an improved equivalent. The soil biota and the food webs are however different (Dick, 1990; Yeates *et al.*, 1997). While the maintenance of the maximum biodiversity in a given habitat would be a laudable aim, it is impossible to provide a full assessment of the diversity and therefore to assess the variation over time (Lawton *et al.*, 1998). A more relevant consideration may be maintenance of functional diversity and keystone species characteristic of given habitats and key to the maintenance of the functioning of given soil-plant systems (Brussaard, 1997).

A key component of soil biodiversity that deserves individual attention is priority and/or protected species, as identified by the UK Biodiversity Action Plan. Many listed invertebrates and reptiles either live entirely in the soil or rely upon the soil for a key life-cycle stage. Specific soil requirements must, therefore, be addressed in the appropriate management of habitats for the protection of these species. Current threats to soil-associated soil organisms have again been identified in national and many regional and local biodiversity action plans. Relationships between these threats and key soil functions could be identified and used to identify appropriate soil indicators. An example of threats to priority listed ant species in Great Britain is shown in Table 9.3.

Table 9.2 Specific requirements and key threats to soil functions in semi-natural habitats. (** Significance of individual threats/pressures will vary between habitats**)**

HIGHER SOIL FUNCTION	SPECIFIC REQUIREMENTS OF SOIL FUNCTIONS	KEY THREATS
Habitat maintenance	maintenance of priority habitats (communities) + protected species (plant), biomass production (grazing, hay, silage), biodiversity maintenance. Medium for plant growth	agricultural intensification, land use change, pollution, inappropriate management - nutrient inputs (animals, agrochemical, sewage sludge, slurries), over/undergrazing, liming, ploughing, reseeding, burning
Filtering, buffering and transforming substances	carbon sequestration, pollutant retention/release, acidification, liming, eutrophication, fertility status, trace gas emissions	climate change + land use policy (ESA/NSZ), atmospheric deposition (S, N, metals, POPs), inappropriate management (liming, grazing, agrochemicals, organic amendments), point source pollution
Reservoir for soil biodiversity	maintenance of protected species (fungal + invertebrate), food supply for birds, reptiles and mammals, mycorrhiza for protected plant species, biodiversity maintenance, gene pool - various reasons (policy … food chains ...maintenance of soil functions)	maintenance of key species for various reasons (policy … food chains ...maintenance of soil functions)
Regulation of water supply	controlled flow, pollutant levels, water quality (colour)	regulation of water flow on and off-site; maintenance of appropriate aerobic/anaerobic conditions, off-site water quality, plant stress
Foundation for human infrastructure	Developments (e.g. tourism builds, wind farms, hydroelectric plants), mining, roads, tracks, footpaths, car parks, pipelines	loss of habitat area, soil erosion through excessive use/inappropriate management, rehabilitation
Preserving cultural heritage	buildings/structures, artifacts, remains, fossils, biodiversity	recognition and maintenance of heritage sites, inappropriate management
Supplying raw materials	peat, sand, gravel, wood coppice, water	sustainable use of resources, loss of habitat area, soil erosion through excessive use/inappropriate management, rehabilitation

Table 9.3 Pressures on maintaining ant species in habitats across Great Britain. Ants are a fundamental component of soil biodiversity. All species listed are on the UK Biodiversity Action Plan.

Ant species	Common name	Pressures
Anergates atratulus	Dark Guest Ant	Loss of suitable heathland habitat through urban or industrial development, agricultural improvement and afforestation. Inappropriate heathland management Inappropriate coastal development or cliff stabilisation. Changes in grazing practice where the host species occurs on short dry acid grassland and cliff-top turf
Formica aquilonia	Scottish Wood Ant	Loss of suitable native pine woodland. Inappropriate woodland management.
Formica candida	Bog Ant	Loss of permanent bog habitat through land drainage and the consequent lowering of the water table, agriculture and afforestation. Natural succession, leading to the overgrowth of carr and scrub. Excessive grazing pressure and trampling of nests. Drought. Pollution and eutrophication of watercourses. Potential genetic isolation, inbreeding and loss of genetic fitness.
Formica exsecta	Narrow-headed Ant	The loss of suitable heathland due to destruction and inappropriate management, for example through agriculture and urban development, inappropriate afforestation, untimely and extensive fires, and encroachment by scrub, trees and bracken leading to shading out of nests and subsequent encouragement of competitive species of ant at sites in England. Loss of natural and semi-natural habitats in Scotland, e.g. Caledonian Pine Forest, and the intensive management of moorland for game birds and red deer. Motorcycle scrambling at Bovey Heathfield in England Excessive grazing and inadequate browsing by inappropriate species of ponies in the New Forest, and the production of dense, single age heather (*Calluna vulgaris*) monoculture with reduced marginal scrub between heath and woodland. Nutrient enrichment of soils and development of grass swath. Habitat fragmentation leading to potential inbreeding and loss of genetic fitness in isolated populations.

Table 9.3 (Continued) Pressures on maintaining ant species in habitats across Great Britain.

Ant species	Common name	Pressures
Formica lugubris	Hairy Wood Ant	Loss of suitable woodland habitat through agricultural clearance, urban or industrial development and unsympathetic afforestation. Inappropriate woodland management, for example through changes in traditional practices, intensive afforestation with conifers or destructive felling operations. Loss of sunny woodland rides and clearings due to overgrowth and scrub invasion.
Formica pratensis	Black-Backed Meadow Ant	Urban development on the heaths and cliff tops around Bournemouth. Inappropriate management and excessive encroachment of scrub on open heath and rough grass. This may lead to the subsequent invasion of competitive southern wood ants (F. rufa).
Formica rufa	Southern wood ant	Loss of suitable scrub and woodland habitat through agricultural clearance, urban or industrial development and unsympathetic afforestation. Inappropriate woodland management, particularly through: changes in traditional management (eg neglect of coppice and reductions in aphid-bearing tree species); overgrowth of woodland rides and clearings leading to excessive shading of nests; intensive afforestation with conifers and destructive felling operations. Repeated disturbance by livestock or human activities.
Formica rufibarbis	Red Barbed Ant	Loss of suitable heathland habitat through urban or industrial development, agricultural improvement and afforestation. Inappropriate heathland management. Excessive or untimely disturbance of nests through, for example, trampling, off-road vehicles, digging, and inappropriate mechanised scrub or heather clearance. Frequent, untimely or intensive heathland fires (although appropriate light burning may be beneficial).
Formicoxenus nitidulus	Shining Guest Ant	Loss of suitable scrub and woodland habitat through agricultural clearance, urban or industrial development and unsympathetic afforestation. Inappropriate woodland management.

9.3.3 Carbon reservoir.

Soils form the main terrestrial store of carbon (Schimel, 1995). In GB, the estimated total carbon held in terrestrial systems is 9952 M tonnes, with 99% (9839 M tonnes) held in soils (Milne and Brown, 1997). The majority of this soil store of carbon is held in uncultivated soils, particularly the soils of semi-natural habitats, but especially in peats and peaty-surfaced soils of the uplands. Thus, it has been estimated that some 46% of the carbon content of GB soils is held in the peat soils of Scotland (Milne and Brown, *op cit*). Any disturbance to the soil-vegetation system, which produces a change the balance between litter input and decomposition, carbon dioxide and methane emissions, will impact on the soil carbon store.

9.3.4 Filter/buffer

Semi-natural habitats, particularly upland habitats, are an important source of potable water, supplying the demands of many of the larger conurbations via reservoir systems. Soils can act as highly effective filters or buffers of pollutant inputs, protecting the drainage waters from these potential contaminants. Some pollutants are retained in the soil system by physico-chemical processes, some degraded biologically and others modified through chemical reactions. Low levels of management are generally characteristic of semi-natural habitats with little of no physical disturbance to the soil, no fertilizer inputs and relatively low grazing densities. The soils are, as a result, relatively ‘uncontaminated’. However, changes in management regime or continued, low-level pollutant input can affect the efficiency of the filtering and buffering. Some of the retained pollutants can also be released into drainage waters if land management or climate changes.

9.3.5 Water supply/flow

As noted above, semi-natural habitats can be a source of high quality water, particularly those in the uplands. Soils also provide a water reservoir, which can buffer the surface drainage system against temporal variations in precipitation. Thus, the retention of precipitation mediates floods and the gradual release of retained water helps to maintain flow during dry periods. Perhaps the most important soils in this respect are the peats and peaty-surfaced soils of the uplands. Changes in management, pollution and climate change can all impact on the water storage and release by soils.

9.4 Threats to the soils of the natural heritage

9.4.1 Land use/management

As noted above, there is a close coupling between the above and below ground systems in semi-natural habitats. Changes in the land management regime can affect the soils directly or indirectly,, with impacts on habitat maintenance, the carbon reservoir, the characteristic biodiversity and the filtering and buffering capacity.

Direct management impacts on soils result from ploughing, the addition of fertilizers, and drainage. These will directly affect soil chemical and physical conditions, which will, in turn, impact on the biology; they will effectively lead to habitat loss. The addition of fertilizers will also impact on the buffering and filtering capacity. In general, the impact is likely to be negative, but additions of lime will increase the capacity to buffer acidity. Changes in pH will also impact on the retention of sulphate and metals on biological processes involved in degradation of organic pollutants; again, in some cases the retention or degradation capacity could be increased.

Drainage, cultivation and addition of fertilizers can affect decomposition rates and the balance between organic matter inputs and decomposition, with impacts on the carbon storage in the soils. In general, the impact will be to reduce the carbon store, but a recent study found no significant change in carbon content of improved versus natural pasture, and a parallel investigation has stressed the importance of local factors in determining impacts.

Drainage also has marked impacts on the retention and release of water by soils. Increased decomposition and loss of organic matter will reduce the storage capacity of the soil, while the drainage system results in more rapid transmission of incoming precipitation to streams. Changes in surface vegetation, as a result of management, can also influence water infiltration, leading to an increase in surface runoff and a reduction in infiltration and storage.

Extraction of raw materials, e.g. sand, gravel, clay and peat, will clearly impact on habitats, essentially leading to destruction of the pre-existing soil profile and associated habitat. Changes in water regimes can also have impact on water supply and the filtering and buffer capacity of the system, and hence on water quality. Peat extraction leads to a direct reduction in the carbon store as well as habitat destruction.

Changes in grazing pressure have more subtle and slower impacts, but will result in changes in soil biota and humus form and accumulation rates. These changes will eventually impact on the rates of nutrient cycling with, in general, increases in grazing intensity leading to an increase in rates of nutrient turnover.

9.4.2 Pollution

The main regional pollution problems are the deposition of increased amounts of acidity and nitrogen derived from the burning of fossil fuels and from agriculture. These can impact on all of the key functions of the soils associated with semi-natural habitats.

Many natural and semi-natural habitats are adapted to conditions with low availability of nitrogen. Increased nitrogen inputs have been shown to result in changes in the vegetation of a number of habitats, with the reduction or loss of stress-tolerator species and an increase in competitors; many valued species are stress tolerators (Bobbink *et al.,* 1998). The plants are responding to changes in the availability of nitrogen, particularly inorganic forms. The increased availability of nitrogen leads to an increased, matching demand for other nutrients, particularly phosphorus in semi-natural habitats. The changes in phosphorus demand can lead to changes in system function, with plants accessing increased amounts of P from organic sources, indicated by changes in P-enzyme activity. Increased uptake of nitrogen leads to increased foliar nitrogen contents, changes in the carbon to nitrogen ratio of plant litter and, eventually, changes in nutrient cycling and soil biota.

Changes in plant species take place long before changes can be detected in bulk soil properties, and the most useful indicators are likely to relate to the processes controlling nitrogen and phosphorus availability, and the nutrient status of the vegetation and litter. However, it is important to note that the sensitivity of habitats to nitrogen deposition varies considerably. Critical loads of nitrogen, below which damage is not expected, have been set for a number of habitats; in general, the most sensitive are upland habitats dominated by slow growing stress tolerators (Hornung *et al.,* 1997).

Acidic deposition can lead to increased rates of soils acidification, with impacts on nutrient availability and eventually on biota. Thus, experimental and time series studies have shown changes in population of *Mycorrhizae, Enchytraeids* and earthworms, in decomposition rates and nutrient cycling. Soils, however vary widely in their sensitivity to acidic deposition. The critical load approach has been develop to quantify the capacity of different soils to buffer acidic impacts and set limits below which damage to the habitat is not expected (Hornung *et al*., 1995). The capacity of soils to buffer acidity and to retain deposited nitrogen within the soil-plant system has important implications for drainage water quality and aquatic biota.

Gaseous pollutants, such as SO_2 and ozone can be directly phytotoxic and produce changes in vegetation. Ambient concentrations of SO_2 over GB are now too low to have phytotoxic effects, but the erosion of peat soils in the southern Pennines has been linked to the loss of *Sphagnum* from them as a result of the high SO_2 concentrations in the late nineteenth and early twentieth centuries. Ozone concentrations are thought to be high enough over parts of GB to impact on the growth of sensitive plant species, but further research is needed to characterise and quantify the impacts on different habitats.

As noted above, changes in vegetation, in this context as result of pollution, can influence water infiltration and storage of soils. But the effects are unlikely to be significant, unless they involve the loss of a water-absorbent moss layer or a reduction in ground cover.

