CENTRE FOR ECOLOGY AND HYDROLOGY
(Natural Environment Research Council)
Defra Contract SP1607

Appendix 1. Defra Soil Protection Research in the Context of the Soil Natural Capital / Ecosystem Services Framework.

Report to Defra for Project SP1607: Synthesis of Soil Protection work 1990-2008.

Final Report

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Contents

Summary:

"A Nation that destroys its soil destroys itself."

This quote from, F.D. Roosevelt, 1937, from a letter written to all state Governors in the USA following the dust bowl, encapsulates the importance of soil protection. The dust bowl brought about legislation to protect and conserve soils as a fundamental natural resource in the USA between 1930 and 1936. In current times we are facing unprecedented pressure on land resources from multiple uses here in the UK and across Europe. In response to these increasing pressures Defra has produced soil protection reports and strategies including the report, ‘Safeguarding our Soils: A Strategy for England’ (PB13297). The vision statement of this document reads, ‘By 2030, all England’s soils will be managed sustainably and degradation threats tackled successfully. This will improve the quality of England’s soils and safeguard their ability to provide essential services for future generations.’ Similarly, the Welsh Assembly Government commissioned, ‘The Welsh Soils Action Plan’ (WSAP, 2009) which has a similar goal. These documents set out the pressing issues with regard to soils, their management and protection, and therefore serve as a useful contextual tool for synthesizing past Defra research with regard to current issues.

This report synthesises soil protection research commissioned by Defra between 1990 and 2008, to provide the state of current Defra knowledge with regard to soil protection. Contextually, an attempt is made to fit the synthesized knowledge into the Natural Capital / Ecosystem Services framework. It offers a bold, fresh approach that will orient the report firmly in the context of strengthening the linking of science and policy through Natural Capital and Ecosystem Services, and firmly aligns the research with ongoing EU efforts. The report is comprised of 5 work packages for Defra project SP1607 “Defra research on soil protection 1990 - 2008: Synthesis of outputs’. Defra has made a firm commitment to adopt the ecosystems approach which is designed to convey the value of ecosystems, their capital, and their goods and services into the decision making / policy development process.

The workpackages address the following:

WP1:
Chapter 1) Place England and Wales soil policy and research efforts in the wider context of European and International policy.
Chapter 2) Identify and synthesize knowledge of needs of farmers, resource managers and the wider society.
Chapter 3) Describe the soil natural capital / ecosystem services framework.

WP2:
Chapter 4) Evaluate current indicators and soil sampling/measurement strategy.
Chapter 5) Evaluate work done on the quantification of soil capital.
Chapter 6) Evaluate work done on the soil Ecosystem Services.

WP3:
Chapter 7) Identify Impact of climate change on soils, soil function, and threats to soil protection.
Chapter 8) Identify threats to soils, for the England and Wales context; Evaluate research tackling threats that may degrade soil capital or reduce services.

WP4:
Chapter 9) Evaluate work done on the valuing of soil Natural Capital.

WP5:
Chapter 10) Future Vision.

1) Place England and Wales soil policy and research efforts in the wider context of European and International policy.

Unlike water and air, soils often receive little attention in terms of resource protection. This has been recognised in policy terms starting with the Royal Commission on Environmental Pollution (RCEP) report on ‘The Sustainable Use of Soils’ (RCEP, 1996). The most recent soil strategy for England published by Defra in 2009 (SSSE) (PB13297) and the Welsh Assembly Government’s Welsh Soil Action Plan consultation document (WSAP) (WSAP, 2009) outline the strategic importance of soils to England and Wales, in terms of maintaining food, and fibre production, combating climate change, and maintaining biodiversity and attractive landscapes, all vital to the sustainability and growth of the UK economy. Given the multifunctional role of soils and their importance to a diverse, and growing, UK population, there is increasing pressure to safeguard this important natural resource. Part of this effort is ensuring that soil continues to function in a way that meets all the diverse usage requirements that include production (e.g. agriculture), cultural (e.g. recreational) and environmental (e.g. ecological & hydrological) functions.

Mankind is demonstrating an ability to alter and transform landscapes at an unprecedented rate; severely impacting our natural resources and altering the function of the earth system through climate and land-use change. Our ability to damage, but also to repair, the earth system is demonstrated globally through the development of the hole in the atmospheres ozone layer, and the global effort to ban CFC’s and restore the layer. In the UK, industrialisation increased acidification of soils and freshwaters in the 1970’s, which has been observed to have reversed due to reduced atmospheric inputs (RoTAP 2010). Soils, like water and air, are subject to ‘change’ on anthropogenic time scales, due to pressures from a range of drivers. Identifying ‘soil change’ and the consequences, is a priority for maintaining the function of the soil resource.

Increasingly, global treaties are developing to protect our environment, natural resources, and functioning of our earth system. Some of this legislation directly impacts soils, for instance, the UK’s agreement to monitor and reduce carbon emissions under the Kyoto Protocol. The importance of soils to carbon mitigation is demonstrated by the calculation that a 1% loss of carbon from UK soils would be equivalent to the UK’s annual fossil fuel emissions (PB13297). Legislation on water and air, brought about because of impacts on human health and the environment, is in place across the European Union, and continually evolves.

