Indicators of soil quality for UK forestry

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Summary

This paper briefly reviews the pressures on forest soils as essential parts of forest ecosystems, and the services expected of them. It reports the use of soil quality indicators in forestry world-wide, and makes recommendations for the utilization of direct and indirect (headline/surrogate/awareness) 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.

Introduction

‘Sustainable Forestry – the UK Programme’ (Anon., 1994), published by the government after the Earth Summit in Rio de Janeiro 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 in a sustainable way. Considerable guidance is available to encourage forest managers towards a responsible attitude in forest soil management. Nevertheless, soil 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, 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 a ‘soil quality indicator’ (SQI) has been put forward as an appropriate means to determine and establish a soil quality baseline including functional ability, from which changes can be observed as a result of pressures exerted on the soil. The soil quality concept has been proposed, tested or adopted in several countries, including the USA (Doran and Parkin, 1996), New Zealand (Lilburne et al., 2002), Europe (Council of Europe, 1992) and the UK (RCEP, 1996). Nevertheless, it has been challenged vigorously by some (Sojka and Upchurch, 1999; Davidson, 2000). In the UK, a consortium led by the Environment Agency recently commissioned research on the identification and development of a set of national SQIs, to be applied across all land uses, including forestry (Loveland and Thompson, 2002). Inevitably, there is a danger that in focusing in on one component of the ecosystem, a more holistic approach to sustainability will be endangered. Nevertheless, this
paper examines the possibilities and practicalities of using SQIs as a quantitative tool in measuring the sustainable use of UK forest soils, as part of a wider set of indicators which attempt to quantify forest ecosystem quality and sustainable development.

Soil quality indicators

In a recent review of soil quality indicators in the UK (Loveland and Thompson, 2002) it was proposed that indicators are useful only if they can be linked to the concept of soil function, and detection of change is likely in an appropriate time-scale. These precepts require understanding of:

• How soil systems work under optimal circumstances, i.e. what are the target values for an indicator which represent optimal function;
• What happens to the system and its functions and how this is reflected in values of the indicator when perturbation occurs;
• How far a system can be perturbed before change is irreversible. This is an estimate of resilience (Loveland and Thompson, 2002).

For forestry, relevant soil functions include:

• Biomass production (timber, above and below ground macro- and micro-flora and fauna);
• Filtering, buffering and transforming substances (pesticides, industrial emissions, wastes – beneficial or otherwise);
• Supporting biodiversity (links to biomass through above and below ground macro- and micro-flora and fauna);
• Catching and releasing water to surface and groundwater (interception of precipitation);
• Preserving heritage (archaeological and geological materials);
• Carbon sequestration;
• Providing a surface for multifunctional forestry activities, e.g. visitor access, forestry operations.

It is highly desirable that indicators can be fitted into a formal framework, in which to identify what shapes a system, what state or condition it is in, and how it might respond to an adjustment. This minimizes the development and use of indicators in an unstructured and/or divergent way.

One framework, the D(river)–P(ressure)–S(tate)–I(mpact)–R(esponse) (DPSIR) model (OECD, 1998) has been used recently by the European Environment Agency (Düwel and Utermann, 1999; Luiten, 1999), and was examined for its value as the basis for the development of SQIs in the UK in the Environment Agency study (Loveland and Thompson, 2002). However, much of the work on soil indicators refers, inevitably, to their ‘state’ only, i.e. their properties measured at some point in time (e.g. DETR, 1998; MAFF, 2000), or changes in state over a period of time. 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 and the direction of policy on soil management (Loveland and Thompson, 2002).

The international and national forestry policy perspective

The Montréal Process

The 1992 United Nations Conference on Environment and Development (UNCED) called upon nations to ensure sustainable development, including the management of all types of forests (United Nations, 1997). Following UNCED, Canada convened an international seminar of experts on sustainable development of boreal and temperate forests. This seminar, held in Montréal in 1993, 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 (see p. 549).

The Montréal Process is the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (Montréal Process Working Group, 1998). The member countries represent about 90 per cent of 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.