Heavy metals and organic pollutants are rarely present in large enough concentrations to impact directly on ecosystem composition and function. The exceptions are close to point sources of emissions or following accidents, again localised. Nationally and regionally, heavy metal deposition from the atmosphere in the UK has declined as more efficient manufacturing methods have been introduced, heavy industry has declined and pollution controls have been implemented. However, organic soils accumulate a variety of deposited metals and these can be released to drainage waters following changes in land management which increase decomposition rates or redox conditions (Stidson and Vincent, 2001).

9.4.3 Climate change

Climate change could impact on key functions of soils associated with natural heritage. The most obvious impacts will be on soil carbon stores and drainage water quality. If changes in the balance between biomass and litter production, on the one hand, and decomposition result in a net increase in the latter, there will be a reduction in soil carbon; this could be of major consequence if it impacts on the peats and peaty soils of the uplands. However, it is difficult to predict the impacts of changes in climate due the lack of precision in the climate predictions and uncertainties in the interactions between processes in the plant-soil system. Thus, the rates of the biological processes involved in decomposition will increase with temperature, within the range of temperatures experienced in the UK, providing there is sufficient moisture available. However, increases in temperature can also lead to increased biomass production, providing the supply of nutrients is adequate. A three-year soil-warming study in the Pennines did show a net increase in decomposition rates with measurable losses in soil carbon in one of the soils studied, but this may have been a short-term impact until the system adjusted to the new temperature regime.

The Pennine experiment also showed in increase in DOC in drainage waters following the heating. Increases in DOC over the past 20 or so years have been reported from sites across north west Europe and are leading to increases in the treatment costs of some UK water companies. It is thought that the increases are a result of more frequent dry periods with elevated temperatures, resulting in net increase in decomposition and DOC production.

Changes in temperature and precipitation regimes could also lead to changes in plant assemblages, which will impact on the associated soils. The changes in such assemblages may be the result of direct influences of the changes in temperature regimes on plant interactions, or due to soil mediated effects, e.g. increased decomposition leading to increased nutrient availability, or changes in soil moisture status.

Changes in precipitation and evapotranspiration will lead to changes in the water storage and release from soils to surface drainage waters. An increase in the frequency of drought periods can also lead to changes in physical properties of highly organic soils and increased cracking and a reduction in water holding capacity.

9.4.4. Broad Habitat specific threats

Specific threats to priority habitats have been identified in Broad Habitat Actions plans and these can be used to identify potential impacts on soil function and subsequent requirements for indicators. Examples of current threats for five priority habitats are presented in Table 9.4.

9.5. Indicators

It can be seen from the above that, because of the close coupling between the above and below ground systems, indicators are needed which provide an assessment of the status/health of the whole system, both above and below ground, and of ecosystem function. Indicators are also needed which provide a measure of the relevant pressures on the habitats; these latter will need to be spatially disaggregated to the level of the individual habitat. Finally, indicators are needed of ‘external’ impacts consequent upon changes in the soil-plant system. In the context of the DPSIR approach used in the study, we are suggesting the requirement for indicators of pressures, state and impacts. Below, we suggest possible categories of indicators with examples of specific indicators for each category; the approach is developed further in Table 12.1. These indicators have been taken from the literature and have shown potential in soil health assessments. In most cases, the indicators have been used on site-specific studies and/or for specific management issues. The application of indicators to specific pressures is discussed in more detail below.

9.5.1 Pressure related indicators

Following from section 9.4, the indicators need to provide information on management related factors, pollution and climatic drivers.

- Management related indicators – grazing intensity, by the different categories of animals (including wild populations); areas of habitat conversion, by for example pasture improvement or afforestation; areas of semi-natural habitats affecting by liming; areas of peat extraction; some measure of drainage schemes as they affect semi-natural habitats.
- Pollution related indicators - deposition rates of acidity, nitrogen, metals and POPs.
- Climate change related indicators – meteorological data, atmospheric CO_2 concentrations

Table 9.4 Currently recognised major threats to five priority habitats in Great Britain (adapted from JNCC, 2000)

Broad Habitat	CURRENT THREATS
ACID GRASSLAND	• Agricultural intensification, particularly fertilisation, ploughing and drainage (lowland). • Lack of grazing leading to an invasion by coarse grasses and scrub (lowland). • Inappropriate grazing regimes by sheep, cattle, ponies and deer, typically excessive grazing levels at the wrong time of the year, which causes the habitat to become degraded (upland). • Forestry planting (upland). • Abandonment and neglect leading to encroachment by bracken *Pteridium aquilinum* (upland). • Liming, ploughing and reseeding around the lower fringes of upland areas (upland).
BLANKET BOG	• Climate change • Pollution, from sulphate and nitrate deposition, may also be significant in certain areas, such as the Southern Pennines. • Drainage - new drains continue to be dug and old drains cleaned in some areas. Even without maintenance most drains continue to lower the adjacent water table and some initiate erosion. • Heavy grazing (by sheep, red deer, cattle and horses) - especially if accompanied by supplementary feeding, burning, fencing and drainage. • Burning - agricultural and sporting management both involve the use of fire to modify moorland vegetation for the benefit of livestock, grouse and deer in particular. Poorly managed and/or accidental fires can be particularly damaging • Forestry - some existing plantations are having an impact on the hydrology and species composition of adjacent areas of blanket bog, notably as the trees mature. Aerial application of fertilisers and pesticides can also result in drift on to adjacent bog. • Peat extraction - commercial extraction, though relatively limited in extent (some 2000 ha in Scotland), can have important local effects. Domestic cutting, most of which occurs on common land, is locally extensive. • Agricultural improvement - drainage, fertiliser application and conversion to pasture has occurred frequently in the past and can be of local significance. • Recreation - walking routes, some used by cyclists and horse-riders. Bog areas are very sensitive to such pressure. The increased use of all-terrain vehicles for recreational, agricultural and sporting activities can also result in local erosion. • Planning developments - wind farms and communication masts + associated infrastructure increasingly being proposed especially at high altitude. There are also threats from hydro-electric schemes in Scotland. • Erosion - high altitude bogs in particular, especially those in the Pennines and south Wales, are losing habitat through constant erosion of the peat mass. Some of this may be due to natural processes. • Water course liming - lochs, lakes and rivers as a treatment for acidification, there may be detrimental implications for adjacent areas of blanket bog. Sometimes the bogs themselves have had lime applied.

CALCAREOUS GRASSLANDS	• Under-grazing or the complete cessation of management occurs at many lowland sites. It results in reversion to rank grassland and eventually to closed scrub and woodland. In a recent study of lowland calcareous grasslands important for butterflies 60% were found to be ungrazed. • Overgrazing in the uplands is adversely affecting species-richness with a particular loss of tall herb and shrub species. • Agricultural intensification in the form of fertiliser use, herbicide application, ploughing and re-seeding may still be damaging or destroying some grasslands. • Industrial and urban development, particularly the in-filling of abandoned chalk and limestone quarries and other industrial sites where calcareous grasslands have established naturally after cessation of working.
NATIVE PINE WOODLANDS	• Poor natural regeneration and reduced diversity due to browsing by deer and sheep. • Fragmentation and isolation of individual woods with consequent loss of wildlife interest and genetic variation. • Limited diversity of structure in many woods related to historical exploitation and Overgrazing.
UPLAND HEATHLAND	• High stocking levels of sheep, and to a lesser extent cattle, lead to heavy grazing of heather and other dwarf shrubs. High numbers of red deer Cervus elaphus are a problem in parts of the Scottish Highlands. Inappropriate methods of supplementary feeding and the absence or minimal use of shepherding also contribute to the problem of overgrazing. • Heavy grazing by sheep, cattle or deer can prevent regeneration by native woodland and scrub, notably along upland heathland margins and streamsides where such habitat additions would be likely to enhance biodiversity value. • Difficulties in negotiating agreements with commoners are hampering take-up of agri-environment schemes • Conversion to grassland occurs through ploughing, reseeding, liming and fertilisation for agricultural purposes, particularly at lower elevations. Drainage and moorland 'gripping' also reduce the interest of wet heath. These factors have become less significant over the past ten years. • Afforestation (mainly by non-native conifers) leads to direct loss of dwarf-shrub habitat, although temporary and permanent areas of heathland are now being created within some existing forests by restructuring after the first rotation. • Poorly managed muirburn (ie large-scale and too frequent in operation) reduces the habitat quality of upland heath by causing a simplification of structure, loss of lower plant assemblages and erosion of peat. • Encroachment by bracken can lead to a loss of biodiversity; this is a significant problem in some upland areas. • Quarries, windfarms, communication masts, access tracks and certain other planning developments. • Acidification, trophospheric ozone and nitrogen enrichment caused by atmospheric deposition can lead to vegetation changes including a reduction in the lichen and bryophyte interest. Nitrogen deposition can increase the likelihood of insect defoliation of upland heathland. • Climate change could potentially lead to changes. • Localised damage and threats from other forms of land use in the uplands, such as military use and recreation, • The interaction of two or more factors : often greatly increases the overall impact on upland heathland vegetation. For example, poorly managed burning followed by heavy grazing will result in the loss of dwarf shrubs more rapidly than would either factor in isolation. It is possible that grazing pressures interact with pollution to influence vegetation change.

9.5.2 Status-related Indicators

Overall habitat status - habitat areas, species level vegetation data, information on the occurrence of characteristic species of birds, animals and insets of the habitat.

Soil-plant system status

Plant nutrient status – foliar N and P, litter C and N.

Soil chemical indicators related to nutrient status and buffering capacity for acidity– pH, base saturation.

Soil chemical indicators related to potential for pollutant release to drainage or the atmosphere – total contents of selected metals and POPs.

Indicators related to biologically mediated processes important in decomposition, nutrient cycling and production of DOC – nitrification potential, P enzyme assay, microbial biomass, BIOLOG or equivalent.

Indicators related to populations important in habitat maintenance and nutrient cycling – mycorrhizal populations, keystone groups in the food web, e.g enchytraeids, earthworms, BIOLOG or some equivalent, bacterial:fungal ratios.

9.5.3 Impact related indicators

The major impacts will be related to trace gas emissions and water quality. The measurement of trace emissions from a wide range of specific habitats is probably impractical.

Water quality – pH, metal contents, nitrate, organic pollutants, pathogens.

9.5.4 Recommended limit values

Following the identification of a range of indicators, it is necessary to define expected or target values, or ranges of values. This may be currently be possible for the pressure and impact related indicators, but for the state indicators the ideal, in the context of the natural heritage, would be to define ranges for each habitat to be monitored. This is not currently possible for many of the indicators suggested above or in Table 9.1 and this should be a priority for research.

9.6 Research needs

Further work is required to develop methodologies and protocols for a number of the state related indicators, particularly those related to biology or biologically mediated processes, which can be applied across a wide range of soil types and habitats.

National baseline data sets are also needed for a number of state related indicators, again particularly those related to soil biology, from which ‘normal’ or expected ranges of values can be derived. In addition to national-scale requirements, baseline data are required for benchmark soils. Further research is required at priority habitat level to define key relationships between plant:soil systems and therefore key soil functions that are essential for habitat and biodiversity maintenance. The keystone species in the food webs of particular semi-natural habitats need to be defined.

10. INDICATORS OF SOIL QUALITY FOR URBAN AREAS

10.1 Introduction

Although the Project team was asked to concentrate on indicators for soils in the non-urban landscape, urban soils provide a unique case with respect to the development of soil quality indicators. They are thus considered here, although to a lesser extent than in agricultural, forest and semi-natural environments. The urban environment is one in which man's impact is extreme and any indicators that may be developed with respect to natural, semi-natural or agricultural soils are likely to be inapplicable to urban soils, or to be of little use in that they will indicate a 'degraded' state. For urban soils therefore, the DPSIR model is considered to be particularly relevant and will be used to develop an environmental indicators concept from first principles.

10.1.1 Drivers

These highlight the question of functions of Urban soils: What are they used for?

- Demand for buildings, roads and 'hard standing' areas. – *A combined foundation-support and environmental health function*.
- Demand for green space areas (Urban 'green lungs'). – *An ecosystems support function.*
- Demand for household gardens and / or allotments – impact on the food chain (human and animal). *A filtering/buffering function.*

10.1.2 Pressures

- Development of 'Brown field' sites – a stated government aim. – surface sealing and enhanced rainfall runoff.
- Increasing vehicle traffic and Business Park development - Increased atmospheric particulates & solutes.
- Demand for access to open spaces - Increased trafficking by humans and machines.
- Deposition of local urban wastes – often unauthorised.

10.1.3 State

The state of urban soils is best considered within a framework that addresses both of the functions and pressures described in the sections above. Such a framework has been developed by SSLRC for English Nature (Hollis, 1992) and includes criteria that relate to:

- The extent of surface sealing.
- Loss of topsoil layers.
- Burial of topsoil material
- Soil aeration,
- Soil density
- Soil permeability
- Soil organic matter status and function

- Soil pH and base-status
- Soil contamination.

None of these criteria are direct measures of soil biodiversity. However, in view of the disproportionate human influence within the urban environment and the general lack of information about soil biodiversity, it is not considered feasible to consider specific biodiversity criteria as environmental indicators for urban soils. Instead, one or more of the above properties can be used to indicate the potential of urban soils to support specific types of ecosystem, some of which may be biologically diverse.

10.1.4 Impacts

- Surface sealing and loss of atmospheric interaction – partial or complete sterilisation.
- Removal of upper soil layers – loss of primary biological function and diversity.
- Introduction of ‘raw’ soil material – loss of biological diversity and burial of existing soil.
- Burial of topsoil layers – decomposition of any original vegetation and drastic modification of the original topsoil environment – reduced aeration, changes in microbial populations and resultant organic / N cycling, release of nitrous oxides and carbon dioxides.
- Compaction and disruption of upper soil layers – reduced aeration and infiltration, increased density and penetration resistance.
- Increasing levels of organic and inorganic contaminants
- Increased volumes and rates and of surface water deposition with associated solutes & particulates.