In the UK, soil protection strategies for England and Wales have identified major issues relating to soil protection. Safeguarding our Soils: A Strategy for England (Defra, 2009) begins with an executive summary outlining the major threats to soils in England, which are identified as:

- **Soil erosion by wind and rain**
- **Compaction**
- **Organic matter decline**

In the subsequent chapters it makes the case for the importance of safeguarding our soils, and outlines areas of protection of strategic importance to England:

> Safeguarding our soils
> Better protection for agricultural soils (1)
> Protecting and enhancing stores of soil carbon (2 and 8)
> Building the resilience of soils to a changing climate
> Preventing soil pollution (6)
> Effective soil protection during construction and development (3 and 7)
> Dealing with our legacy of contaminated land (6)
> Future research and monitoring

The numbers at the end indicate how each theme corresponds with subsequent threats identified at EU level by the EU Thematic Strategy.

In Wales, the Welsh Soil Action Plan consultation document highlights the principle threats to Welsh soils as being:

Climate Change and Decline in Organic Matter (2)
Soil Loss to Development (Soil Sealing) (7)
Contamination, Diffuse and Gross (including Acidification and Eutrophication) (6)
Soil Erosion (1)
Degradation of Soil Structure (3 and 2)
Soil Loss by Extraction

In later chapters of the Welsh Soil Action Plan consultation document, it goes on to specifically address the issues of, 'Soils and Climate Regulation'; 'Water Resources and Flood Risk Management' and 'Support of Biodiversity' within the ecosystem services context.

Concurrently, at the EU level, soils are increasingly regarded as an important natural resource to be protected. The European Commission has a 'Soil Thematic Strategy' regarding soil protection (COM(2006) 231). "The Communication (COM(2006) 231) sets the frame. It explains why further action is needed to ensure a high level of soil protection, sets the overall objective of the Strategy and explains what kind of measures must be taken. It establishes a ten year work program for the European Commission." "The proposal for a framework Directive (COM(2006) 232) sets out common principles for protecting soils across the EU. Within this common framework, the EU Member States will be in a position to decide how best to protect soil and how use it in a sustainable way on their own territory." "The Impact Assessment (SEC (2006) 1165 and SEC(2006) 620) contains an analysis of the economic, social and environmental impacts of the different options that were considered in the preparatory phase of the strategy and of the measures finally retained by the Commission." The EU Soil Thematic Strategy identifies 8 major threats to soils including, erosion, organic matter decline, compaction, salinization, landslides, contamination, sealing, and biodiversity decline. Based on the Impact Assessment (SEC(2006) 620) these threats are estimated, on an annual basis, to cost the EU:

- 1) erosion: €0.7 – 14.0 billion
- 2) organic matter decline: €3.4 – 5.6 billion
- 3) compaction: no estimate possible,
- 4) salinisation: €158 – 321 million
- 5) landslides: up to €1.2 billion per event
- 6) contamination: €2.4 – 17.3 billion
- 7) sealing: no estimate possible
- 8) biodiversity decline: no estimate possible

Most of the threats identified at an EU level correspond with threats identified for England and Wales. Salinisation and landslides, due to their low impact in England and Wales are not considered priorities as they are in other EU countries. Protecting carbon stores is a major priority in England and Wales, given the importance for soil structure, nutrient retention and mitigating climate change. Preventing erosion, pollution and sealing are also seen as major priorities. The Welsh Soil Action Plan consultation document and Safeguarding our Soils: A Strategy for England bring out the importance of certain issues in the respective countries that the broader EU threats may not emphasise, for instance in Wales soil acidity is a big issue with regard to maintaining fertility, where as in the arable soils of England building resilience into soils is seen as a best approach to maintaining soil quality whilst providing food production.

Within the UK, the Ecosystems Approach, which includes the Natural Capital / Ecosystem Services framework (Costanza et al., 1993; Daily et al., 1996) is increasingly recognized as a useful tool for enhancing the interface between scientific research and policy/decision making. The UK is currently undertaking a National Ecosystem Assessment (NEA, 2009), in addition the Natural Capital Initiative published a first report in 2009 (Anon, 2009) on the symposium held that year. Though soils are often referred to, they fail to maintain the resource profile like water and the atmosphere. It is this lack of profile that contributes to difficulties in protecting the soil resource at the national level. By integrating soils with the Natural Capital / Ecosystem services framework it should help to raise the awareness of soils at the national level, and make work done on soils more easily integrated into developing policy tools. The aim of the framework is to identify the value of natural services provided by ecosystems so that decision making can evaluate the full social and economic benefit of an ecosystem. This concept is in its infancy as applied to soils, but provides a useful and important tool for identifying the value of capital and services obtained from the soil resource. It is important for soil protection to transition into this area given Defra's policy of embedding the ecosystem approach (PB12853).

Aims and Objectives of this Report:

The aim of this report is to synthesise Defra commissioned research between 1990 and 2008 in the context of the general themes that arise from soil protection strategies, using the Natural Capital /Ecosystem Services framework.

This will be met through the following objectives:

I) Identify, evaluate and synthesise Defra soil protection research (1990 and 2008), providing the state of current knowledge with regard to the emphases in soil protection strategies for England and Wales.
II) Use the Natural Capital / Ecosystem Services approach as a contextual framework for the synthesised information.

References

Defra reports:
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PB12853 Securing a healthy natural environment: An action plan for embedding an ecosystems approach
PB13297 Safeguarding our soils a strategy for England

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2) Identification of policy statements and research needs with regard to soils.

The soil resource must be capable of fulfilling multifunctional uses across England and Wales. It is therefore important to understand the knowledge needs that landowners perceive to be important in order for them to best manage their land. Understanding, and input from stakeholders, can help to inform and prioritise soil protection strategies.