In February 1995, Montréal Process nations agreed to a large set of ‘criteria’ and ‘indicators’ (Table 1) for forest conservation and sustainable
management. There is one criterion specifically relating to the conservation and maintenance of soil resources, which can be measured by the following four indicators:

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

It is clear that none of the indicators above are based on specific soil properties, or can be used as a direct evaluation of soil quality; rather an attempt is made to quantify land area affected by degrading forestry practices. These are akin to ‘headline’ or ‘surrogate’ indicators (see p. 563). Individual member countries of the Montréal Process have taken forward their own thinking on how these indicators can be applied. For example, Australia has published useful guidance (Anon., 1998; Rab, 1999). Lack of systematic data has led to a number of interim indicators and approaches which are based, to a limited extent, on soil properties (Table 2). Nevertheless, no threshold values have been published.

The European dimension

The ‘Ministerial Conference on the Protection of Forests in Europe’ (MCPFE) is an initiative for cooperation of 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 (Liaison Unit Vienna, 2000).

The implementation of forest-related results of the UNCED Earth Summit was discussed at the Second Ministerial Conference, held in 1993 in Helsinki. Thirty-seven states and the European Community agreed upon a common definition of Sustainable Forest Management. At the First Expert Level Follow-up Meeting in 1994, pan-European criteria and indicators were proposed for evaluating progress towards sustainable forest management at the national level. These were consolidated at the next meeting of the MCPFE in 1998 (MCPFE, 1998) (Table 3). The set of criteria and indicators included both headline/surrogate indicators and also a few direct measurements of soil properties.

The UK position

The UK Forestry Standard was published in 1998 (Forestry Authority, 1998). It sets out standards for managing UK woodlands and forests, and includes criteria and indicators to be used in monitoring forests to check that they are being managed in a sustainable way. The UK Forestry Standard is compatible with the Pan-European system described above, but the criteria and indicators have been interpreted to put them into a UK context. Those that deal specifically with soil are shown in Table 4.

The forest management plan is the basic reference for monitoring assessment at this scale. At the forest scale, maintenance of soil quality is mainly exercised by adherence to forestry practices recommended as suitable by the Forestry Commission.

Since 1998, further development of the UK indicators has taken place, and a new set has been published recently (Forestry Commission, 2002). As with MCPFE, no threshold values have yet

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**Table 1: Definition of criteria and indicators used in the Montréal Process**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Criterion:</strong></td>
<td>A category of conditions or processes, by which sustainable forest management may be assessed. A criterion is characterized by a set of related indicators, which are monitored periodically to assess change.</td>
</tr>
<tr>
<td><strong>Indicator:</strong></td>
<td>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.</td>
</tr>
</tbody>
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Drivers and pressures and their impacts on UK forest soil quality

Following the DSIPR system, the principal drivers and pressures on UK forest soils are briefly discussed below. For convenience, they are discussed individually, but it is recognized that many inter-relate with one another. 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).

Forest establishment

Historically, forest plantations have tended to be located on comparatively infertile, poorly drained or thin soils in Britain. At a national scale, a disproportionate number are found on gleys and peats, and locally, individual forests tend to occur on the poorest soils in the region. In addition, many soils present pedological impediments to deep rooting, such as iron-pan 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 iron pans where necessary.

The effects of these practices on the water environment were appreciated in the 1980s and current UK guidance is far more restrictive in advocating minimal and shallow cultivation wherever possible (Paterson and Mason, 1999; Forestry Commission, 2000). Nevertheless, all...
types of cultivation affect soil conditions and functions, including the minimal types described above. In many respects, cultivation could be regarded as a means of increasing rather than degrading soil quality, and Paterson and Mason (1999) have recently summarized the main effects for forest soils. However, the potential for cultivation to promote obvious negative effects such as erosion and nutrient loss must be acknowledged. The ability of the soil to sequester carbon may also be compromised.

Harvesting

In contrast to forest establishment, when purposeful and, hopefully, beneficial intervention is made to the soil, harvesting operations are considered to have the most potential for the inadvertent degrading of forest soils. In the UK, harvesting is increasingly mechanized 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 (Greacen and Sands, 1980; Fisher and Binkley, 2000). These will have concomitant effects on other soil properties and functions. Limited research in the UK has confirmed that sensitive soils (principally gleys and peats) are prone to these forms of damage, and surveys have confirmed that it can take place. Nevertheless, to minimize damage to the soil, significant protection 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 (Wood et al., 2001; Hutchings et al., 2002).

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 density of roads is dependent on forest production, and will vary with size of woodland and species planted. Road location is greatly affected by surface drainage, topography and terrain, but soil type probably plays a small part in choice of location.