10.2 The need for environmental indicators of urban soil quality

In considering possible responses to the pressures and impacts on urban soils, an immediate problem arises in that the drivers include two conflicting demands: space for buildings and hard surfaces and space for green areas. In addition, the potential soil quality indicators for these two drivers are very different and often conflicting, in that one elaborates the foundation-support function whereas the other elaborates the ecosystem support and maintenance function. The third driver for urban soil quality indicators is the demand for household gardens and allotments and, for this purpose, a set of indictors that elaborate the potential for non-contaminated biomass production is required.

In practice, the three identified drivers for soil indictors in the urban environment are not usually applied with equal weight. In most cases, the demand for building space and associated hard standing supersedes the demand for green spaces or allotments. This trend has recently been reinforced by the Government’s stated objectives to focus house building on ‘Brown-field’ sites. A secondary factor is that householder’s demands for property with significant garden space seems to be decreasing and, in any case, is usually subordinate to property developers’ desire for high density housing. *Realistically therefore, any indicators of soil quality in the urban environment should be based principally on the foundation support and environmental health function of soil.*

Nevertheless, the fact that the market usually rules with respect to urban development should not prevent local authority planners from having an urban soil quality indicator based on the extent of land available for the development and / or maintenance of green spaces. *A second* *set of urban soil indicators could therefore be related to the extent of non-sealed surfaces (excluding household gardens?) and their potential for supporting ecosystem functions, recreational activities and non-contaminated biomass production.*

10.3 Principles for the development of urban soil environmental indicators

10.3.1 Soil-loss indicators

An initial indicator based on the fraction of unsealed surface present (excluding household gardens?) in administrative districts and the average annual rate of loss over the last 10 years.

This could work as follows:

$$\text{Indicator:} \quad 100 \times \frac{\text{10 year average annual area of unsealed soil lost}}{\text{(Total area unsealed – desired minimum area unsealed)}}$$

>20	Urgent action required, total soil loss within 5years.
10 – 20	Action required, total soil loss in 5 to 10 years.
5 – 10	Review action, total soil loss in 10 to 20 years.
<5	No action required, review in 5 years time.

The exact cut-offs and action requirements would need to be agreed by the local stakeholders.

10.3.2 Building development indicators

Two sets of properties are important for developing indicators for this soil function. The first relate to foundation stability and the second to environmental health and the presence of contaminated land. It is proposed that these be combined within a two-dimensional matrix to indicate the level of action required to develop a site.

10.3.3 Environmental Health and contaminated land.

This is a particularly difficult issue as the definition of trigger levels for contamination of land and related legislation is under continuing development and review. It is therefore not proposed to define any specific levels for contamination as part of this exercise. Instead, the development of indicators will be based on a stepped approach to the need for action. This would work as follows:

<u>First level.</u>
Comprehensive site de-contamination required. This level of indicator would be based on prior knowledge of the site being associated with specific levels of contamination. It would require either removal of contaminated materials or prolonged in-situ de-contamination before development could proceed.

<u>Second level.</u>
Comprehensive Site investigation required. This level of indicator would be based on the proximity of the site to potentially contaminating activities. It would require a systematic site survey for a specified range of contaminants and further action would be based on the results of this survey.

<u>Third level.</u>
Screening site investigation desirable. This level of indicator would be based on the presence of potentially polluting activities within a specified radius of the site. It would require a

targeted reconnaissance survey to ascertain whether specific pollutants were present. Further action would depend on the results of the survey.

Fourth level
No contamination likely. This final level would be based on the lack of any potentially polluting activities within a specified radius of the site. No further action would be required.

The exact radius within which potentially polluting activities trigger specific actions would need to be agreed by the local stakeholders

10.3.4 Foundation stability.

The factors that affect the stability of building foundations such as shrinkage potential, the presence of soft unconsolidated material, *etc*, are well documented and covered within building regulations. It is not proposed to discuss them as part of this report. Instead, it is proposed that a second tier of indicators of action be used in a similar format to those for environmental health and contaminated land. These would be as follows:

First level
Specific foundation requirements likely. This level of indicator would be based on prior knowledge of the presence of site conditions that would require special remedial measures, such as deeper than normal foundations, the provision of conduits to take away excessive surface waters or the provision of localised flood defences. Actions at this level could be to defer development in favour of other sites, or to ensure a high level of on-site inspection.

Second level
Specific foundation requirements possible. This level of indicator would be based on prior knowledge of the presence of conditions requiring special remedial measures within a specified radius of the site. Actions at this level would be to carry out a site inspection and base recommendation for development on the results.

Third level
No specific foundation requirements. This level of indicator would be based on prior knowledge that no conditions requiring special remedial measures are present within a specified radius of the site.

The exact radius within which conditions requiring special remedial measures would trigger specific actions would need to be agreed by the local stakeholders. Information on such conditions is readily available through various institutions and data holders.

10.3.5 The combined indicators.

Overall indicators for building development are simply based on combining the two sets of indicator levels and associated actions. For example:

Comprehensive site de-contamination required; Specific foundation requirements possible.

No contamination likely; Specific foundation requirements likely

No contamination likely; No specific foundation requirements.

10.3.6 Green space indicators

Ecosystem support (green lungs)
Each category defined according to a score based on integration of the following criteria:

- ‘State of biological development’ (raw to mature).

- The ability to support a wide range of ecosystems as opposed to specific types of ecosystem.
- The ability to accept an average amount of urban pollution from atmospheric deposition.
- The ability to accept and re-distribute urban runoff water.

11. STAKEHOLDER VIEWS

11.1 The Stakeholder Questions

Several stakeholders were approached during the scoping phase of this Project and asked a standard set of questions about Soil Quality Indicators (SQI), although they were free to express their views in whatever format they chose. The questions were:

1. Which soil functions need to be considered in terms of soil use and sustainable use of soil?;
2. What pressures are there on soils which might affect these functions ?;
3. Can these pressures be ranked in order of national and/or local importance ? If so, on what basis ?
4. Which indicators would, in your view, be best for showing whether these functions are operating at an appropriate level in a range of soils and environmental conditions ?;
5. How might we decide what is an 'appropriate level of function' ?;
6. Which measurements are required to provide these indicators ?;
7. Whether measurements of a particular property might act as a surrogate for another property which might, of itself, be extremely difficult to measure; if so, which ?
8. What characteristics those measurements should have in terms of robustness, spatial cover, density of observations etc. ?;
9. Does your organisation have any views on benchmark or critical values for any of the measurements or indicators suggested ?
10. How might these measurements be incorporated into a soil monitoring programme; especially with regard to the appropriate time-steps for different measurements ?;
11. Whether, in your view, there are indicators of soil quality which can be applied uniformly across the UK (so-called 'global' indicators), or whether you see the need to have separate indicators for different soil uses or landscapes ?

Their replies are given below. Many have been changed deliberately in order to meet a convention of anonymity and the text changed where necessary to reflect that, although care has been taken not to change any meanings.

11.2 The New Zealand Approach

Drs Louis Schipper and Graham Sparling, Landcare, New Zealand.

Dr Goulding (IACR_Rothamsted) met Drs Schipper and Sparling on a British Council-funded Link visit to New Zealand during February 2001. The standard questions were not used. The following is a description of the approach to indicators of soil quality developed over the last 6 years in New Zealand in the ‘500 soils’ project. The work was published in the *Soil Science Society of America Journal*, 2000**,** 64, 300-311, and can be viewed on the website at:

http://www.landcare.cri.nz/sindi

In 1994/5 Drs Schipper and Sparling established 5 trial sites in 3 Regions of NZ to test the Doran and Parkin (1994) approach to Soil Quality Indicators (SQI). They used a paired comparison of soil types with yearly sampling and tested which SQIs distinguished soil types. Stakeholders (the Regional Councils) were allowed to choose sampling sites. These initial tests reduced the 17 indicators in Doran and Parkin’s system to 7 on the basis of their (in)ability to distinguish between soil types and the ability of a group of soil scientists to interpret the data; e.g. soil microbial biomass and specific respiration were both omitted because of problems over interpretation.

This was followed by a period of testing the ability of the remaining indicators to separate land uses. From dominant New Zealand soils and land uses, 25 cores were taken from a 50m transect at each site and bulked; there were no replicates within sites. Sites were grouped according to soil orders (New Zealand Soil Classification System) and function. This established a set of ‘dynamic’ SQIs which respond to management. A matrix of soil order against land use was created. Soils are separated into ‘At risk’, ‘Stable’ and ‘Baseline’ (undisturbed sites) categories. There are some gaps in the matrix: no land use has all the soil types.

‘Target Zones’, i.e. ranges of measured values of properties, were established by a team of experts for each SQI on all soils and all land uses, on the basis of environmental and productivity criteria, e.g. for Olsen P, the environmentally-set maximum might be 50 on the basis of the Change Point. This is the limiting value at which a property is deemed 'acceptable' or not for a given purpose, and a productivity-derived minimum of 25 on the basis of crop response. These limits were tested with stakeholders to see if they were practicable.

Interpretation is regarded as the key to the success of the system, particularly in setting the Target Zones within which indicators should lie. An expert group was used to produce response curves identifying ideal levels, maxima and minima according to soil order and land use. Sites within the target zone are regarded as having acceptable SQ. Sites that fall outside of it may not be at risk if they can be restored within an agreed length of time; at the moment this is 25 years, an approximate farming generation. Some problems can be fixed quickly, e.g. pH and nutrients; physical problems may take months or years; soil organic matter decades.

SQIs have been analysed by Principle Coordinate Analysis, which shows 4 main axes: ‘organic resources’, e.g. total C; ‘fertility’, Olsen P only; ‘acidity’, pH, base cations; ‘physical conditions’, bulk density, macroporosity. The system identifies which Principle Co-ordinates (PCs) are outside limits, which components of each PC is causing the problem, then how the problem could be remedied. The aim is to bring about behavioural change before enforcement by legislation.

Sampling frequency is 3-5 years for rapidly-changing soils such as those being turned into market gardening, moving from beef to dairy, receiving effluent or being irrigated; 10-15 years if stable (unless they are affected by some destructive process such as a hurricane destroying a forest).

The importance of any measured change is weighted according to area in that land use; later, when more analyses have been made, it will be on the basis of the number of sites exceeding the target value.

Stakeholders, the End Users, like the scheme. As results came in and the system was proved to work, more Regional Councils joined the scheme. Now most North Island councils are in the scheme. At present (20/02/01) there are 440 sites in the project.

The scheme can be interrogated to ask what a soil type can be used for.

The 6 years that the work took could be achieved in other countries in 1 year because the initial assessments of indictors, variation and framework has been established.

11.3 Forestry Commission

Views were sought from appropriate personnel in the Forestry Commission and Forest Enterprise in England, Wales and Scotland. Five responses were received as a result of email, telephone and personal visits.

Stakeholder 1 Policy and Practice Division, Forestry Commission HQ, Edinburgh

Which soil functions need to be considered in terms of soil use and sustainable use of soil?
Supply of nutrients, water, and oxygen; medium for mechanical support; nutrient capital.

What pressures are there on soils which might affect these functions?
Growth of forest crop; removal of forest products; compaction by harvesting machinery; cultivation; pollution with insecticides, herbicides, machinery oils; N and S deposition.

Can these pressures be ranked in order of national and/or local importance ? If so, on what basis?
Pressures could be ranked at both national and local level on the basis of likelihood and severity of effect. I have attempted a ranking in increasing order of importance.
In most cases N and to a lesser extent S are sub-optimal so inputs are actually a benefit but in some soils of low buffering capacity this could lead to acidification. The quantities of chemicals used in forestry are small in absolute and relative terms with respect to agriculture, and, if current guidelines are followed, pollution should be avoided therefore this is the lowest pressure.
Growth of the crop itself has many possible effects on the soil (e.g. reduction in moisture content and increased oxidation; increased scavenging of N and S leading to a reduction in pH, increased penetration of root channels leading to greater moisture infiltration). Experience suggests that these are generally of low importance though the risk of unsustainable changes is greater the lower the inherent nutrient status of the soil. Compaction is unlikely on soils with a high organic matter content in the upper 40+cm. Moreover these soils should be protected by using brash to support machinery so compaction is probably of low-medium importance. Compaction on soils with a greater mineral content is a possibility of uncertain extent and severity. Repeated removal of residues is likely to be the greatest pressure.

Which indicators would, in your view, be best for showing whether these functions are operating at an appropriate level in a range of soils and environmental conditions?
Pore size distribution, nutrient availability, organic matter content, and soil depth seem to me to be the attributes most closely related to function but I anticipate that there would be great difficulty actually using them because of spatial and temporal variability and resilience of the system.

How might we decide what is an 'appropriate level of function'?
For a given time of year and stage in the management cycle, the means should not vary significantly ($p=0.05$) or by a given amount, say >20%, from one rotation to the next. When evaluating the effect of afforestation the comparison should be between samples taken in the crop after canopy closure and ones taken in adjacent ground that is similar but unforested. This comparison begs the question: is the pre-afforestation condition a valid baseline ?

Which measurements are required to provide these indicators?
The meaning of this is unclear; answers to Q3 might apply here.