Key findings:

- In general soil is not recognized as a resource with an intrinsic value, but a resource whose value depends on function (e.g. production, climate regulation), which depends on Government priorities.
- National soil policy is perceived as being biased toward environmental protection (climate change) by some sectors. They would like to perceive policy as having a more holistic approach to managing and protecting the soil resource, recognising both its agronomic and ecological functions in support of the earth-system.
- Press articles highlight food production, habitat and environmental protection, and human health protection as important public issues.

Synthesis of Policy Statements and Knowledge Needs

The soil resource does not conjure the same preservation stimulus, as for instance certain ecological habitats do; nor is it viewed by an increasingly urban wider society as a vital resource like air or water, without which life would not exist as we know it. As such, it tends to be valued in response to functions it fulfils, rather than having an intrinsic or inherent value. The non-governmental organizations (NGO's) considered, indicate that soil policy tends to be driven by wider Government objectives, e.g. climate change, rather than because soils are viewed as a resource worthy of protection as a habitat, process moderator and life support system, in the way we value air and water.

An analysis of the topics of importance within Government bodies regarding soils indicates a firm emphasis on the relationship between soils and the atmosphere, with regard to both climate change and non-point-source pollution. In addition, the protection of soil biodiversity is apparent. Some organisations interpret this as bias toward ecological function of soils more than the production function. This perhaps indicates that the importance of biodiversity and the gene pool for all functions has not been fully communicated. For instance, the understanding that much of modern medicine with regard to antibiotics was dependent on the isolation of soil organisms is not widely known. Both landowners (e.g. RSPB), and NGO's (e.g. NFU and the Soil Association), clearly articulate the need for a holistic approach to soil management including physical, chemical and biological aspects. NFU in particular emphasises the need for training, education and knowledge transfer.

The national press provides an interesting barometer of issues of interest to the public at large. Soils *per se*, rarely make the headlines. Of a survey of 5 main broadsheets (2005-2010), only 12 articles regarding searches on soil were identified outside of gardening. However, they identify questions of national importance, including, the sustainability of food production with regard to nutrient mining and water use; the stores of soil carbon with regard to climate change; the use of precision agriculture to manage soils; the unknown impact of nano-particles on human health in the soil and water environment; protecting soil biodiversity as a resource and potential source of pharmaceuticals, and the unknown consequences of introducing GM plants for food production.

Evidence for the Synthesis

Increasing population pressure in the UK and changing societal pressures on land in the UK, which include a mix of recreation, infrastructure, food production, preservation and environmental concerns, require that soils fulfil multi-functional roles. Major functions identified in report (LQ06-Sniffer) include, food and fibre production; environmental interaction (earth system regulation); support for ecological habitat and diversity; provision of raw materials; protection of cultural heritage and archaeology; and providing a platform for the built environment. In the following section we draw together differing perspectives and statements made about soils that cover the UK and are pertinent to England and

Wales, and aim to draw out the knowledge requirements for managing soils to maintain function and protect against loss or degradation.

Perspectives on soils - Major Land Owners in the United Kingdom

Finding recent data that explicitly identifies major institutional land ownership in England and Wales is difficult. However, recent figures are available for the United Kingdom's largest landowners, and this provides an indication of the largest landowners in England and Wales; the Forestry Commission, the Ministry of Defence, and the National Trust top the list. The top 10 institutional landowners as of 2001 are presented in Table 2.1. Of these we focus on the Forestry Commission, MoD, National Trust for England and Wales, The Crown Estates and the RSPB, which all have centralized organization.

Table 2.1 Top institutional landowners in the UK as at 2001, adapted from Cahill (2001). Italics denote relevant to Scotland only.

Institutional Landowner UK	**Estimated acreage**
The Forestry Commission	2,400,000
The Ministry of Defence	750,000
The National Trust for England and Wales	550,000
The Pension Funds	500,000
The utilities: water, electricity, railways	500,000
The Crown Estate	384,000
The County Farms	300,000
Scottish Dept Agriculture	*281,355*
The RSPB	275,000
The National Trust for Scotland	*176,000*

Forestry Commission: The Forestry Commission conducts and supports research into the protection and sustainability of forest soils. The Government publication 'Sustainable Forestry - the UK Programme' acknowledges that the soil is an important part of the forest ecosystem, and must be used 'sustainably'; guidance for soils in forestry is provided in the UK forestry standard (Anon, 2004). Human actions, from local-scale forest operations to international scale air pollution may compromise forest soil sustainability. Forestry Commission policy is to develop and implement practices to prevent soil degradation. Current guidance is given in the Forests and Soil Conservation Guidelines (Anon, 1998). Areas of particular interest include, nutrient cycling, impact of harvesting, 'acid rain' / non-point-source atmospheric pollutants, climate change, carbon sequestration and identifying soil quality indicators.

Ministry of Defence: The MoD provides a comprehensive set of 'Sustainability and Environmental Appraisal Tools' through their Sustainability and Environmental Appraisal Tools Handbook (Powell et al., 2006). Their policy specifically addresses soils and is clearly developed for the protection of soil function based on the EU soil threats. In particular they identify impacts through military vehicle trafficking, construction and engineering works, contamination from ordinance, chemical, fuel handling, or waste management.

National Trust: The National Trust outlined a soil protection strategy in 1999 (Anon, 1999). Contained in the strategy, they identify activities of concern with regard to soil protection, these include, under agriculture, arable farming, livestock production, land drainage, eutrophication, acidification and contamination; forestry, conifer plantations impacting native communities ; recreation, paths and car parks (soil sealing erosion); atmospheric pollution, soil acidification; and extraction, peat cutting.