Tree growth and woodland development
Changes to soil properties and functioning are also caused by the growth of the trees themselves, notably where land-use changes from agriculture to forestry. In peat soils and some gleys, tree crops may cause irreversible shrinkage and cracking, leading to altered hydrological behaviour (King et al., 1986).

Atmospheric pollution
Concern that atmospheric pollution could adversely affect forest soils was first raised in the 1980s. Soil acidification demonstrably causes soil nutrient depletion and increased concentrations of aluminium which can result in toxicity. Due to the successful implementation of international abatement protocols, sulphur deposition is falling. However, acidification is still perceived as a threat because it also arises when nitrogen deposition is in excess of ecosystem demand. Nitrogen deposition, which is mainly a consequence of vehicle exhaust fumes, remains at elevated levels. Nitrogen pollution is a ‘double-edged sword’; in the medium term the so-called ‘fertilization effect’ may enhance growth, but with emissions left unchecked long-term acidification may occur (Aber et al., 1989). The result

<table>
<thead>
<tr>
<th>Criteria for sustainable forest management (SFM)</th>
<th>Source of national-level indicators</th>
<th>Forest management unit indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest soil condition 1. Soil changes in EU long-term monitoring plots 2. Annual statistics for afforestation of restored land Forest soil condition is stable or improving towards a more stable condition</td>
<td>Evidence that: 1. The use of cultivation, drainage, herbicides and fertilizers is selective with potential impacts taken into account 2. Anti-erosion precautions are planned and carried out in vulnerable situations 3. Pollution of soils is avoided by correct procedures for handling and disposal of substances and containers 4. Establishment, maintenance, harvesting and roading methods are chosen to minimize soil damage 5. Silviculture complements other measures designed to improve soils of damaged or reclaimed sites</td>
<td></td>
</tr>
</tbody>
</table>
is a system in which other macro-nutrients become limiting, a situation exacerbated by the fertilization effect of the nitrogen.

Although heavy metals exist naturally as products of mineral weathering in forest soils, potential anthropogenic sources include atmospheric pollution (mainly as a result of industrial activity during the twentieth century) and organic fertilizer application, such as sewage sludge and wood ash. The metals can become tightly bound 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.

Mayer (1993) has highlighted the potential for the build-up of organic pollutants in highly organic forest soils. Matzner et al. (1981), in Germany, found that polycyclic aromatic hydrocarbons in beech and spruce were almost 90 times higher in Oi/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 the mobilization of these compounds rendering them ‘ecologically active’ and free to enter living cells and water supplies.

Fertilizer application
Fertilizer application is not as common in forestry as it is in agricultural systems and the interpretation of fertilizer use as a pressure is therefore debatable. Indeed, fertilization for the successful establishment of first rotation stands on previously degraded agricultural land has been perceived as soil quality improvement (Fox, 2000). Prolonged use of fertilizers on agricultural land is known to cause soil acidification and can also elevate concentrations of metals such as cadmium. Therefore fertilization 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 a use to counter unsustainable biomass removal.

Pesticide use
Pesticide use in forestry is small (Moffat and Williamson, 1991). Pesticides are used primarily to prevent weed competition during the establishment phase. Improvements in pesticide legislation have removed use of the chemicals of the organo-chlorine group, which remain in the soil for several years. However, there remain concerns that modern pesticides, or their breakdown products, may still have the capability to affect non-target organisms and biological processes in the soil (UKWAS, 2000a).

Brash management
There is no doubt that, on certain sites, the fate of harvesting residues may be critical to the subsequent soil nutrient resource. Where brash is mounded or removed entirely from the site (whole tree harvesting), the potential is created for nutrient depletion, and concerns about Ca, P and K have been expressed (Dutch, 1993). Conversely, whole tree harvesting can be useful in areas showing visible signs of nitrogen saturation so it is not necessarily the case that residue removal is ‘bad’.