Whether measurements of a particular property might act as a surrogate for another property which might, of itself, be extremely difficult to measure; if so, which?
Growth could be used as a surrogate but it is unlikely that both genotype and management practices will be the same from one rotation to another. Nutrient capture by resin bags seems a useful surrogate for nutrient availability since the values represent a longer time span than point samples, the determinations would be faster and easier than incubations, and the values might represent what is available for plant uptake. Resin bags would be preferred to cotton strips as a surrogate for microbial decomposition and hence nutrient availability.

What characteristics those measurements should have in terms of robustness, spatial cover, density of observations etc.?
The sampling and analytical procedures must be repeatable to <5% variation. As a very rough estimate it is hoped that the indicators could be used at a density of 1-5 observations per ha. The issue of temporal frequency is more difficult since it is well known that there are inherent cycles in many variables due to seasonal effects, crop age, and management practices.

Does your organisation have any views on benchmark or critical values for any of the measurements or indicators suggested?
We have broad requirements for soil fertility and moisture regime for the main species but we have not established critical values for any of the measurements suggested.

How might these measurements be incorporated into a soil monitoring programme; especially with regard to the appropriate time-steps for different measurements?
See A7

Whether, in your view, there are indicators of soil quality which can be applied uniformly across the UK (so-called 'global' indicators), or whether you see the need to have separate indicators for different soil uses or landscapes?
We would expect that there will be general indicators that could be applied across all land uses, albeit with different critical values for different land-uses, plus a smaller number of indicators for specific land uses.

Stakeholder 2 Forest Commission Environment Group / Sustainability Unit Management for Wales.

What pressures are there on soils which might affect these functions?
1. Lack of information within the forestry sector, for example on soil types.
2. Economics
   - Cost benefit analyses never come out in favour of the environment because the environment does not have a cost associated with it. There is a need for developments in environmental economics;
   - The long term nature of the industry requires a longer term view which is often lacking;
   - A tendency to compartmentalise different aspects of the environment – a more holistic approach is required.
3. Wood fired power stations;
4. Public perceptions driving policy and practice. e.g. Targets of 50% continuous cover forestry in Wales in the next 20 years when the national average is 20% driven by a public perception that CCF is a ‘good’ thing, E.g. Public perception that Broadleaves equate to

low impact management and Conifers, high impact. What should upland 'high impact forestry' be replaced by ?

Can these pressures be ranked in order of national and/or local importance? If so on what basis?
Legislation inevitably drives rankings. If a forest manager is faced with more than one environmental issue, the one that involves a potential violation of legislation or affects a licence will always be addressed first. Therefore to rank indicators we need to look at current soil legislation. We should consider what social/human rights legislation may come in the future.

Which indicators would, in your view, be best for showing whether these functions are operating at an appropriate level in a range of soils and environmental conditions?
The stakeholder did not feel that it was necessarily their place to propose these, but did suggest indicator species and water quality as possible surrogate indicators. (see later note on surrogate indicators).

How might we decide what is an appropriate level of function?
For non plantation forestry, if indicator recordings are not to be compared to those at the start of monitoring, then ancient semi-natural woodland status should provide a base line. We already have a lot of information on ancient semi-natural woodland, both conifer and broadleaves, through English Nature. For plantation forestry this may not apply.

Whether measurements of a particular property might act as a surrogate for another property which might, of itself, be extremely difficult to measure; if so, which?
Careful thought needs to be put into the use of surrogate indicators – these should not be used if the genuine justification is that they are cheaper and easier. If a more direct indicator would be better it should be used.

What characteristics those measurements should have in terms of robustness, spatial cover, density of observations?
The following properties of indicators where considered to be important

- Rigorous but simple;
- Allow us to paint an unbiased picture;
- Non political;
- Applicable to a sensible time frame of monitoring, i.e. demonstrate something within 3-5 years;
- Should be applicable to private industry also – currently they receive a woodland grant and are then left to their own devices;
- Relevance not just to what forestry is now but what it might be in the future, therefore relevant to the objectives of strategies with e.g. 50 year vision;
- Feedback loops need to be in place so that monitoring informs policy;
- There should be transfer of knowledge so that owners/managers undertaking the recording understand the purpose of the indicator;
- The number of sites should be dependent on the diversity of the landscape.

Does your organisation have any views on benchmark or critical values for any of the measurements or indicators suggested?
Guidance publications include:

- The UK forestry standard;

- Various guidelines and bulletins;
- UKWAS;
- EA bench marks that apply to FC, e.g. to water quality;
- CCW benchmarks;

However, the first three are rarely detailed enough to supply benchmarks or critical values.

How might these measurements be incorporated into a soil monitoring programme; especially with regard to the appropriate time-steps for different measurements?
They could be incorporated into site checks currently done under compliance monitoring. They could be incorporated into biodiversity plots, more of which are required in Wales.

Whether in your view there are indicators of soil quality which can be applied uniformly across the UK (so-called 'global; indicators), or whether you see the need to have separate indicators for different soil uses or landscapes?
A two fold approach with a strategic national set and localised sets separated on the basis of a) land-use b) soil types c) altitudes/climates was suggested.

Stakeholder 3 Forest Commission Biodiversity Group, England

It is agreed that we need a set of common standards to assess soil quality …'

'Maintenance of soil quality is a sustainability objective which FC will need to be aware of in our UK Forest Standard appraisals (and therefore WGS decisions). From this it seems that Woodland Officers will need to be able to make assessments of soils at some level so we need as simple a system as possible'

Stakeholder 4 Forest Management and Environment Group, Forest Enterprise, South Scotland

Very much against any expectation of responsibility for soil monitoring within the industry, e.g. at Forest District Level. The best protection for forest soils is to promote and ensure 'best practice', as exemplified in 'Forests & Water Guidelines' and 'Forest and Soil Conservation Guidelines'. Fearful that assessment of soil properties may be used out of context, and supports interest in soil functioning instead.

Concerns about soil protection focussed on (a) soil erosion, (b) ground preparation for restock, (c) whole tree harvesting, and (c) soil compaction. Soil erosion was especially hard felt when it impacted on water quality draining forest sites. However, the Forests & Water Guidelines were felt to be very effective in preventing this problem, with few exceptions. Less easy about certain forms of ground preparation for restocking, and mentioned dolloping in South Scotland. However, although this is visually intrusive, there is no evidence that it is synonymous with soil degradation. The mixing of organic and mineral soil in the dolloping process may lead to improved soil fertility, i.e. soil improvement. Whole tree harvesting was also considered by some as a threat to the soil, but it was pointed out that there was often no alternative on steep terrain. Compaction was also another perceived problem, but recent research again supported 'best practice' as a good means of soil protection.

Stakeholder 5 Planning, Forest Enterprise.

Which soil functions need to be considered in terms of soil use and sustainable use of soil?

Growth medium for plants and soil flora and fauna – nutrient supply and water holding capacity;
Structural support - for plants, and for engineering structures;
Carbon storage;
Buffering/filtering capacity influencing water quality and quantity;
Recycling capacity for organic matter;
Historic record of natural and anthropogenic activity on the site.

What pressures are there on soils which might affect these functions?

Pressures include:
Trafficking - possible compaction, mixing, and erosion;
Biomass and nutrient removal – harvesting and leaching;
Change in land use, including development;
Pollutant inputs – atmospheric deposition / pesticide applications;
Drainage;
Climate Change.

Can these pressures be ranked in order of national and/or local importance ? On what basis?

It is not certain that this is really possible as, for example, trafficking and climate change are both pressures on the soil, but they operate at different scales both temporally and geographically. They will also affect different soil functions in different ways. Not sure that's very helpful.

Which indicators would be best for showing whether these functions are operating at an appropriate level in a range of soils and environmental conditions?

Growth medium for plants, soil flora and fauna: Indicators – plant growth, populations of soil organisms.
Structural support: Indicator -?
Carbon storage: Indicator – carbon content;
Buffering/filtering capacity: Indicator – water quality;
Recycling capacity for organic matter: Indicator – decomposition rates;
Historic record: profile disturbance.

However, with most of these indicators the natural changes over a season, and during the development of a forest rotation need to be allowed for.

How might we decide what is an 'appropriate level of function'?

Difficult. Perhaps the best that can be done is an appreciation of whether the direction of change in the measurement indicates increasing or decreasing soil quality in a particular situation.

Which measurements are required to provide these indicators?

Plant growth: yield grouped by species and site type.
Carbon content: loss on ignition from whole profile.
Water quality: pH? nitrate ?

Decomposition rates: litter bags ?

Whether measurements of a particular property might act as a surrogate for another property which might, of itself, be extremely difficult to measure: if so which?
This is thought to be inherent in the definition of an indicator? However, even more removed as an indicator of soil quality what about the existence of soil maps and evidence of their use ? Or existence of guidance on soil use and again evidence that they were used ? Indicates that effects on soil of operations were being considered.

What characteristics those measures should have in terms of robustness, spatial cover, density of observation etc.?
In practice, it is thought that it needs to be accepted that the measures and particularly the interpretation of the level of any measure, will need to vary in different site types and land uses. With particular regards to forestry, the changes resulting from afforestation, and the natural variation over the course of a rotation will need to be allowed for in any measurement.

Does your organisation have any views on benchmarking or critical values for any of these measures?
Just to note that it is very important that any such benchmark or critical values reflect variations between sites and land use. It would be unrealistic to use values from undisturbed soil in semi-natural ecosystems to evaluate more intensively used soils directly.

How might these measures be incorporated into a soil monitoring programme; especially with regard to the appropriate time-steps for different measurements?
This is too complex a question for a simple answer. It will depend on the indicators chosen.

Whether there are indicators of soil quality which can be applied uniformly across the UK, or whether you see the need to have separate indicators for different soil uses or landscapes?
Some indicators might be ‘global’, other will need to vary by soil use or site. What is more important to recognise is that the interpretation (e.g. benchmarks) of these indicators will probably not be global.

Summary

A general understanding of pressures on forest soils and support for a system that supports feedback on forest management as it pertains to soil ‘quality’. However, a realisation that such a system must be scientifically robust (especially difficult for forest soils which are notoriously variable in time and space) and workable if to attain the support of the forestry industry. Reference to existing policy and guidance on soil working which must be accommodated in a new system and a reticence to impose a new system on forest managers. Support for soil monitoring *per se*, but identification of problems with respect to setting threshold values for soil indicators.

11.4 Wildlife and Countryside Division, DETR

Which soil functions need to be considered in terms of soil use and sustainable use of soil?
Should include ability to support semi-natural habitats, native flora and fauna and biodiversity in general. This includes soil functions in hydrology at site and catchment levels.

What pressures are there on soils which might affect these functions?
Land use change, climate change, drainage, acidification, eutrophication, soil erosion, contamination (heavy metal/pesticide/organic pollutants).

Can these pressures be ranked in order of national and/or local importance? If so, on what basis?
Probably would need to be done on a habitat by habitat basis.

Which indicators would, in your view, be best for showing whether these functions are operating at an appropriate level in a range of soils and environmental conditions?
Some basic soil variables (chemical, physical and biological) and some measures of soil processes

How might we decide what is an 'appropriate level of function'?
By reference to target conditions of habitats and biodiversity.

Which measurements are required to provide these indicators?
Don’t know.

Whether measurements of a particular property might act as a surrogate for another property which might, of itself, be extremely difficult to measure; if so, which?
Vegetation characteristics as a surrogate for biodiversity.

What characteristics those measurements should have in terms of robustness, spatial cover, density of observations etc.?
Need to be able to detect change with respect to target habitats.

Does your organisation have any views on benchmark or critical values for any of the measurements or indicators suggested?
Refer to favourable condition assessment of SSSIs.

How might these measurements be incorporated into a soil monitoring programme; especially with regard to the appropriate time-steps for different measurements?
Could be developed within a national sampling programme, e.g. CS2000, but requires targeting on particular habitats, including protected sites.

Whether, in your view, there are indicators of soil quality which can be applied uniformly across the UK (so-called 'global' indicators), or whether you see the need to have separate indicators for different soil uses or landscapes?
There may be some ‘global’ indicators such as soil organic matter and soil biodiversity, but I would expect that indicators or target levels will differ according to soil use, habitats etc. Soil fitness for purpose

11.5 NERC-BBSRC Soil Science Advisory Committee; Vice-President: British Society of Soil Science; Head: Agriculture and Environment Division, IACR-Rothamsted

General Points
Likes the DPSIR matrix approach because it forces logical thinking. Believes that, until now, concern about soil quality has been driven by environmental regulations – pollutants and setting limits. We now need to include positive aspects: crop growth, biodiversity, etc. We also need to avoid the Australian, New Zealand and US approach of viewing soil quality merely as an aid to farmers, producing test kits (Doran’s approach), because this is no use for national monitoring.

Response to set questions

Which soil functions should be considered?
Multiple functionality important. Main functions are agriculture, filtering/buffering water quality, regulating the atmosphere, reservoir for biodiversity, protecting archaeological sites, basis for natural and semi-natural habitats. Some uses are mutually exclusive, e.g. intensive agriculture and species-rich hay meadow.

What are the pressures on soils and what is their order of importance?
The main pressures on soil vary with the locality. In some areas this pressure will be from intensive agriculture, e.g. on soil organic matter (SOM); in the uplands it may be overgrazing or walking; nationally, pollutant deposition and urbanisation are important. [Note: No ranking given.]

Which are the best indicators of these functions and what measurements are needed?
Agriculture: yield and crop quality, or the sustainability of yield; also nutrient status.