Crown Estates: The majority of The Crown Estates land is held under agricultural tenancies; as such The Crown Estate has limited direct influence over soil management activities undertaken by their tenants. However, they take an active role in facilitating and promoting best practice in land management through the adoption of agri-environment schemes and compliance with regulatory provisions, through an integrated approach. Woodland and commercial forest management is consistent with the Forestry Commission (FC) Forest and Water Guidelines and the UK Woodland Assurance Standard (UKWAS) – which set the framework for the management of Crown Estate forest soils. The Crown Estate is developing strategies for the management of forests located in areas where there are soils with a high carbon content as part of their forest management policy – and this relates very closely to best practice promoted by the Forestry Commission (Chamberlain and Wells, 2010, personal communication).

Royal Society for the Protection of Birds: The RSPB has over 1 million members in Europe. The Society manages the largest number of conservation estates in the UK, covering more than 100,000 hectares with 19,000 in Wales. Recent emphasis has been on carbon-sensitive management of soils and the maintenance and protection of biodiversity, where in partnership with Countryside Council for Wales (CCW), the Environment Agency Wales and the Forestry Commission Wales, they have been actively involved in projects aimed at restoring active blanket bog in Welsh uplands. With regard to land management in farming RSPB states that farming can be good or bad, “For example, the soil on a farm can be managed so that it stores, filters and recycles carbon, rainwater and nutrients, or so that it erodes, loses fertility or compacts, losing its value.” (Anon, 2010); which indicates the need for a rounded knowledge of soil management including water, nutrients and organic matter.

Perspectives on soils - Government and Bodies Involved with Soil Policy or Management in England and Wales

Parliament: the Parliamentary Office of Science and Technology produced a postnote (Butler, 2006) entitled, UK soil degradation, stating, “Soil degradation involves both the physical loss (erosion) and the reduction in quality of topsoil associated with nutrient decline and contamination.” The note highlighted the following areas of concern:

- Physical degradation (erosion, loss of structure, surface sealing and compaction);
- Chemical (pollution) and biological (loss of soil organic matter and biodiversity) degradation;
- Climate and land use change (which may accelerate the above factors).

Natural England: manages over one million hectares of land that have been identified as “special” for their habitats, plants, animals or geology, representing the best examples of natural features throughout England. There are 4,114 Sites of Special Scientific Interest (SSSIs) in England, these include wetlands, heaths, bogs, woodlands and other habitats. Natural England has produced a draft position statement on soils that outlines the importance of protecting soils in England. It recognises that, ‘Soil should be valued as a finite multi-functional resource which underpins our well being and prosperity’ (NE, 2009) In addition to recognizing the importance of the EU soil threats, their statement also identifies the importance of understanding changes in soil moisture due to climate change, the links to ground water and its protection, and nutrient cycling.

Countryside Council for Wales: (CCW) has been actively involved in promoting the sustainable management of soils, especially with the Welsh Assembly’s Soil Action Plan for Wales consultation document (WSAP, 2009). Recent research funded by CCW has focused on soil biodiversity and ecosystem function and carbon in soils.

Environment Agency: (EA) in their 2007 Soil Strategy, ‘Soil a precious resource’ (EA, 2007), the EA clearly lay out research priorities for soil protection arising from their 2004 report, ‘The State of Soils in England and Wales’ (EA, 2004):

- Integrating management of air, soil and water – air, soil and water are closely linked and must be managed as a whole so that we can tackle diffuse pollution to improve water quality, protect soils from air pollution and manage flood risk.
- Tackling the impacts of agriculture – agricultural activities can be damaging to soils and water. Wiser use of soils and other resources needs to be promoted to reduce diffuse pollution from agriculture, to prevent persistent chemicals and excess nutrients from building up as well as to control erosion.
- Protecting soil in the built environment – greater recognition is needed of the importance of green spaces in the urban environment, which provide leisure opportunities and help manage flood risk. We also need to address contaminated land, as this can pose a risk to water quality and deter re-development.
- Understanding soil biodiversity – the nature and role of soil biodiversity is vital to healthy soils and we need to understand it better.
- Improving the knowledge base – we need to extend our knowledge and improve access to practical information on soils and the pressures on them.

Perspectives on soils - Non Governmental Organizations (NGO's) and the National Press

National Farmers Union: NFU represents 56,000 farm businesses in England and Wales involving an estimated 155,000 farmers, managers and partners in the business. NFU has actively provided responses to many aspects of soil management over the years, but here we draw on a consultation document with regard to soil protection in SSSE (PB13297) from June 2008. In addition to climate change, NFU stresses the need to recognize the importance of maintaining food security and adapting to high energy prices in soil management. In order to achieve soil protection, emphasis on maintaining and developing the evidence base is important, at the same time as developing education, awareness and knowledge transfer. Aims of soil protection should balance protection of agronomic potential as well as environmental protection.

NFU agrees that to halt the decline in soil carbon Defra must develop the evidence base. However, NFU points out that much of the drive with regard to research on soil carbon appears to come from the national and EU climate change agenda, rather than on improvement of soil productive quality. Again with regard to soil amendments, NFU would like to see emphasis placed more on the potential of organic materials to maintain carbon levels and productivity, whilst at the same time protecting soils from contaminants that may be contained in such materials.

With regard to soils in the built environment, NFU agrees that equal attention with regard to issues, policies and strategies must be developed for soils in all environments, not just agronomic. However, when it comes to monitoring and research, NFU points out that much of the current emphasis on soils is with regard to environmental and bio-geographical factors, rather than agronomic. Monitoring should be relevant and useful to the functions represented in the landscape which includes food and fibre production as well as ecological. With this in mind they emphasize the need for 'process' oriented research, contributing to our understanding of soil erosion, nutrient and pesticide movement, water infiltration and food safety, as well as data collection on the 'state' of soils.