Climate change
Predicting the impacts of climate change on forest soils is difficult. Studies based on increases in temperature alone have suggested that mineralization and CO₂ release from the soil would increase, leading to a depletion in soil C stocks. However, increases in forest growth as a direct response to elevated CO₂ conditions (the so-called ‘CO₂ fertilization effect’) may sequester more carbon into the forest ecosystem. Other effects include increased nutrient demand as rising CO₂ drives growth rates, soil moisture deficits exacerbated by increased growth rates, a build-up of the products of mineralization during extended periods of drought, with subsequent heavy flushes during precipitation events (Nisbet, 2002). Secondary effects include higher wood densities which may affect decomposition, the introduction of new provenances altering soil chemistry and water demand, and improved growth resulting in reduced rotation length and an increased frequency of trafficking.
Conclusions concerning drivers and pressures on UK forest soil quality

Forest soils experience a range of drivers and 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, 1997, 2002; Malcolm and Moffat, 1996; Worrell and Hampson, 1997; Moffat et al., 1997). Of the threats to soil chemistry, eutrophication and acidification are probably the most serious, and worthy of monitoring (Emmett and Reynolds, 1996; Moffat, 2002; Kennedy, 2003). The main physical effects are due to harvesting operations, and may result in rutting, soil disturbance and possible soil compaction.

Historical use of soil quality indicators in forestry

One of the earliest soil quality standards and guidelines was developed by the US Forest Service (Griffith et al., 1992). Table 5 summarizes these guidelines for north-west North America (Page-Dumroese et al., 2000). 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 United States Forest Service (USFS) region regardless of soil or ecosystem properties.

Another comparatively early attempt to

Table 5: USFS soil quality standards for north-west USA

<table>
<thead>
<tr>
<th>Disturbance variable</th>
<th>USFS region*</th>
<th>Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil displacement</td>
<td>1</td>
<td>Loss of 2.5 cm of any surface horizon, usually the A horizon</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Loss of either 5 cm or 0.5 of the humus-enriched topsoil, whichever is less</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Loss of 50% of the A horizon</td>
</tr>
<tr>
<td>Compaction</td>
<td>1</td>
<td>Bulk density increase of 15%, usually in the A horizon</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Reduction of &gt;10% soil porosity or a doubling of soil strength</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>15% bulk density increase (volcanic soils: 20%)</td>
</tr>
<tr>
<td>Rutting and pudding</td>
<td>1</td>
<td>Wheel ruts at least 5 cm deep</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Ruts or hoof prints in mineral soil or Oa horizon</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Ruts to at least 13 cm depth</td>
</tr>
<tr>
<td>Erosion</td>
<td>1</td>
<td>Visual evidence of detrimental soil loss and maintenance of minimum (surface) ground cover based on local conditions (soil loss should be &lt;2–4 t ha⁻¹ a⁻¹)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Establish local minimum ground cover guidelines to limit erosion (not to exceed the natural rate of soil formation)</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Visual evidence of detrimental soil loss and maintenance of minimum ground cover based on erosion hazard class (not to exceed the soil formation rate)</td>
</tr>
<tr>
<td>Soil cover</td>
<td>1</td>
<td>Enough cover to prevent erosion from exceeding natural rates of formation</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Too little to prevent erosion from exceeding natural rates of formation</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>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)</td>
</tr>
<tr>
<td>Organic matter</td>
<td>1</td>
<td>Local guidelines developed based on ecological type</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Local guidelines developed based on ecological type</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Local guidelines developed based on ecological type</td>
</tr>
<tr>
<td>Burned conditions</td>
<td>1</td>
<td>Forest floor lost and A horizon has intense heating</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Loss of either 5 cm or 0.5 of litter layer, whichever is less</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Mineral soil oxidized and near 1.5 cm blackened due to charring of organic matter</td>
</tr>
</tbody>
</table>

*1 = Northern Region; 4 = Intermountain Region; 6 = Pacific Northwest Region (from Page-Dumroese et al., 2000).
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. 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 forest soil quality indexes:

- a physical index based on soil strength, that integrates soil density, structure and moisture content;
- a nutritional index based on laboratory analyses of soil mineralizable nitrogen, that integrates soil organic matter quality, content and microbial activity, and
- 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 indexes form the basis of a realistic system for monitoring soil quality that is also simple and economic.

Adams et al. (2000) recently proposed two soil 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 cation exchange capacity (CEC), base saturation, buffering capacity, measures of sulphate steady-state and N-saturation, and foliar nutrient levels. For the second, they suggested pH, base neutralizing 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. (2000) concluded that further work was necessary to establish this kind of system across the range of forest types in eastern USA.