(i) Some measure of SOM is an appropriate indicator for all functions, but set in context. For example, texture and land use history can be used in a model such as ROTH-C to predict SOM. If the measured value is different from that predicted then this could be used to indicate the state of the function. The measurement of some SOM fractions is also likely to be useful.
Expected values of the ratio of biomass C:total C or biomass specific respiration (CO_2/unit SMB) can also be used as indicators, with benchmark values defined for various land uses and climates.
These ‘national’ indicators are useful for all functions, but are likely to have different benchmark (not critical) values for different functions.

(ii) There is no good indicator of soil biodiversity yet. BIOLOG, FAMES, etc. may prove to be useful but more research is needed to run alongside the search for indices.

(iii) Some measure of pollutants is needed, but these are difficult to interpret. pH is a very important indicator of pollution.

How do we decide on an appropriate level of function?
Society must decide how much functionality we need to maintain. It also depends on the function. For example, agriculture impacts on water and air. Do we minimise the impact of agriculture to protect the environment and biodiversity or maximise agricultural output in some areas and leave others for environment or leisure or biodiversity (e.g. intensive farmland in East Anglia, meadows on downland)? Prof Powlson believes that we should look for a good level of agricultural function, but minimise environmental impact. Buffering areas must provide adequate buffering, even if nothing grows. For GHG emissions we need to take a national view and balance emissions from agricultural and other areas.

Surrogate measurements?
It is agreed that hydrograph readings could indicate soil physical state, structure; also that water and air quality reflect soil quality, and that floral and faunal biodiversity also indicate soil chemistry/biology/physics.

Robustness, spatial cover, density?
Core sites and more extensive measurements are both required. For example, the ECN could act as the core sites with its well-established protocols, plus more extensive measures from sites such as those in CS2000 or the NSI. [Prof Powlson suggested that we need to reference the recent MAFF-funded research on sampling intensity, led by the University of Reading]

Benchmark or critical values for indicators?
Benchmark values, not critical values are appropriate. These can be set for pH, metals, biomass C/total C, SOM.

Soil monitoring programme?
Recent MAFF-funded projects at Rothamsted and MLURI examining sampling strategy indicated 5 years for some indicators (e.g. pH, metals) and 20 years for those that change slowly such as SOM. This could be put into practice on a 5-year rolling programme of sampling 20% of the sites each year.

Global indicators?
See Q4. Yes, but with different benchmark values.

11.6 National Farmers' Union

The National Farmers' Union (NFU) represents the interests of approximately 70 000 agricultural and horticultural businesses. We welcome the opportunity to respond to this paper on the '*Identification of a set of national indicators for soil quality*' as farming and horticultural practices have a major influence on the productivity of land, on conservation management, landscape features and the environment.
We are aware of the work that organisations such as MAFF and DETR have already developed on national indicators which relate to soil use and management and we are pleased to be given this opportunity to comment on this continuing discussion.
For ease of reference, we have addressed the questions raised by the paper in the sequence outlined in the invitation.

Which soil functions need to be considered in terms of soil use and sustainable use of soil?
From the agronomic perspective, soil functions that need to be considered include the use of soil for animal and crop production (and on a more detailed level also include soil characteristics such as soil fertility, soil pH, soil organic matter content, soil contamination

and soil erosion), the use of soil as a buffer for fertilisers, the use of soil to recover wastes (such as manure) and the use of soil as a store for water.

We acknowledge that other soil functions of importance that agriculture has an influence and that also need to be considered include land development and ecological and environmental issues. However, in this paper we will choose to focus on soil quality indicators with an agronomic function in more detail.

What pressures are there on soils which might affect these functions?
There is a number of different pressures on agriculture which may directly or indirectly affect soil use and the sustainable use of soil. Direct pressures include land management practices such as the type and intensity of production (such as arable cropping or livestock production), the type, frequency and timing of cultivation and additions of animal wastes.
Pressures or influences which may indirectly affect land management practices include legislation, voluntary environmental agreements (such as agri-environment agreements), neighbouring development and Government policies/EU Directives (such as the Bathing Water Directive which bans the disposal of sewage sludge at sea).

Can these pressures be ranked in order of national and/or local importance? If so, on what basis?
Day-to-day land management decisions such as the type and frequency of cultivation will have a direct influence and be of local importance.
Policies and legislation imposed will have an indirect influence and are of national importance.

Which indicators would, in your view, be best for showing whether these functions are operating at an appropriate level in a range of soils and environmental conditions ?
The indicators already identified by MAFF in their publication *Towards Sustainable Agriculture: A Pilot Set of Indicators* provides a useful foundation for the development of indicators of the main agronomic functions of soil use. Using these indicators has the added benefit that the data already collected by MAFF could be used in defining benchmark figures.
The MAFF indicators identify environmental as well as agronomic issues which may be used as a measure of soil use and sustainability and include agricultural productivity, adoption of farm management systems, pesticide use, nutrients (nitrate and phosphorus losses from agriculture, phosphorus levels of agricultural topsoils), manure management, emissions from agriculture (ammonia, nitrous oxide and methane), water use for irrigation, organic matter content of agricultural topsoils, accumulation of heavy metals in agricultural topsoils and the change in use from agriculture to hard development.
Many of the DETR Quality of Life indicators offer additional insights directly and indirectly to soil health and function. These include indicators such as net loss of soils to development, concentrations of organic matter in agricultural topsoils, area converted to organic production and emissions of greenhouse gases.
Indicators not already identified by MAFF or DETR include: the potential for soil to act as a water store, the potential for soil to act as a buffer for fertilisers and the land-spreading of wastes (other than manures such as sewage sludge and industrial wastes), and the loss of soil through erosion.

How might we decide what is an 'appropriate level of function'?
An appropriate level of function will differ according to factors such as soil type, the region of the country, and the type of production. Benchmark figures or quantitative measures for

each soil indicator need to be established to aid in the interpretation of the data that is collected from any programme and to determine an ‘appropriate level of function’.

Which measurements are required to provide these indicators?
Many of the indicators may have similar measurements, but if we take each of the additional indicators we have suggested in turn:

- The potential for soil to act as a store for water could be measured through soil hydrology measures and the type of land management.
- The potential for soil to act as a buffer for fertilisers and recovery of wastes could be measured through soil structure, soil organic matter content, NPK, heavy metal content, pH and soil microbial activity.
- The loss of soil through erosion is a state indicator. Diffuse pollution from agricultural land is increasingly being seen as a soil management issue. An indicator, which identified the spatial extent of soil erosion across the UK may provide a helpful input to policy development. Figures of soil loss per annum need to be measured. Consideration needs to be given to the type of production and soil type.

Measurable and replicable soil characteristics can be used to define these indicators. Benefits in using these characteristics are that changes in soil quality over a fairly short space of time can be detailed and followed.

Whether measurements of a particular property might act as a surrogate for another property which might, of itself, be extremely difficult to measure; if so, which?
We acknowledge that some soil properties may be difficult to measuring this context it will be more important to develop models of soil function rather than impute the state of such soil properties.

What characteristics those measurements should have in terms of robustness, spatial cover, density of observations, etc.?
Those measurements must be representative, replicable, the methods applied consistently and the number of samples taken must be statistically viable at least on national and regional scales. In addition, any data gathered must be collected from farming areas and representative sampling techniques established.

Does your organisation have any views on benchmark or critical values for any of the measurements or indicators suggested?
The establishment of baseline standards or benchmark figures is critical for the interpretation of any data. This is particularly important where indicators may be used to make recommendations, guidance is developed or advice on policy development is given.
The establishment of benchmark figures must be determined prior to the development of the soil monitoring programme. The importance of this is demonstrated by the fact that soil organic matter content reduces on conversion from grassland to arable, but reductions level off when a new equilibrium is established.
The NFU is not in a position to suggest or propose benchmark figures for these measurements or indicators, but any information provided by the MAFF Sustainable Agriculture indicators would be a valuable starting point.

How might these measurements be incorporated into a soil monitoring programme; especially with regard to the appropriate time-steps for different measurements?
In order for us to comment on this particular proposition, some background information is needed on any existing soil monitoring programmes including the location of the sample sites,

the land use type they represent (i.e. grassland, arable, upland, etc) and how frequently they are sampled.

Whether, in your view, there are indicators of soil quality which can be applied uniformly across the UK (so called global indicators), or whether you see the need to have separate indicators for different soil uses or landscapes?
Different indicators from those identified by us may indeed be needed for landscapes such as forestry or wildlife habitats where the measurements used to define the indicators may differ.

11.7 Agriculture Department, Scottish Executive Rural Affairs Department

It is suggested that the following basic principles link the use of soils to sustainability:

Soil Physical Characteristics

- **Climate**)
- **soil depth**)
- **soil structure**) Baseline information available from existing
- **soil texture**) MLURI data
- **gradient**)
- **stoniness**)
- **organic content** - subject to change but measurable

These, in combination, determine other important factors such as trafficability, poaching risk, droughtiness, compaction, wetness, erosion (wind and water).
Episodic events such as flooding, frost, snow or drought etc may well effect land use and quality in the short term and hence indicator measurements, but be of little significance in the longer term.
Other influences such as application of chemicals and disposal of unwanted materials could have serious implications for long term soil use and sustainability.

Biological Characteristics:

- **Vegetation -** measurable
- **micro fauna/flora and biodiversity -** Unclear how this can be measured. It is assumed the measurements will relate to the organisms involved in biological soil processes e.g. the N-cycle.

Land Use:

- Agriculture
- Forestry
- Land Fill
- Development/Industry

To a large extent land use is often dependent on the land quality, but over extended periods of time it has been greatly influenced by government polices such as agricultural and forestry subsidies and planning regulations. However in general terms modern efficient farming and the protection and sustainability of Scottish soils should not be viewed as competing aims indeed they should be mutually supporting and are vital to the future success of the industry and our wider rural viability.

Rather than re-invent the wheel entirely,, perhaps any set of national soil indicators could firstly be based on the LCA mapping work carried out so well by MLURI in the 1980s to which could be added indicators relating to other external influences such as pollutants, biodiversity etc. We would then need to establish a wide range of selected indicators from both existing and new information for each of the more important of the above components to determine a baseline so that these "levels" can be measured in the future.

Specific questions.

Which soil functions need to be considered in terms of soil use and sustainable use of soil?
It is suggested that the key functions in terms of soil use and sustainability that should be considered are LCA classification, soil biodiversity, soil organic matter and level of contaminants.

What pressures are there on soils which might affect these functions?
The pressures on these functions are dependent on use. In agricultural terms, certain types of management both (cropping and grassland) could result in erosion, compaction or contamination of the soil as well as loss of structure and biodiversity. The functions could also be affected by factors largely outwith our control such as climate and flooding.

Can these pressures be ranked in order of national and/or local importance?
It is probably possible to determine on an national basis which pressures have the most detrimental effect on soil quality. However, local factors such as soil type, rainfall, topography etc will also inevitably have an influence on this.

Which indicators would, in your view, be best for showing whether these functions are operating at an appropriate level in a range of soils and environmental conditions?
Establish baseline figures for the key criteria of LCA classification (already mapped), organic matter levels, biodiversity and contaminants for different soil types then monitor at set frequencies to determine change.

How might we decide what is an appropriate level of function?
At this stage it is difficult to answer this question. Further discussion between interested parties is required.

Which measurements are required to provide these indicators?
Scientific colleagues will no doubt be able to suggest appropriate criteria.

Whether measurements of a particular property might act as a surrogate for another property which might, of itself, be extremely difficult to measure; if so which?
It is difficult to answer until indicators have been agreed, but from a non-scientific point of view, it seems that with the large number of variables that can affect any given outcome it would be difficult to use measurements of one property as a surrogate for another with a satisfactory level of accuracy.

What characteristics those measurements should have in terms of robustness, spatial cover, density of observations etc.?
From an agricultural viewpoint, density of measurements would vary between land types with lowland intensively farmed land requiring a greater level of observation than an extensive upland situation.

Does your organisation have any views on benchmark or critical values for any of the measurements or indicators suggested?
The benchmark values are likely to vary in different parts of Scotland, depending on the various factors identified above and therefore will require to be tailored to local situations. Critical values will vary accordingly to present land quality and use.

How might these measurements be incorporated into a soil monitoring programme; especially with regard to the appropriate time-steps for different measurements?
Scientific colleagues will no doubt be able to suggest appropriate criteria. It will be important to reflect the effects of seasonality on soil conditions when considering time-steps. Rate of change in soils is likely to be slow and therefore any measurement or monitoring should at widely spaced intervals.

Whether, in your view, there are indicators of soil quality which can be applied uniformly across the UK (so-called “global” indicators), or whether you see the need to have separate indicators for different soil uses or landscapes?
We would suggest that the MLURI Land Capability for Agriculture Classifications is a satisfactory indicator of soil quality in Scotland.

11.8 Scottish Natural Heritage

All soil functions need to be considered as part of this work, particularly the 'environmental' functions such as supporting habitats, biodiversity and the cultural/natural heritage value of soils. The main pressures that come to mind are land-use change, climate change and contamination at local and national levels. I feel that there needs to be a new approach for identifying indicators for these 'non-agricultural' functions of soil, some of which maybe the same but we still need to identify which soil properties and processes are key to the environmental functions. Level of function depends upon end-user. I would hope it aims to maximise the multifunctional approach? I also feel we need to widen the net of indicators away from just those we currently have data for and include the more difficult ones such as biological indicators. Indicators need to be robust, reflect soil conditions accurately and be relatively easy to obtain? With regards to 'benchmark' values and/or sites the country agencies should be able to supply a suite of potentially undisturbed or 'semi-natural' soils with their typical surface vegetation (plus those of cultural/historic value). These have significant potential as benchmark sites? With regards to monitoring these benchmark sites (along with benchmark soil properties) could be used as part of a wider monitoring scheme. The time frame for sampling depends upon which indicators are chosen i.e. biological ones may require more frequent sampling, others such as texture may not? It is hard to envisage a global set of indicators with fixed thresholds - more likely function will dictate these - the '*Landcare*' system in New Zealand has a basic set of indicators from which a subset can be selected, with differing threshold values, according to landuse - this sounds like a possibility?