With regard to research, NFU have published a report entitled, 'Why Science Matters for Farming' (Anon, 2008a). Within this report they highlight the importance of science for farming, noting advances in precision agriculture and the need for the ability to map soil property variability including texture, moisture and nutrient status at the field/farm scale. Given the growing threat of climate change there is a major emphasis on drought protection and technologies aiding water management. All of these rely on advanced sensor technology which is recognized in the report and which can help with soil protection.

Soil Association: has produced a policy document on soils that states: The soil performs many vital functions for the environment and society. A healthy soil is important for:

- maintenance of the basic resources for food production: soil, clean water and stable climate.
- maintenance of terrestrial and aquatic biodiversity (soil life is the basis of much over-ground life.
- healthy soil minimises agro-chemical pollution and nutrient leaching into watercourses.
- regulating the flow of water on the planet, including reducing flooding.
- reducing water cleanup costs (through reduction in pesticide and nutrient pollution).
- reducing climate change (soil is a major carbon store and it reduces atmospheric methane).
- reduction in the need for water for irrigation in agriculture.
- improvement in animal and human health through an increase in the nutrient content of food.
- reduction in pesticide residues.

In addition to carbon, biodiversity, nutrients and contaminants, water conservation is clearly articulated.

World Wildlife Fund: has made statements about soils policy and food security (Anon, 2008b) as well as having commissioned a report on soil erosion in England and Wales (Inman, 2006). In providing evidence for the Environment, Food and Rural Affairs Committee's enquiry into securing food supplies up to 2050 (Anon, 2008b) they highlight a 'fragmented' approach to the nitrogen cycle and phosphorus, and identify threats from soil erosion.

National Press: (Guardian, Independent, Observer, Telegraph, Times) a review of articles appearing in the national press in the last two years highlights a low level of coverage for soils outside of gardening. Recent progress on soil protection in the UK has resulted in national press coverage, as has the issue with food security. A variety of other issues regarding soils have also gained the headlines, these include sustainable farming, precision agriculture, nanotechnology, climate change, biodiversity and GM foods; sources are identified in Table 2.2.

Articles have stated, "Soil must be protected says minister" as part of a campaign to save our soils[1]. In addition they have included information from Defra's chief scientist saying, "Safeguarding soil is 'critical' if food production is to increase in the UK in the next 20-30 years"[2]. Recently the Telegraph ran with this headline, 'Britain facing food crisis as world's soil 'vanishes in 60 years''[3] based on research presented by Prof. John Crawford in Australia, who argued that we are using soil fertility faster than it can be replenished. Concern has also been voiced about the use of nanotechnology in food production and the unknown consequences to human health[4]. In addition the use of GM crops and their unknown consequences on health and the environment remains controversial[5]. The challenge was outlined by the former Environment Secretary, Hilary Benn, who stated that, 'Britain must grow more food, while using less water and reducing emission of greenhouse gases, to respond to the challenge of climate change and growing world populations.' The issue over GM crops has previously drawn criticism from the Soil Association, who argue, 'Malnutrition arises from a deficiency of many micronutrients, and cannot be solved simply by the development of crops engineered to provide specific nutrients. What is needed is a varied diet based on a diversity of crops; promoting further monoculture cultivation through GM seeds will not solve the problem.'[6]

Other threats highlighted in the press include the invasion of non-native earthworms and the impact this may have on soil processes[7], as well as the increase in soil invertebrates[8]. The importance of soil biology and biodiversity to our own human health is well established with the first commercial antibiotics having been isolated from soils by Mr Rene Dubos (Van Epps, 2006), and more recently highlighted by the hope of finding a drug to fight MSRA from the soil[9]. Climate change research continues to highlight the importance of soils to the functioning of the earth system and in terms of carbon storage[10]. An article released in the Independent claimed that, "A Finnish research group has proved that the present standard measurements underestimate the effect of climate warming on emissions from the soil" the researchers claiming that greenhouse gas emissions would be higher from soils under a warming climate than previously thought. Both organic farming[11], and no-till agriculture[12] are being proposed as methods of protecting soils and producing food sustainably. The Government is supporting precision / high-tech agriculture though this is controversial having been, 'dismissed as unnecessary and potentially damaging by environmental groups and organic farmers'[5].

Table 2.2. Recent Newspaper articles published in the British press, with a link to soils. Numbers correspond to those in text.

1.	Gray, "Soil must be protected says minister" 2009, Sept 29, Telegraph
2.	Vidal, "Loss of soil threatens food production, UK government warns" 2009, Sept 24, Guardian
3.	Hough, "Britain facing food crisis as world's soil 'vanishes in 60 years'" 2010, Feb 3, Telegraph
4.	Smithers, "Need for research on nanotechnology in the environment" 2010, Jan 8, Guardian
5.	Vidal, "Plans for British 'GM food revolution' come under fire" 2010, Jan 7, Guardian
6.	Tomlinson, "GM isn't the solution" 2009, Dec 14, Guardian
7.	Smith, "Earthworm invaders nudging out British species" 2009, Nov 2, Telegraph
8.	Jowit, "Number of bugs in Britain's soil rises by nearly 50% in 10 years" 2010, Feb 28, Guardian
9.	Wilson, "Soil could hold superbug cure" 2005, April 16, Independent
10.	Jowit, "Rise in UK carbon emissions disputed by report" 2010, March 7, Guardian
11.	McCarthy, "Organic farming may counter climate change" 2009, Nov 26, Independent
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3) The Natural Capital / Ecosystem Services framework for soils.