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-Dumroese et al., 2000), and that site-specific information is important.
- Most effort has been expended on indicators as they relate to biomass production. Little effort has been given to the development of multi-functional indicators.
- Considerable research is necessary before meaningful thresholds can be erected, and it is important to evaluate whether this should form the basis of a research campaign, given the high cost and risk involved.

Suitability of forest soil quality indicators for the UK

Forest soil chemical indicators

Although there might be a prima facie case for choosing soil chemical indicators that are proposed or used in agriculture, there are significant differences as far as their use and assessment are concerned. Powers et al. (1998) and Fisher and Birkley (2000) have demonstrated that many analytical methods used in agriculture are 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 (Schonholtz et al., 2000). Inference is often used in the selection of soil chemical properties for quality assessment, despite a lack of critical threshold values. Henderson et al. (1990) pointed out that inductive indices are very dependent on our understanding of the underlying mechanisms.
In addition, forest ecosystems are naturally complex and perhaps too complex to expect soil quality indices that will relate to all pressures and drivers. Changes in soil quality indicators cannot be easily interpreted unless their relationship to important ecosystem processes (Smith and Raison, 1995) and, ultimately, productivity is known (Richardson et al., 1999).

For example, soil organic carbon is widely regarded as a structural and functional component of soil productive capacity and provides the critical link between management and productivity for both agricultural and forest soils (Henderson et al., 1990; Henderson, 1993; Nambiar, 1996; Burger, 1997; Schoenholtz et al., 2000). However, Nambiar (1996) pointed to the lack of quantitative relationships between soil organic matter and soil quality or forest productivity. Indeed, there are some cases of reduction in forest productivity associated with accumulation of soil organic matter (Grigal, 2000).

Similarly, because soil acidity influences so many biological and chemical relationships, soil pH provides little direct information about which soil process is critically affected and in turn critically affects the soil productive capacity and forest ecosystem productivity. Rather, pH is simply a surrogate for this complex of potentially nutrient-limiting processes (Schoenholtz et al., 2000). In forestry, UK research shows that the relationship between pH and yield often found in agriculture is less certain in forestry (Fourt et al., 1971; Moffat et al., 1997).

Site/yield studies are valuable in identifying important soil factors which determine and constrain tree growth (forest productivity). From such studies, one might expect the identification of useful quality indicators, and Table 6 reviews a selection. It should be appreciated that 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

<table>
<thead>
<tr>
<th>Table 6: Some examples of site/yield studies in forestry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
</tr>
<tr>
<td>Zutter et al. (1997)</td>
</tr>
<tr>
<td>Worrell and Malcolm (1990)</td>
</tr>
<tr>
<td>Tyler et al. (1995)</td>
</tr>
<tr>
<td>Shrivastava (1982)</td>
</tr>
<tr>
<td>O’Carroll and Farrell (1993)</td>
</tr>
<tr>
<td>Macmillan (1991)</td>
</tr>
<tr>
<td>Jokela et al. (1988)</td>
</tr>
<tr>
<td>Johnson et al. (1987)</td>
</tr>
<tr>
<td>Fourt et al. (1971)</td>
</tr>
<tr>
<td>Corona et al. (1998)</td>
</tr>
<tr>
<td>Blyth and MacLeod (1981)</td>
</tr>
<tr>
<td>Day (1947)</td>
</tr>
</tbody>
</table>
explain tree growth. Species may also differ in their response to different soil factors. Nevertheless, the results suggest that there are no consistent soil variables which relate to tree growth. Soil fertility, notably, does not materialize as a frequent explanatory factor, perhaps in contrast to agricultural studies of a similar kind. This may be for several reasons:

- total soil elemental measures such as N or P do not correlate with the plant available fraction;
- many tree species are conservative in their nutrient requirements, and are satisfied by supply;
- uptake from atmospheric sources confounds the relationship between soil supply and tree growth;
- 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 some soil measures. Foliar analyses reflect uptake and integrate across soil horizons which, in forest soils, may be starkly contrasting. They avoid difficulties of establishing the depth of soil required for evaluation, which partly depends on rooting depth.

In addition, concerns about declines in soil fertility are probably less founded in UK forestry than in agriculture. Use of fertilizers to remediate infertility in UK forestry is very small (Moffat and Williamson, 1991), and for some nutrients atmospheric inputs represent a large proportion of uptake and consequent removal from site at harvest. Forest soils generally hold on to plant nutrients, and losses from leaching, denitrification and volatilization are small, localized or infrequent when taking a forest stand and a rotation length into consideration (Moffat, 1991). Table 7 summarizes the chemical indicators most commonly encountered in the scientific literature along with comments on their general suitability for forest soils.