11.9 Environment Protection Unit, Scottish Executive Rural Affairs Department

Recycling & Waste Team:

Although these comments are more concerned with waste management, they are nevertheless relevant to soil quality. As an initial thought, the following activities could have significant effects on soil quality and sterilisation of ground. It would be beneficial from a policy viewpoint to quantify and track the activities over time.

1 Fly tipping
1.1 Number of incidents
1.2 Locations and quantities

2 Agricultural Fertilisers
2.1 Locations , Organic Quantities (per hectare)
2.2 Locations, Inorganic Quantities (per hectare)

3 Set Aside
3.1 Location and area(hectare)

4 Landfill Sites
4.1 Site locations, open (hectare)
4.2 Site locations, closed (hectare)

Most of the data required are already recorded (except for flytipping). More detail for each indicator would be helpful but a balance needs to be struck, otherwise the indicator becomes unwieldy and data more difficult to establish.

It is presumed that the initial findings of the trawl will be presented in the near future. We would be interested in seeing/hearing the intentions in more detail and in particular the number of indicators anticipated (others could be provided) and the detail of these.

SEPA Water Team:

The main comment is that the project should be aware of the SAC work being taken forward in Ayrshire. This work is examining the flow of pollutants through soils and in the water environment to determine the potential for impacting upon bathing waters and potentially other water types.

11.10 Scottish Environmental Protection Agency:

SEPA has recently called for a soil protection strategy an essential part of which, we believe, is the establishment of a soil monitoring network. Prior to a monitoring strategy we also believe it is necessary to survey the quality of soil and the extent of degradation.

Specific answers to the set questions:

Which soil functions need to be considered in terms of soil use and sustainable use of soil?

- the ability of soil to act as a buffer to pollution protecting other environmental compartments;
- as a medium to support indigenous plant growth and ecosystems;
- as a carbon store;
- the multifunctional nature of soil. Perturbations must be reversible;

- role in bio-geochemical cycling.

Should soil quality always be viewed in respect to a function or can we consider inherent soil quality as the soil processes and conditions which exist under pristine conditions and try and maintain those irrespective of function.

What pressures are there on soil which might affect these functions?
- atmospheric deposition of acidity, eutrophying N, heavy metals and POPs;
- agricultural practices which lead to soil erosion (including the uplands), loss of organic matter, loss of soil fertility, build up of pesticide residues;
- point source chemical contamination;
- creation of derelict and vacant land, urbanisation;
- the application of wastes;
- climate change.

Can these pressures be ranked?
The impact of each pressure will vary according to the environment. Perhaps rank pressures with reference to the ecosystem/land use type ? The impact and extent of many of these pressures is unknown and data needs to be collected.
From SEPA's perspective the most important pressures are atmospheric deposition of pollutant and the application of wastes to land. Point source chemical contamination is also an issue although I understand this is being dealt with in a separate project.

Which indicators would be best for showing whether functions are operating at an appropriate level in a range of soils and environmental conditions?
Indicators should be easily measured, reproducible and reflect a process of interest. Although many indicators will require further research a minimum dataset such as that proposed by Doran and Safely (attached) would be very useful if tailored to UK ecosystems. Indicators must encompass and ideally integrate chemical, physical and biological soil attributes and relate to soil processes which sustain an ecosystem. Included would be variables such as levels of organic matter, respiration rates, levels of essential nutrients, heavy metal concentrations, pH, decomposition rates, soil bulk density, water infiltration capacity. Although problems exist with linking concentration to function such data would provide a useful indication of temporal changes.

How might we decide what is an 'appropriate level of function'?
Benchmark sites need to be established where optimal ranges for critical soil processes can be established. Perturbations must be reversible with the aim of supporting the soil functions which would occur under pristine soil conditions. A number of criteria should be selected on the basis that they are the soil conditions essential to the maintenance of the required functions. These could then be fed into a scoring system to represent, for example, poor, intermediate or good quality soil. Establishing numerical limit values will require an extensive literature search and in many cases further research.

Which measurements are required to provide these indicators?
See Table 11.1.

Whether measurements of a particular property might act as a surrogate for another property.
There may be many instances where it is cheaper and/or simpler to measure surrogate properties. For example, the deposition of atmospheric pollutants, if the subsequent fate of the pollutant in soil can be accurately modelled.

What characteristics those measurements should have in terms of robustness etc.?
Spatial variability will be a problem. The number of measurements required to give a statistically significant result at any one site should be established. Indicators must be independent of conditions such as short term variations in rainfall. They should be able to integrate over time and space.

Benchmark/critical values
Indicators will be compared with pristine sites in Scotland.

How might these measurements be incorporated into a soil monitoring programme?
Sites should be stratified according to land use and soil type. A 5 year reporting interval is envisaged to inform policy.

Global indicators of soil quality
Ideally, indicators will be identified which will be specific to land uses and soil types with a subset that can be compared across the UK. For example, trends in organic matter concentration would be useful from many land uses across the country but indicators such as nitrification rates will provide useful information for only specific land uses. If a site/soil stratification is carried out then it will be relatively simple to compare indicator values across the country.

Table 11.1 A proposed minimum dataset of physical, chemical and biological indicators for soil quality

Indicator of soil quality	Relationship to soil quality and function	Comparisons for evaluation
Physical		
Texture	Retention and transport of water and chemicals	Less eroded sites or landscape conditions
Depth of soil, topsoil and rooting	Estimate of productivity potential and erosion	Non-cultivated sites or varying landscape positions
Infiltration and soil bulk density	Potential for leaching, productivity and erosion	
Water holding capacity	Related to water retention, transport and erosion	Row and/or landscape positions
		Precipitation intensity
Chemical		
Soil organic matter	Defines soil fertility, stability and erosion extent	
pH	Defines biological and chemical activity thresholds	Non-cultivated or native control
Electrical conductivity	Defines plant and microbial activity thresholds	Upper and lower limits for plant and microbial activity
Extractable nitrogen, phosphorus and potassium	Plant available nutrients and potential for nitrogen loss	Upper and lower limits for plant and microbial activity
Biological		Seasonal sufficiency levels for crop growth
Microbial biomass carbon and nitrogen	Microbial catalytic potential and repository for carbon and nitrogen	
Potentially mineralisable nitrogen	Soil productivity and N supplying potential	Relative to total carbon and nitrogen or carbon dioxide produced
Soil respiration, water content and temperature	Microbial activity measure	
		Relative to total carbon or total nitrogen contents
		Relative microbial biomass activity, carbon loss versus inputs and total carbon pool

adapted from Doran and Safley (1997)

12. RECOMMENDATIONS FOR INDICATORS OF SOIL QUALITY

From the foregoing Chapters, it is obvious that there is a large number of potential indicators of soil quality and a number of schemes by which they might be derived. However, we **recommend**

that the UK should follow the outline proposed by Blum (1993) and also focus on what has been called 'soil resilience' by Greenland and Szabolcs (1994), i.e. the ability of a soil to buffer against and / or recover from an imposed stress.

The latter is important because it indicates whether the soil is able to continue with its function or functions. It is, however, a concept that is not well-developed in the UK and will require further research before it can become a practical concept. In summary, Blum (*loc. cit*.) proposed that the key soil functions are:

Biomass production (food, timber, biodiversity)
Filtering and buffering (chemicals - natural and anthropic inputs, water resource and quality))
Bio-reactor (breakdown and turnover of added materials
Preserving heritage (geology, archaeology)
Foundation for the built environment (roads, houses, buried services)

In order to continue these functions, soils need to be *resilient against applied stress*. It is important to note that this 'model' applies at all scales and to all soils.

Because soils and demands on them are so diverse, we believe that there should be greater rigour in the assessment of soil quality and soil function(s). Thus, we **recommend**

that any assessment of soil quality or function(s) should be undertaken using a formal approach based on procedures similar to those we have proposed earlier in this report.

These procedures require the potential user to address specific questions about the function(s) the soil is expected to perform. In essence, simple questions are posed, such as:

- what function or functions is this soil performing at present ?
- what function(s) could this soil perform ?
- what functions do we wish it to perform ?
- is this a sensible use of this soil, and why ?

This leads inevitably to questions about how these functions might be assessed. The indicators below assist in that assessment; indeed, they might also be a sign that such an assessment is required because they identify a problem. It is also inevitable that such an approach will identify gaps in knowledge and information, some of which can be rectified easily, but some will require considerably more research and / or an acceptance of expert judgement. A further advantage of using a formal assessment procedure for soil function, is that it can be used to underpin cases where expert judgement becomes the main source of information.

We also believe that there is a requirement for both an overarching assessment of soil function at the national, regional or catchment level, as well as the need to assess diversity within the landscape through the measurement or derivation of soil properties at specific sites. There is no doubt that the latter measurements will also impinge on the former assessments.

Table 12.1 lists the indicators that have been proposed either by members of the Project Team, the Project Board or Stakeholders, as well as those found in the literature. We have attempted to associate each potential indicator with one or more soil functions, but this is by no means a fixed association. Different users will see different degrees of indicator-function relationship and, indeed, many indicators can inform more than one function at a time. Similarly, we have attempted to show which part of the DPSIR framework is best served by each indicator. We do not believe that this approach is entirely successful. For reasons given earlier in this Report, the separation of Drivers from Pressures risks becoming facile. Furthermore, indicators – by their very nature – need to link with both State and Response if they are to be useful. That of itself means that, almost inevitably, the indicator becomes embroiled with an assessment of Impact; thus, the distinctions between these parts of the DPSIR model become difficult to sustain at a practical level.

It is also clear from Table 12.1, that there are large gaps in the data sources and there are large gaps in our ability to link indicator clearly to function. Despite this, we are confident that some of the indicators are robust enough to be brought into use immediately, whilst others could be used within a reasonable time-frame, and yet others will need considerable research investment. We have grouped the indicators into three classes:

- ‘headline’ indicators, which we believe will convey important messages about the soil to a wide audience. Further work is sometimes required to make these indicators usable. indicators, which are often of a more detailed or technical nature. These indicators will be required to answer more specific questions about areas of land, specific habitats, more detailed aspects of soil function and similar issue. They can also have a role in supporting the headline indicators. They might also require further research to make them usable and they should be regarded as second in the order of priorities
- ‘research’ topics. These are areas of knowledge, which could become useful and important indicators, but also require considerable research of one kind or another.

Thus, we **recommend**

that consideration be given to the use of the headline indicators as a primary tool in the assessment of soil quality in the UK as soon as practicable.

We also recommend

that work be carried out to assess the resources required to bring these potential indicators forward, or at least a selection of them, as soon as is practicable.

One problem we have identified, especially in relation to soil monitoring, is that many of the potential indicators would be more easily measured if there is portable equipment. This is particularly true of some of the biological assessments. Thus, we **recommend**

that consideration be given to the development of standardised and portable test kits so that the effort required for soil monitoring at large numbers of sites can be minimised.

Finally, we have considered the question of soil monitoring and see no technical barriers to the implementation of a national soil monitoring programme. However, there are a number of technical issues which need to be addressed as these will clearly affect the nature of such a network. We recommend

that the final selection of the headline and secondary indicators be made as soon as practicable

that the necessary work to translate existing information into a usable indicatoror indicators be carried out as a matter of urgency

that the potential effect of this selection of indicators on he design of a soil monitoring network, and issues such as site selection, sampling strategies, field and laboratory data collection etc. be assessed as rapidly as possible

that topics requiring further research (and any necessary investment in improved technology) be identified

that the appropriate time-scale for a review of the effectiveness of the indicators, the introduction of new indicators and the soil monitoring network be 5 years or multiples of that.

Table 12.1 Potential soil quality indicators. The proposed Headline indicators are shown in bold type and in shaded boxes; the proposed *Secondary* indicators are shown in *italic* and the boxes are shaded; the areas for further research are left in normal type and are unshaded. Where more than one function is given, the primary function is underlined.