The soil Natural Capital (NC)/ Ecosystem Services (ES) framework is an attempt to create an overarching framework that identifies soil stocks, and the goods and services we get from soils that contribute to human well-being. It aligns soil science with the ecological (MA, 2005) and hydrological (Brauman et al., 2007) disciplines in efforts to do likewise, and in terms of UK policy it links with efforts to identify the UK's Natural Capital (Anon, 2009). Defra has adopted the **ecosystems approach** and published 'Securing a healthy natural environment: An action plan for embedding an ecosystems approach' (PB12853). This has been followed by the report, 'Delivering a healthy natural environment' which outlines progress to date (PB13385). At present no Natural Capital / Ecosystem Service framework has been fully outlined for soils. The focus has been on Ecosystem Services, which works broadly within the MA (2005) structure. However, this may be more appropriate for a large scale framework for global ecosystems, and less suited to national and regional policy development. In this section we contrast and compare current thinking on Ecosystem based frameworks relevant to soil protection.

A fundamental question facing soil protection is: What is the magnitude and direction of 'soil change' compared to a soils inherent state? The focus of this synthesis is to understand how soil protection research commissioned by Defra has been able to contribute to answering this question, and how this new knowledge can be used to encourage beneficial change, and remedy degradation. In order to do this an important aspect of this synthesis is to develop a common terminology that encompasses research within the ecosystems approach.

The following definitions provide a basis for developing the soil Natural Capital / Ecosystem Services framework later in the chapter, the definitions are a synthesis from recent work, especially ideas contained in work by Robinson et al. (2009) on soil natural capital, Daily et al. (1997) on ecosystem services, and Tugel (2005) on soil change. An important reference on the assessment of soil and ecosystem change can be found in the USDA report (Tugel et al., 2008). We also acknowledge that other frameworks have been proposed (Dominati et al., 2010), and discussion and debate about their appropriateness will continue.

Definitions

Natural Capital (NC): Defined by Costanza et al (1997), "capital is considered to be a stock of materials or information that exists at a point in time." Synonymous with soil 'state variables'

Ecosystem Services (ES): Defined by Daily (1997) as, "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life. They maintain biodiversity and the production of *ecosystem goods*, such as seafood, forage, timber, biomass fuels, natural fibre and many pharmaceuticals, industrial products and their precursors."

Soil Natural Capital: Defined by Robinson et al. (2009) as, "the stocks of, mass, energy and their organization (entropy) within soil."

Soil Ecosystem Services: "the conditions and processes through which soils, and the organisms that make them up, sustain and fulfil human life. They maintain soil function and biodiversity and provide *ecosystem goods* such as pharmaceuticals and fuel" altered from Daily (1997).

Soil Function: "Soils ability to sustain, regulate, and control biotic and abiotic processes through its interactions with the biosphere, hydrosphere, atmosphere, and lithosphere." Altered from Yaalon (2000),

Soil Change: Defined by Tugel et al. (2005) as, "the variation in soil properties at a specific location over time." Particularly referring to change that occurs over anthropogenic time scales.

Soil Dynamic and Static Properties: Dynamic soil properties are considered those that change over a human life span or less, and are particularly associated with processes, for instance soil moisture content or soil pH, and are often termed 'soil state variables'. Conversely 'static' properties are those that are subject to slow dynamic change, beyond the human lifetime scale, for instance texture and mineralogy.

Actual, Inherent and Attainable Functional Levels: Soil management requires a baseline for assessment, against which the current condition can be compared. The current condition is therefore termed the actual functional level. Soils are generally considered to exist in a dynamic equilibrium with a stable state dependent on inputs and outputs. Left to the environment, without the impact of management intervention, soil forming factors, CL, O, R, P, T (CLimate, Organisms, Relief, Parent-material all as a function of Time) determine the inherent functional level (Jenny, 1994). Given the introduction of management, soils might be 'improved' with regard to certain functions reaching a new stable state; this concept embodies the idea of the attainable functional level.

Soil Quality: The Soil Science Society of America ad hoc committee on soil health define soil quality as, "the capacity of a specific type of soil to function, within natural or managed ecosystem boundaries, to sustain plant or animal productivity, maintain or enhance water quality, and support health and human habitation" (Karlen et al., 1997). This definition links soil quality to 'use'. Soil quality has been historically linked with agricultural productivity and links with similar ideas on water and air quality (Singer and Ewing, 2000), though increasingly soil quality has evolved to include environmental aspects.

Soil Health: Singer and Ewing, (2000) define soil health as, "the state of a soil at a particular time." Taken from Carter et al (1997) it is equivalent to the 'dynamic' soil properties that change in the short term, e.g. organic matter content.

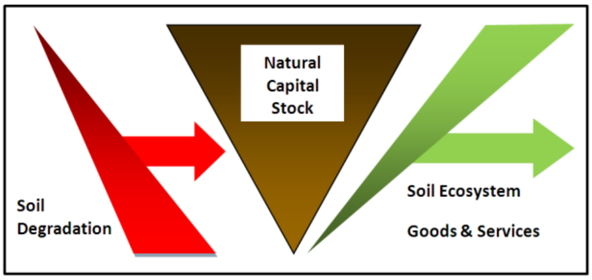
Soil Degradation: Blum (1998) defines this as, "a loss or a reduction in soil energy. As all soil functions and soil uses are based on energy, it can also be said that soil degradation is equal to a loss or reduction of soil functions or soil uses." In this work we focus on the loss or transformation of soil function, and extend this definition to consider degradation as a loss or transformation of energy or a loss of mass, or organization.