**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, but are valuable for soil characterization. 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 soil physical properties that seem to be most important for further consideration as forest soil indicators are given in Table 8.

**Forest soil biological indicators**

The inadequacy of soil chemical properties in explaining tree growth or response to fertilizer 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 9). Four critical barriers to the development and use of suitable indicators were identified:

1. indicators must have ecological relevance;
2. indicators should be properly documented across various ecosystems;
3. indicators must be easy to 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 9 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.

---

**Table 7: Common soil chemical quality indicators, and comments on value for forest soils**

<table>
<thead>
<tr>
<th>Soil chemical property</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon</strong></td>
<td>Pivotal role in many soil functions which may be its downfall – it is unclear if detected changes would inform the user. For example, supporting indicators reflecting climate change and acidity status would also need to be erected.</td>
</tr>
<tr>
<td>Organic C and organic matter, O layer depth</td>
<td></td>
</tr>
<tr>
<td><strong>Nutrient availability</strong></td>
<td>Total N and C : N ratio are probably the most useful. Potential mineralizable N requires further investigation. The different forms of N vary too much naturally over a rotation. 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 tree growth associated with climate change may mean these become increasingly limited and could be of more value for the future.</td>
</tr>
<tr>
<td>N: total, organic, mineralizable (potential or actual), extractable NH₄, NO₃, C : N ratio</td>
<td></td>
</tr>
<tr>
<td>P: Mineral, extractable, Bray, P sorption</td>
<td></td>
</tr>
<tr>
<td>K: Exchangeable and extractable</td>
<td></td>
</tr>
<tr>
<td><strong>Cation exchange capacity (CEC)</strong></td>
<td>A useful general indicator of the soil's capacity to supply nutrients (excepting N).</td>
</tr>
<tr>
<td><strong>Nutrient balances</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Soil acidity</strong></td>
<td>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 in a UK context.</td>
</tr>
<tr>
<td>pH</td>
<td></td>
</tr>
<tr>
<td><strong>Acid neutralizing capacity (ANC)</strong></td>
<td>More valuable than pH in terms of interpretation, but requires analysis of full suite of acids and bases in the soil.</td>
</tr>
<tr>
<td>Base saturation and Ca : Al ratio</td>
<td>Fairly established indicators for which limits have been extensively debated.</td>
</tr>
</tbody>
</table>
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 good start has been made in...

**Table 8**: Common soil physical quality indicators, and comments on value for forest soils

<table>
<thead>
<tr>
<th>Soil physical property</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil depth/depth to permanent waterlogging</td>
<td>Unlikely to change dynamically; important baseline characterization</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>Important for characterizing forest soil type; useful in pedotransfer functions</td>
</tr>
<tr>
<td>Bulk density</td>
<td>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</td>
</tr>
<tr>
<td>Surface topography/rutting</td>
<td>Invaluable indicator of soil damage by poor husbandry, and susceptible to routine monitoring</td>
</tr>
<tr>
<td>Available water capacity</td>
<td>Important measure of plant available water; likely to be affected by malpractices such as untimely trafficking</td>
</tr>
<tr>
<td>Soil strength</td>
<td>Related to rootability, but dependent on soil water content, making variable difficult to use for monitoring purposes</td>
</tr>
<tr>
<td>Erosion/deposition</td>
<td>Very site/time-specific and incapable of insertion 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</td>
</tr>
<tr>
<td>Aggregate stability</td>
<td>Not important in forest soil quality</td>
</tr>
<tr>
<td>Infiltration capacity</td>
<td>Valuable for assessing water access into soil, but unimportant in a forestry context (unlikely to be useful as an indicator of soil quality); forest cultivation, drainage and rotation stage much more important in determining surface water characteristics</td>
</tr>
</tbody>
</table>