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Sustainability	*Total land area*	*The UK needs to know if it is losing or gaining significant amounts of its finite land resource, e.g. by marine erosion or accretion*	*D; reflects overall drive for resource protection in the UK*	*Not known / Simple, easily understood; clear warning signal*	*National land holding statistics; increasingly from remote sensing*	*More work is probably needed to assess historical change*
Awareness	**Number of hits on one or more WWW-sites devoted to soil information**	**There is a pressing need to make more information on soils available to a wide audience; this has an important educational function**	**R**	**Would need to be judged on its merits / WWW is becoming the norm for public information and this will increase**	**The Soil Surveys, research Stations, DEFRA, EA, FC etc.**	**To make it effective, there would need to be a co-ordinated strategy; such (a) web-site(s) would need regular updates to keep it attractive and useful**
Awareness	*Number of 'awareness-type' publications issued per year*	*Indication of growing awareness of soil issues among the population; indicates greater desire for soil information*	*R*	*Would need to be judged on its merits / probably a weak indicator compared to the WWW*	*Agencies, Government Departments, National Organisations, Institutes*	*Could be difficult to collate effectively*
Biomass production	**Total non-urban land area**	**There is a need to know how the finite land resource of the UK is partitioned between biomass production and non-biomass use**	**P; reflects competition for land; effectiveness of soil protection strategy**	**Not known; set at 1 % per year ? / Easily understood and gives an overall signal**	**National statistical data; increasingly from remote sensing**	**Assessments of historical change known; could support an expert judgement of what is acceptable**
Biomass production	*Area of potentially productive land*	*This indicator would show what land could be used for production in a national emergency.*	*P*	*An absolute value / Probably not a powerful indicator as would be dispute about definition*	*Based on an assessment of existing data; updated regularly as technology changes*	*This is strategic planning and would underpin understanding of just how much home grown food and timber might be produced.*
Biomass production	*Area taken by land use classes, e.g. arable, ley grass, permanent grass, timber, organic farming etc.*	*The UK needs to know, at a first glance, if any decline in production is simply due to a decline in the area devoted to that sector*	*State: reflects the current position, Impact: could be due to a change of policy, e.g. organic farming*	*Not known; base on historical changes / Easily understood but data would need rapid collection and assessment*	*National Census Data; number of accredited organic farmers and/or area of certified land; LEAF members or similar index*	*Probably need for better data to give a finer analysis at the county or regional level or by soil type.*
Biomass production	**Total above-ground biomass production**	**The UK needs to know if there is a decline in the long-term productivity of soils, which cannot be explained readily by political, market or climatic factors, for example.**	**State: reflect current position; Impact/Response .**	**Not known / Easily understood and gives a clear signal**	**National Census Data a starting point, but not enough for all land uses**	**Needs more research, especially to establish the basis of measurement, e.g. as C, and to establish the uncertainty in any estimate.**

Soil function	**Indicator**	**Relevance of Indicator**	**Fit to D, P, S, I, R**	**Significant change / Advantage of Indicator**	**Data Source(s)**	**Additional Comment**
Biomass production	Net primary production	Gives an overall assessment of soil potential to produce above ground biomass; any decline would indicate a need for further investigation	S, I, R	Not known / Possibly a good 'ecological' indicator but relevance to all land uses might be difficult to establish; not easily explained	Literature might give some values; various national surveys e.g. CS2000 might also assist.	Needs more research; link to soil types little understood; might be more suited to semi-natural than agricultural land or managed forestry
Biomass production	*Yield of winter wheat*	*UK needs to maintain a careful watch on its ability to produce adequate stocks of home-grown food*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means /* *Easily understood and longer-term changes are important*	*National Census Data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Yield of spring barley*	*UK needs to maintain a careful watch on its ability to produce adequate stocks of home-grown food*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/* *Easily understood and longer-term changes are important*	*National Census Data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Yield of OSR*	*UK needs to maintain a careful watch on its ability to produce adequate stocks of home-grown food*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/* *Easily understood and longer-term changes are important*	*National Census Data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Yield of meat products*	*UK needs to maintain a careful watch on its ability to produce adequate stocks of home-grown food*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/* *Easily understood and longer-term changes are important*	*National Census Data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Yield of milk*	*Indicator of the ability of the UK to produce adequate stocks of home-grown food*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/* *Easily understood and longer-term changes are important*	*National Census data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Biomass production	*Area occupied by winter wheat; yield per unit area*	*Indicator of whether a given yield was being produced more, or less, intensively, and thus possibly show whether soils were under greater stress or not.*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/ Easily understood and longer-term changes are important*	*National Census data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Area occupied by winter barley; yield per unit area*	*Indicator intensity of production and thus whether soils were under greater stress or not.*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/ Easily understood and longer-term changes are important*	*National Census data*	*More detailed statistics would be needed so that yield data could be related to soil type.*
Biomass production	*Area occupied by spring barley; yield per unit area*	*This would show whether a given yield was being produced more, or less, intensively, and thus possibly show whether soils were under greater stress or not.*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/ Easily understood and longer-term changes are important*	*National Census data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Area occupied by OSR; yield per unit area*	*This would show whether a given yield was being produced more, or less, intensively, and thus possibly show whether soils were under greater stress or not.*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/ Easily understood and longer-term changes are important*	*National Census data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Area converted from cereal production to grassland (or other use) or vice versa*	*This would show whether a given yield was being produced more, or less, intensively, and thus possibly show whether soils were under greater stress or not*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/ Easily understood and longer-term changes are important*	*National Census data*	*More detailed statistics would be needed so that yield data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Animal stocking density*	*This would show whether a given yield was being produced more, or less, intensively, and thus possibly show whether soils were under greater stress or not; could also be related to indicators for soil surface condition and erosion*	*S, I, R*	*Not known; could be set by expert judgement; use rolling 5-year means/ Easily understood and longer-term changes are important*	*National Census data; the crucial factor is stocking density above some acceptable level, e.g. area above a given percentile – 75%?*	*More detailed statistics would be needed so that data could be related to soil type; otherwise the value of the indicator would be severely reduced*
Biomass production	*Area of forest / woodland*	*As a general indicator of land use; would be more useful if it could be related to specific soil types*	*S, I, R*	*Not known; could be assessed by expert judgement*	*Linkage between Forestry Commission data and, for example, National Soil Map*	*Probably require more data depending on the level of linkage to soil type*

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Biomass production	**Area of forest / woodland on brownfield sites**	**Indicator of appropriate use of land otherwise difficult to use, for example, because of nature of pollutants, clean-up costs; could be seen as an indicator of 'urban greening'.**	**S, I, R**	**Not known; could be assessed by expert judgement / gives a clear, easily understood signal**	**Might be possible to derive the information from local Authority and FC data sources**	**Possibly needs more work to ensure that information is collected in a uniform manner.**
Biomass production	**Area of new planting (from agricultural land)**	**Could be used as an indicator of less intensive land use, or of the more appropriate use of certain soils**	**S, I, R**	**Not known; could be assessed by expert judgement / could be useful**	**National Census Data; FC data; possibly from remote sensing in the future**	**Probably needs more work to ensure that information is collected and reported in a uniform way.**
Biomass production	*General Yield class by sub-compartment*	*This would be a measure of timber productivity*	*S, I, R*	*Not known; could be assessed by expert judgement / more for the specialist; probably lacks public 'resonance'*	*FC data*	*Linkage to soil types is not obvious; more work needed on this.*
Biomass production	*Area under UKWAS or WGS*	*An indicator of forestry conducted to a defined environmental standard; could be seen as less stressful for soils*	*S, I, R*	*Not known; could be assessed by expert judgement / more for the specialist but could fit into an 'eco-friendly' approach*	*FC data*	*Linkage to soil types might not be obvious, as above; more work might be needed on this*
Biomass production	*Yield for a number of commodities in relation to a unit of input*	*This could be a measure of production efficiency, e.g. more N- or P-efficient crops could mean less potential pollution*	*State: current position; Impact/Response: possible effects of policy change*	*Many could be derived nationally from current statistics / more for the specialist; probably lacks public 'resonance'*	*National statistics*	*Probably need for better data to enable analysis to be made at county of regional level*
Biomass production	*Foliar chemistry*	*Indicates the ability of the soil to supply required nutrients (macro- and micro-).*	*S, I, R*	*Not known / more for the specialist; probably lacks public 'resonance'*	*Probably a considerable literature*	*Could be an indicator (or set of indicators – one for each element) of production potential or stress; might be a sensitive way of indicating problems at an early stage*
Biomass production / Biodiversity	**Area(s) of specific habitats such as bog, moorland, ancient woodland etc.**	**Indicator of biodiversity potential**	**S, I (R?)**	**Not known; a judgement would be required as to the significance of any change / could send out a powerful signal in an ecological context**	**National surveys**	**Commonly regarded as of considerable interest to natural heritage, but the biodiversity potential of common land uses should not be neglected**
Biodiversity	Keystone species within the soil	Both macro- and micro-faunal diversity and abundance are seen as indicators of soil 'health'; absence of key species are a potential indicator of stress	S, I, R	Not known' decisions need to be made about which species need to be measured / could become an indicator of considerable public resonance over time.	Not known	Needs more research; very difficult to know if presence / absence of a species really indicates stress or the action of another factor which might be acceptable

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Biodiversity	Keystone macro-flora	Decline or increase in floral abundance could indicate increase of decrease in stress on the soil	S, I, R	Not known / could become an indicator of considerable public resonance over time.	Countryside Surveys; various botanical surveys (BRI ??)	Needs more research especially into the interactions between floral occurrence, abundance on specific soil types and relationship to other properties. Ellenberg's indicators could be a starting point for data assessment
Biomass production / Filtering and buffering (Biodiversity) / catching and transmitting water	**Soil organic carbon content**	**Viewed as a general indicator of 'soil health'; relevant to soil fertility, microbial activity, adsorption of agro-chemicals, greenhouse gas emissions; contributes to cation exchange capacity and thus relevant to buffering / acidification issues; relates to soil structure, erosivity, dark water, eutrophication (N and P)**	**S, I, R**	**Debatable; might be lower desirable limit of 1% for arable soils – many people argue for 2%; magnitude of change depends on purpose; decline increasingly seen as a sign of a soil less able to deal with increased stress / strong signal, relates to many policy areas, easily understood**	**Soil monitoring databases (NSI, RSSS, ECN, ICP and conventional soil surveys)**	**More work will be needed to reach agreement on desirable ranges for different soils and their uses; link with biodiversity is especially uncertain; nature of carbon might be more important than amount**
Biomass production / Filtering and buffering (Biodiversity)	Microbial biomass carbon/ soil organic carbon	Indicates 'activity' of soil microbial biomass – relevant to soil fertility, ability to transform chemicals; diversity of microbial population	S and (possibly) I	Unknown; generally felt that the nearer the value is to unity then the better. Decline indicates reduced ability of the soil to deal with added wastes and supply nutrients and might indicate increased stress / contaminant load / may never have much public resonance	Literature might give a range of values for specific soil-ecosystem combinations	Needs more research; variability in space and time not sufficiently known at present; nor is the robustness of the methodology; gives little information on microbial diversity
Biomass production / Filtering and buffering (Biodiversity)	Respiration Quotient based on carbon dioxide carbon as a proportion of biomass carbon	Indicates 'activity' of soil microbial biomass – relevant to soil fertility, ability to transform chemicals; diversity of microbial population	S and (possibly) I	Unknown; decline indicates reduced ability of the soil to deal with added wastes and supply nutrients and might indicate increased stress / contaminant load / a specialist indicator, unlikely to catch the public eye	Literature might give a range of values for specific soil-ecosystem combinations	Needs more research; variability in space and time not sufficiently known at present; nor is the robustness of the methodology; gives little information on microbial diversity

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Biomass production / Filtering and buffering (Biodiversity)	Respiration Quotient based on the soil N-mineralisation potential	Indicates 'activity' of soil microbial biomass – relevant to soil fertility, ability to transform chemicals; diversity of microbial population	S and (possibly) I	Decline probably indicates reduced ability of soil to deal with added wastes, supply nutrients and might indicate increased stress and /or contaminant load / a specialist indicator, unlikely to catch the public eye	Literature might give a range of values for specific soil-ecosystem combinations	Needs more research; variability in space and time not sufficiently known at present, nor is the robustness of the methodology
Biodiversity / Filtering and buffering	BIOLOG score	Indicates the microbial diversity of the soil and its potential to break down organic materials, including agro- or industrial- chemicals and other wastes.	S and (possibly) I	Decline indicates reduced ability of the soil to deal with added wastes and supply nutrients and might indicate increased stress and/or contaminant load. a specialist indicator, unlikely to catch the public eye	Literature might give a range of values for specific soil-ecosystem combinations	Needs more research; variability in space and time not sufficiently known at present, nor is the robustness of the methodology
Biodiversity / Filtering and buffering	DNA-based microbial diversity index	Indicates the microbial diversity of the soil and its potential to break down organic materials, including agro- or industrial- chemicals and other wastes.	S and (possibly) I	Decline indicates reduced ability of the soil to deal with added wastes and supply nutrients and might indicate increased stress and/or contaminant load. a specialist indicator, unlikely to catch the public eye	Literature might give a range of values for specific soil-ecosystem combinations	Needs more research; variability in space and time not sufficiently known at present, nor is the robustness of the methodology
Biodiversity / Filtering and buffering	Enzyme assays	Indicator of fungal and possibly microbial activity and diversity; indicates potential ability of soils to degrade wastes, to assist nutrient uptake and perhaps to form stable structure	S and (possibly) I	Not known a specialist indicator, unlikely to catch the public eye	Literature might give a range of values for specific soil-ecosystem combinations	Needs more research; variability in space and time not sufficiently known at present, nor is the robustness of the methodology; not enough known about which enzymes are relevant in which situations