Emergent Property or Process: the resulting product of complex non-linear behaviour or phenomena, that are not simply additive, for instance soil aggregation.

Given the range of definitions we can explore how these concepts fit together, and why the ecosystems approach is appealing as a working framework. Unlike soil quality and soil health, which tend to have a more narrowly defined 'use' focus, the ecosystems approach is based on identifying all components of the soil stock, that contribute to soil function, and identifying the flows of goods and services that are derived from soils to support human well being, and attempting to value this. This means soil Natural Capital stocks and ecosystem goods-and-services can be identified, and their contribution to either production, or sustaining both production and the earth-system assessed and valued. The overarching framework tries to embody all the important contributions soils make to sustaining life in natural, managed and 'semi-natural' systems so that ultimately these contributions can be considered in policy / decision making frameworks. Decision makers need to account for, or at least be aware of, our soil resource Natural Capital and the services it provides, so that the full social and economic cost of decisions can be ascertained. More importantly environmental, rather than engineering solutions to problems facing society, might be more cost effective and acceptable to society; though recognizing that an engineering solution may be the only fix. The framework therefore, offers a better way of incorporating the true value of nature, and our natural resources, into the decision making process.

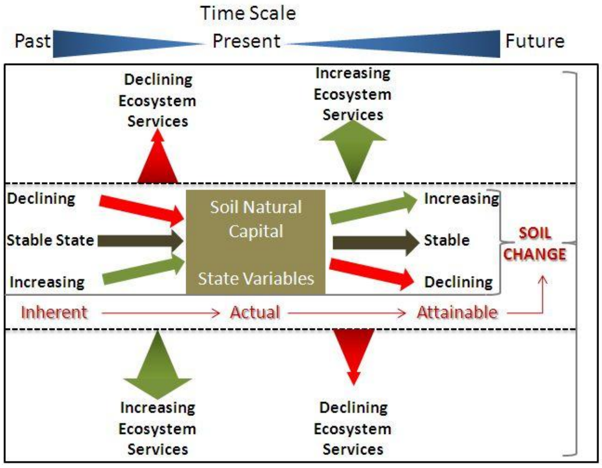
Soils are a natural resource containing stocks of materials, the relative importance of which to society changes depending on societal priority. The soil Natural Capital framework must not be biased by these perceived priorities, but must identify all stocks from which further assessment or interpretation can be made. Given our ability to identify stocks we can endeavour to identify how these stocks are changing, and subjective decisions can then be made about whether a change is positive or negative. Ecosystem Services describe the flow of goods and services derived from soils that may result from processes and a change in Natural Capital. They serve as a means of identifying and valuing soil functionality within the decision making process. Conversely, soil degradation assesses the loss of soil Natural Capital or the loss of soil function. Soil degradation and the provision of goods and services work in opposition as shown in Figure 3.1. As degradation increases, Natural Capital stocks reduce and ecosystem goods and services decline.

Figure 3.1 Relation between soil natural capital, degradation and ecosystem goods and services. Soil degradation and ecosystem services work in opposition to each other, as the soil degrades, the natural capital decreases and the goods and services decrease.



The concepts of NC and ES provide us with the stocks and flows of goods and services but there is no explicit link to time. Time is however explicit in the concept of 'soil change' (Tugel, 2005). By linking these concepts together we begin to develop a fuller picture of the soil resource. Figure 3.2 illustrates the connection between these three interrelated concepts, working together to determine the soil functional state. 'soil change' is mostly focused on alteration in soil NC that occurs through time, but also includes changes that occur to the provision of ES. An important aspect of soil change is the focus on anthropogenic time scales and change in dynamic properties at those time scales (Tugel et al., 2005). This is important as it makes all these concepts firmly linked to the goals of soil protection. An additional benefit of evaluating soil NC is that it is synonymous with soil state variables, linking better with established scientific terms for understanding and modelling soil systems. Soil state variables are used as the basis for modelling the dynamics of soil processes, used by environmental modellers to produce predictive models that describe the soil properties and processes that we are keen to protect. The ES, or what are sometimes called 'diservices', for instance runoff causing flooding, are more closely related to the flows and transforms of mass and energy that occur.

Figure 3.2 The linkage between TIME and, soil natural capital and ecosystem goods and services, through the concept of 'soil change'.



The Soil Natural Capital Framework

Soil NC forms the basis of what we want to preserve through soil protection, thus it is important to have a clear understanding of what is meant by 'soil Natural Capital'. The soil NC framework is taken from the proposed structure reported in Robinson et al. (2009). It is defined as, "the stocks of, mass, energy and their organization (entropy) within soil." These are further subdivided with each sub component having a quantity or quality aspect associated with it Table 3.1.

Table 3.1. A summary of the soil Natural Capital. The table does not provide an exhaustive list but acts as a guide to classification, adapted from Robinson et al. (2009).