**Table 9**: Potential biological indicators for forest soil quality monitoring (from Staddon et al., 1999)

<table>
<thead>
<tr>
<th>Category</th>
<th>Potential microbial indicators of soil quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microbial biomass</td>
<td>Direct counts; Muramic acid; Ergosterol; Fumigation – incubation; Substrate-induced respiration; Phospholipids; C and N; Biomass C/total organic carbon</td>
</tr>
<tr>
<td>Soil enzymes</td>
<td>Dehydrogenase; Phosphatase; Arylsulfatase; Arginine</td>
</tr>
<tr>
<td>Activity measurements</td>
<td>Respiration; ( q_{\text{CO}_2} )</td>
</tr>
<tr>
<td>Microbial community structure</td>
<td>Sole-carbon source utilization; Phospholipids; Nucleic acids; whole population DNA amplification of specific genes by PCR</td>
</tr>
<tr>
<td>Indicator organisms/process</td>
<td>Nitrifying bacteria/nitrification</td>
</tr>
</tbody>
</table>
the investigation of the 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.

**Challenges in using soil quality indicators in forestry**

*Spatial variability*

Compared with agricultural soils, forest soils are notorious for their spatial variability (Mader, 1963; McFee and Stone, 1965; Blyth and MacLeod, 1978; Quesnel and Lavkulich, 1980; Arp and Krause, 1984; Riha et al., 1986). 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 lead to uneven soil disturbance, and woodland animals also disturb the soil. Finally, cultivation may increase or decrease soil homogeneity, depending on scale and frequency. Such variability requires particular attention to soil sampling design, and number of samples to be taken to express a mean tendency accurately.

*Temporal changes*

That forests are dynamic ecosystems cannot be overlooked in a discussion on indicators. Plantation forests are not climax communities – they are usually planted on ex-agricultural or marginal land unfit for agriculture. Many 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 throughout a rotation as the crop moves through distinct stages of nutritional demand and light, water and pollutant interception capacities (Miller, 1981). These hypothesized stages are reflected in chronosequence studies of forest soil chemistry. For example, both Paré and Bergeron (1996) and Fons and Klinka (1998) found decreasing pH and N mineralization 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 period up to canopy closure. Some soil properties, such as pH, may be expected to stabilize in the long term if the land remains under forestry, whereas others, e.g. C, N and organic matter volume, may 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. Comparatively recently forested stands planted on ex-agricultural land cannot be expected to conform to any indicator threshold considered ‘typical’ for forestry.

These growth cycle changes will be further compounded by the effects of management such as thinning. Annual measurements are not sensible: 5- or 10-year 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.

**Consequences of spatial and temporal variability**

Establishing temporal changes in forest soil indicators based on soil property 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 (1) the soil property measured, and (2) 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, e.g. 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 mineralization (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.

**Soil quality indicators for multifunctional forestry**

Understandably, most effort in the development of soil quality indicators for agriculture and forestry has centred on biomass production. However, in an era where the multifunctional aspects of forests are stressed (e.g. Forestry Authority, 1998), there is obvious interest in examining whether SQIs can also inform on other soil functional abilities. In Table 10, possible relationships are identified between important forest soil functions and those SQIs which have already received attention, or are most likely to do so. It is clear that, while some indicators may have some value in informing on several soil functions, many indicators will be required to cover fully the range of functions identified. In addition, some functions such as preserving heritage are poorly served by conventional indicators, and additional ones may need to be developed. The difficulty of using SQIs to quantify soil quality in a multifunctional manner (Sojka and Upchurch, 1999) is endorsed in this examination.

**Information on forest soil quality 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, b). These were revisited in the 1970s and 80s (Howard and Howard, 1984, Anderson, 1987). A fortuitous ability to study soil change under forests was taken by Billett et al. (1988, 1990a, b, 1991, 1993) under coniferous forest in northeast 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. Johnston et al., 1986; Goulding et al., 1988; Blake et al., 1999). Smaller studies have been undertaken, for example by Moffat and Boswell (1990) and Wilson et al. (1997).

In recent years, systematic study of soil change has been facilitated in two main ways:

- **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 2 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 2 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 there will be a repeat exercise after about 15 years. 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.

In addition, there is a National Soil Inventory dataset for England and Wales based on soil evaluation at the 5-km grid density (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.