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Filtering and buffering	**Topsoil pH**	**Indicator of overall acidity or alkalinity of the soil; has considerable influence on land use and biodiversity; land use might also affect pH so cause-effect needs to be clarified**	**S, I, R**	**Change of 0.5 of a pH unit quite significant; areas of soils in specific pH classes, e.g. <pH4.5, pH4.5 – 5.5 etc. / a strong signal, easily presented as 'more acid', 'less acid etc'. – good public understanding**	**Several datasets (NSI, RSSS, ECN, CS2000 and earlier, ICP**	**More work needed to establish actual / desirable ranges for soil types and ecosystems; could be worth trying to link these data to vegetation indexes particularly for semi-natural systems?**
Filtering and buffering	*Cation exchange capacity to 1m depth*	*Indicator of the absolute ability of the soil to buffer against certain inputs; could be a measure of potential resilience; a component of this is due to organic carbon*	*S and possibly I (if organic carbon increases or decreases)*	*Not known; could probably be derived fairly readily for major soil type / OC combinations./ a specialist indicator, not easy to 'sell' to a wider public*	*Limited data; might be derived from pedo-transfer functions but debatable; many different methods of measurement*	*Needs more data and investigation of relationship to soil types and ecosystems; not meaningful for highly organic soils*
Filtering and Buffering	**Base saturation to 1 m depth**	**Indicates the 'reserves' left in the soil to buffer against further additions of, for example, acidifying substances**	**S, I, R**	**Change of between 10 and 15 % could be a starting point for discussion / a specialist indicator, not easy to 'sell' to a wider public**	**Limited data; might be derived from pedo-transfer functions but debatable; many different methods of measurement**	**Needs more data and investigation of relationship to soil types and ecosystems; not meaningful for highly organic soils**
Filtering and Buffering	Anion adsorption capacity	Indicator of the ability of the soil to retain substances such as sulphate and phosphate and possibly some pesticides	S, R	Not known / a very specialist indicator, not easy to 'sell' to a wider public; might not be easy to interpret	Not known; little investigated in the UK	Needs more data and research
Filtering and Buffering	*Concentration of 'Pollutant elements'*	*Indicator of stress, especially on the soil microbial population; potential links to food and water quality*	*(P), S, I, R*	*Magnitude of change is commonly judged in terms of total concentrations some of which are covered by regulation; most data are for urban or agricultural soils little is known for semi-natural environments / a popular indicator concept, but rates of change are slow and might not actually be very useful; could be difficult to resist politically*	*A number of survey data sets are available*	*Could be several indicators, one for each element (Cd, Cu, Zn, Cr, Pb, Ni, Hg, Se, As, radionuclides). There is considerable dispute about the value of 'total' concentrations; criteria for bioavailability require more research*

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Filtering and Buffering	*Concentration of organic pollutants*	*Indicator of stress, especially on the soil microbial population; potential links to food and water quality*	*(P), S, I, R*	*Not known with any great certainty for many soils and ecosystems / could be a popular indicator with a considerable political message*	*Some survey data are available*	*Could be several indicators based on single compounds or families of compounds; little is known about bioavailability; more research needed.*
Catching and releasing water	**The catchment hydrograph**	**Indicator of the change of catchment response to precipitation; increase prompt further investigation**	**P, S, I, R**	**Not known; could be derived from expert judgement and historical records / strong signal and easily presented although links to soils might not be as obvious as thought**	**Environment Agency data**	**Needs more research to make it a useful tool;**
Catching and releasing water	*Surface-water turbidity*	*Not a direct soil indicator; increase might indicate increasing catchment run-off, less infiltration, greater flood risk.*	*P, S, I, R*	*Not known / potentially a strong signal and easily presented although links to soils might not be as obvious as thought*	*Few time series data*	*Would need care in interpretation; increased turbidity might simply reflect more stream-bed disturbance for reasons not connected to soils.*
Catching and releasing water	Biological status of rivers with and without sewage treatment works.	Not a direct indicator; might be useful in identifying ‘pollutant’ stress.	P, S, I, R	Not known ?? / could be a strong signal if data could be interpreted clearly	RIVPACS data ??	Needs more research to relate findings to catchments and soils
Catching and releasing water	**Number of eutrophication incidents per year**	**Not a direct soil indicator, but a measure of surface water quality; might indicate ‘breakthrough’ of potential pollutants from soils, increase in run-off etc.**	**P S, I, R**	**Not known; might be related to water quality criteria in EU Directives / could give a strong, clear signal, easily understood, but links to soils might be difficult to demonstrate clearly**	**Environment Agency data**	**Needs care in interpretation; links to soils not always simple**
Catching and releasing water	*Topsoil surface condition, e.g. well-structured, capped, slaked*	*Indicates potential for change in infiltration capacity and hence greater or less run-off, erosion risk, stream sediment load, nutrient run-off*	*P, S, I, R*	*Not known / more of a specialist indicator, although could give a clear, strong signal to the land-based and water industries*	*Few UK data; might be related to soil erosion and similar field surveys with a scoring system for soil surface structural features*	*Needs further research; could be difficult to measure condition reliably due to effects of recent rainfall, cultivation etc.*

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Catching and releasing water	*Topsoil aggregate stability*	*Indicates general stability of the soil surface; relevant to erosion risk, run-off potential*	*S, I, R*	*Not known; large literature, but data are confounded by plethora of methods/ more of a specialist indicator, although could give a clear, strong signal to the land-based and water industries*	*Some UK data; might be related to soil texture and soil organic carbon matrix, but data are confounded by plethora of methods*	*Needs further research; could be difficult to measure aggregate stability reliably due to effects of recent rainfall, cultivation etc.*
Catching and releasing water	*Soil bulk density to 1 m depth*	*Indicates general degree of compaction of the soil surface*	*S, I, R*	*Not known; might be derived from national datasets / more of a specialist indicator, although could give a clear, strong signal to the land-based industries; might not actually change much over time*	*National soil databases; few for semi-natural sites or forested sites*	*Needs further work to analyse existing data and to put them into a useful framework; not certain of enough change over time to be a useful indicator*
Catching and releasing water / Foundation for the built environment	Topsoil plastic limit for most non-urban situations; to I m depth or more in the urban environment	Indicator of soil workability and structural stability; also relates to the bearing strength of the soil	S, I, R	Not known / more of a specialist indicator, although could give a clear, strong signal to the land-based industries; might not actually change much over time	Few UK data for extensive areas of soil; partly related to clay and carbon content – pedotransfer rules might be useful in some soils	More research needed, both on relationships to other soil properties, e.g. friability and dispersion and whether the property changes enough with time to be a useful indicator
Catching and releasing water	Time to ponding	Indicates the infiltration properties of the soil; relevant to water storage, run-off potential, flood risk	S, I, R	Not known; literature might yield some values / more of a specialist indicator; difficulties of reliable measurement make it less attractive	Few or no UK data	Could be difficult to organise measurements in the field at a suitable scale.
Catching and releasing water	*Water dispersible clay*	*Indicates the tendency of the soil to disperse under rainfall and / or mechanical disturbance; relevant to flood risk, run-off potential*	*S, I, R*	*Not known; research indicates 5% increase on a scale between 5% and 20% indicates a serious decline in stability / could give a clear strong signal if presented properly; might make a good indicator*	*Research data; not systematic national data*	*Small change over narrow range implies serious decline in soil structure; needs further research to validate this approach for a wide range of soils and land uses.*
Catching and releasing water	*Number of locations (all landscapes, not just agriculture) with erosion features*	*Indicates the area land which is has problems accepting precipitation and / or which is suffering from increased surface damage (or vice versa)*	*P (?), S, I, R*	*Not known; desk study of existing data could probably suggest a sensible value / could give a clear strong signal if presented properly*	*Research data; not systematic national data*	*This could be derived from a site-based scoring system and / or from remotely sensed data; needs more research; need to separate water from wind erosion; not just for agricultural land*

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Catching and releasing water	Integrated air capacity to 1 m depth	Indicator of the soil's ability to store water (to a given depth); relevant to water resources, erosion risk, flood risk	S, I, R	Not known – depends of soil texture class; starting point might be 10% change / a specialist indicator; not sure if it would show significant enough change to be useful	SSLRC data might be sufficient for some broad classification	Needs further work to assess usefulness across a range of soils.
Foundation for the built environment	**Area of greenfield land lost to development**	**Indicator of encroachment on the finite soil resource**	**P, S, I, R**	**Absolute changes need to be measured; expression as a percentage could give sense of false security / potentially a clear, strong indicator with considerable public resonance**	**National Census Data (Local Authority planning statistics ?); likely that remote sensing will have a bigger role in future**	**Ideally needs to be broken down by area of soil type lost, with the latter assessed in terms of potential function**
Foundation for the built environment	**Area of land / number of sites protected from development or number of sites, e.g SSSI's, ESA's, NVZ's and similar classes**	**Indicator of land protected for reasons of biodiversity, environmental quality improvement and related issues.**	**S, I, R**	**Absolute changes need to be measured; expression as a percentage could give sense of false security / potentially a clear, strong indicator with considerable public resonance**	**Numerous national datasets**	**Ideally needs to be broken down by area of soil type protected, with the latter assessed in terms of potential function**
Foundation for the built environment	*Area of land lost to mineral workings*	*Indicator of absolute loss of resource; certain types are of particular significance, e.g. soils over limestones, peat soils*	*S, I, R*	*Absolute changes need to be measured; expression as a percentage could give sense of false security / although equally strong and clear as the above, might not carry quite the same impact*	*Numerous national datasets*	*Needs to be broken down by area of soil type, with the latter assessed in terms of potential function; needs interpretation with care, e.g. loss of low quality land and restoration to biodiversity could be a benefit*
Foundation for the built environment	Topsoil bearing strength for non-urban situation; to 1 m depth to urban areas	Indicator of the ability of the soil to support (light) structures	S I (?), R (?)	Not known / a specialist indicator, unlikely to capture a public	Numerous site specific data; integration and assessment rare ?	More research needed; not certain if it would show meaningful overall change
Foundation for the built environment	*Pollutant load*	*Indicator of increase or decrease in level of potential contamination and its spatial extent*	*S, I, R*	*Absolute amounts need to be measured and converted to a deposition by mass / / would reflect many public concerns, but not easy to measure and relate reliably to soils*	*Reliable spatial data for urban soils are rare / in confidential reports; deposition data from NETCEN*	*More research required into urban soils; regulatory values might be a starting point for initial assessment*

Soil function	Indicator	Relevance of Indicator	Fit to D, P, S, I, R	Significant change / Advantage of Indicator	Data Source(s)	Additional Comment
Heritage / archaeology	**Change in the area of ploughed land**	**Indicator of potential damage to archaeological sites**	**P, S, I, R**	**Absolute change needs to be measured; expression as a percentage could give sense of false security / with proper presentation could make a powerful indicator with a strong, clear signal**	**Uncertain that current datasets are at fine enough resolution**	**More research needed into ways of acquiring high resolution data; area of change needs to be translated into number (and kind) of sites affected; simple national percentage would be insufficient**
Heritage / archaeology	**Change in cultivation depth**	**Indicator of potential damage to archaeological sites**	**P, S, I, R**	**Not known; small changes can be significant / with proper presentation could make a powerful indicator**	**No data ? could be derived from tine spacing ?**	**More research needed; soil type important**
Heritage / archaeology	*Area of land / proportion of sites with archaeological management plans*	*Indicator of potential risk of damage to sites*	*(P?), S, I, R*	*Not known; small changes could be significant / more of a specialist indicator but, with appropriate presentation could be a useful indicator*	*Not known*	*More research needed*
Heritage / archaeology	Sediment loss or redistribution from erosion events	Archaeological remains can be threatened by removal of soil by erosion and by deeper burial by re-deposited soil (especially if this has very different properties)	S, I, R	Not known, absolute measure of affected areas or number of sites affected might be required / probably not a strong indicator as effect on remains is difficult to assess	Erosion surveys might allow an estimate of the magnitude of the effect	More research required to see if there is a significant problem, its magnitude and whether it relates to specific soil types and regions
Heritage / archaeology	pH	Decline in soil pH (more acid) could threaten certain kinds of remains	S, I, R	Not known / probably not a strong indicator as effect on remains is difficult to assess	National soil monitoring data	Magnitude of any change would need to be assessed in relation to sites and soil types
Heritage / archaeology	*Potential soil moisture deficit (PSMD)*	*Change in this property over time, with anticipated climate change, may lead to greater ground heave (shrink-swell); this could threaten certain kinds of sites; increased water abstraction could have similar effects*	*S, I, R*	*Not known / could become an important factor, but translation into an indicator could be difficult (what would one do about it ?)*	*Could be modelled from soil and land use data*	*Needs further research to assess how many sites of what type might be affected and in which soils they are found*

13. CONCLUSIONS

the Project Team concludes that:

- the considerable literature on soil quality and soil quality indicators is heavily oriented towards agriculture and sustainable land use;
- there is a stakeholder view that the UK needs to move away from this 'agricultural' view to one which encompasses all soil functions;
- that most proposed indicators are actually reflections of state rather than function or process;
- that the UK needs to move to a 'goods and services' approach to soils;
- that these 'goods and services' are driven by soil function, i.e. what do we require a particular soil / combination of soils to do;
- that soil function is an open-ended concept, i.e. it should be revisited every time there is a proposed change in use of the soil;
- the DPSIR framework is a useful tool for focussing the questions that need to be asked about soil function;
- that the DPSIR framework is not, of itself, the vehicle to derive soil quality indicators as it is too cumbersome;
- that soil quality indicators could operate at three levels: measured soil properties linked to soil function, a group of environmental properties which affect a soil function, a high-level indicator which reflects how soils are functioning within a defined system;
- that the design of a soil monitoring network should reflect this hierarchy of soil quality indicators;
- that research should be put in place rapidly to bring the necessary information together to populate the indicators for a wide-range of soils and ecosystems;
- that this research should inform the design of a soil monitoring network over the next few years;
- that attention should be given to technological developments to make the measurement of soil indicators more feasible in the field, especially for biological indicators;
- that the concept and usefulness of chosen indicators and soil monitoring should be reviewed at approximately 5-year intervals.

14. LIST OF FIGURES

15. LIST OF TABLES

16. BIBLIOGRAPHY

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