It is clear that existing monitoring networks have the capability to support some soil chemical monitoring. However, soil physical and biological monitoring is not part of the protocols for the sites, and they have not been set up to encompass these types. 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 on which to build 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
### Table 10: Relationships between forest soil functions and possible soil indicators

<table>
<thead>
<tr>
<th>Forest soil function</th>
<th>Chemical indicators</th>
<th>Physical indicators</th>
<th>Biological indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Organic carbon</td>
<td>Nutrient content</td>
<td>CEC pH</td>
</tr>
<tr>
<td>Biomass production</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Filtering, buffering and transforming substances</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Supporting biodiversity</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Catching and releasing water to surface and groundwater</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Preserving heritage</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Carbon sequestration</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Providing a surface</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
</tbody>
</table>

CEC = cation exchange capacity, ANC = acid neutralizing capacity, PSD = particle-size distribution, AWC = available water capacity.
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 coordinates 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 (Technical Development Branch, 2000) has already been used by the Forestry Commission for assessing soil disturbance during harvesting operations.

**Surrogate, headline and awareness soil indicators for forestry**

In the absence of a comprehensive system for obtaining information on forest soil state or functioning ability, some have proposed that other non-soil data can be used to help inform on soil protection, and maintenance of quality. These are termed ‘surrogate’ indicators. Other indicators can be used to establish the scale of forestry impact. For example, knowledge of land area under forests and woodland allows forest soil protection policies to be placed in context with those for, say, agricultural land. These are called ‘headline’ indicators. A third group of ‘awareness’ indicators can be used to evaluate the degree to which awareness of forest soil quality and protection is being taken up. Table 11 contains potential indirect 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 Forest Enterprise Districts, Forestry Commission Conservancies or UKWAS (UKWAS, 2000b). Nevertheless, it must be appreciated that, although such indicators may help to play a part in the soil protection debate, they are no substitute for the installation of a set of soil indicators based on sound scientific principles.

---

**Table 11: Possible headline, surrogate and awareness indicators for soil quality**

<table>
<thead>
<tr>
<th>1. Area under forest/woodland – headline indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. Area of forest/woodland on specific soil types (reliant on 1:250 000 soil maps)</td>
</tr>
<tr>
<td>1.2. Area of forest/woodland on brownfield land</td>
</tr>
<tr>
<td>1.3. New planting (ex agricultural land)</td>
</tr>
<tr>
<td>1.4. General yield class by subcompartment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Area of forest/woodland managed to specified standard – possible headline indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Area with UKWAS accreditation</td>
</tr>
<tr>
<td>2.2. Area supported by Woodland Grant Scheme (WGS)</td>
</tr>
<tr>
<td>2.3. Areas of ancient and semi-natural woodland categories</td>
</tr>
<tr>
<td>2.4. Area with biodiversity/conservation management plans</td>
</tr>
<tr>
<td>2.5. Area with archaeological management plans</td>
</tr>
<tr>
<td>2.6. Area managed by ‘Continuous Cover Forestry’</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Surrogate indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1. Foliar analysis (for soil fertility)</td>
</tr>
<tr>
<td>3.2. Stream sediment via colour/turbidity (for soil erosion)</td>
</tr>
<tr>
<td>3.3. Stream chemistry (for soil loss)</td>
</tr>
<tr>
<td>3.4. Input–output nutrient budgets (Ranger and Turpault, 1999)</td>
</tr>
<tr>
<td>3.5. Forest industry fertilizer and pesticide use</td>
</tr>
<tr>
<td>3.6. Ground vegetation (Wilson et al., 2001)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. Awareness indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1. Uptake of ‘Forests and Soil Conservation Guidelines’ and other soil-related Forestry Commission publications</td>
</tr>
<tr>
<td>4.2. Number of hits/downloads to/from the Forestry Commission website on soil-related material</td>
</tr>
</tbody>
</table>
Conclusions

UK forestry has a clear need 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) has already produced a list of criteria and indicators under the umbrella of continual development of the UK Forestry Standard (Forestry Commission, 2002). Some of these relate to soil quality both at 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 forest monitoring networks which are already used to inform on the sustainable use of forest soils. These could be utilized 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 (Loveland and Thompson, 2002) should be compatible with the requirements identified above. 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. This is equivalent to the quality soil management concept of Sojka and Upchurch (1999).

Forest ecosystems are complex. More chronosequence studies to develop our understanding of 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 except in specific or local circumstances. ‘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 will be necessary to provide such information, and in many cases a judgement must be made as to whether this research would be cost effective. Biological indicators have considerable potential due to their predictive (rather than responsive) capacity, but further research in this area is necessary before these indicators can become useable. This paper 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.

Acknowledgements

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