Natural capital	**Measurable or quantifiable soil stock**
1) MASS	
Solid	*Inorganic material I) Mineral stock and II) Nutrient stock*
	Organic material I) OM/Carbon stock and II) Organisms
Liquid	*Soil water content*
Gas	*Soil air*
2) ENERGY	
Thermal Energy	*Soil temperature*
Biomass Energy	*Soil biomass*
3) ORGANIZATION / ENTROPY	
Physico-chemical Structure	*Soil physico-chemical organization, soil structure*
Biotic Structure	*Biological population organization, food webs and biodiversity*
Spatio-temporal Structure	*Connectivity, patches and gradients*

Table 3.1 provides the basic structure for the synthesis of the soil protection research conducted over the last 18 years. Many of the stocks highlighted are those also recognized by the soil protection programme as important to preserve, for instance, soil organic matter/carbon stocks, soil biotic structure and biodiversity, soil physico-chemical structure and the topsoil which includes the mineral and nutrient stocks. Others are implied but not dealt with explicitly, for instance the importance of soil moisture, soil temperature, both vulnerable to 'change', given alteration in land-management practices and climate change. Soil oxygen content is vital for healthy plant growth, and is usually covered in soil protection by prevention of compaction. An advantage of defining the NC in this way is that we identify the fundamental properties that we need to protect to maintain healthy soils. By identifying NC with soil state variables we forge an important conceptual link between the soil stocks, measurement and modelling efforts used to assess them, and economic approaches required to determine losses or gains. This provides a firm foundation for development of an integrated soil protection evaluation tool, unlike simply focusing on the evaluation of ES, which remains ill-defined and is often subjective.

Soil Ecosystem Goods and Services

The soil ES are the flows of goods-and-services derived from the soil. A brief review of the literature indicates that there are many ES that can be identified and attributed to soils (Daily et al., 1997; Clothier et al., 2008; Wall, 2004). The ES we derive from soils depend on soil NC stocks as seen in Figure 3.1. In this report we follow the framework suggested by Daily et al., (1997). In essence the Ecosystem Services are the functions that soil fulfils in support of human well being, and can be divided into, supporting, regulating, provisioning, and cultural, Table 3.2. Conversely, soils also provide disservices, which don't contribute to human well being and may be detrimental. Given the multifunctional use of landscapes, the level of services provided will depend on the land-management goals of productivity, waste recycling and environmental protection emphasised in the use of the soil resource (Andrews et al., 2004). We can now see how the NC / ES approaches work together, the NC is based on stocks, can be identified and measured, and provides an objective assessment of the resource. ES can also be objective but tend to be more closely tied to a subjective societal or political assessment that relates to the importance or priority society places on each service (which will affect its economic value). This will lead to some kind of subjective ranking which will depend on perspective and intended use. This begs the question as to who has the final say – what is deemed the priority service amongst several competing interest groups and who has the "authority" to make the decision? This will often come down to a subjective assessment of the goods and services derived from soil function, based on the land management goals deemed important. The priority that society gives the ES will determine, to a large extent the value of the resource. Both the concepts of soil degradation and ES are largely used subjectively because they depend on human perception of value to our wellbeing, and what might be of gain to some, may be considered as loss by others. As a result ES is proving to be a hard concept to operationalize at local and regional scales.

Table 3.2 Soil ecosystem services identified by Daily et al. (1997).

SUPPORTING
Physical stability and support for plants
Renewal, retention and delivery of nutrients for plants
Habitat and gene pool
REGULATING
Regulation of major elemental cycles
Buffering, filtering and moderation of the hydrological cycle
Disposal of wastes and dead organic matter
PROVISIONING
Building material
CULTURAL
Heritage sites, archeological preserver of artifacts
Spiritual value, religious sites and burial grounds

As an example of the objectivity of NC, and subjectivity of degradation and ES used in the societal prioritization sense, we can consider the drainage of an organic soil in the Welsh uplands. In terms of NC the soil moisture stock reduces through the drainage, the oxygen stock increases, carbon stocks may be altered by loss through volatilization but show increase by net primary production. The NC stocks can be assessed and quantified, and the 'soil change' determined through measurement or modelling. Degradation and ES as commonly used now show subjectivity, which becomes apparent as they both depend on 'use' and 'perspective' as outlined by imagined stakeholders below:

The farmer: The aim of the farmer was to turn the land into improved grassland for grazing and animal production. In his opinion the land has been improved and the ES increased.

The environmentalist: They consider the loss of a habitat, and the release of locked up carbon to the atmosphere, and so perceive the soil to be degraded.

The river manager: They consider the drainage to have increased the capacity of the soil to absorb water, so that it may enhance infiltration. Thus they consider the land to have been improved. However, dissolved organic carbon increases and river water quality is reduced.

The rambling club: Some walkers appreciate the new managed landscape, some would have preferred it to have remained the same, therefore some consider its aesthetic value to have increased, and some see it as having decreased.

This overview of the frameworks developing in the wider literature creates a set of emerging questions to be addressed by this synthesis:

1. What is the appropriate soil framework to use under the ecosystems approach?
2. What is the state of knowledge with regard to the identification and assessment of soil stocks?
3. What is the state of knowledge regarding soil threats?
4. How do we value soil natural capital and ecosystem services?

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PB12853 Securing a healthy natural environment: An action plan for embedding an ecosystems approach

PB13385 Delivering a healthy natural environment

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4) Assess current soil quality indicators and sampling/measurement strategy.

Soil is a complex material, and it is the complex processes of biota combined with physical processes acting on granular inorganic materials that creates soil. These complex processes produce emergent soil properties that make soils distinctive from; for example, sediments and regolith. They include soil horizonation, physico-chemical structure, aggregate and ped formation, and complex biotic structure resulting in broad biodiversity. In order to protect soils it is necessary to obtain indicators that can inform land owners and managers about the ‘state and change’ of the soil resource. Moreover, soils must be monitored and sampled so that soil indicators can be obtained in an unbiased way in order to inform our understanding of soil ‘state and change’. It has been recognised that indicators and soil sampling are related to soil protection strategies (e.g. within, SSSE, (PB13297) and in WSAP (WSAP, 2009)). By obtaining indicators of ‘soil change’ through monitoring and by understanding whether soils are improving or degrading, the state of the soil NC and the ES that flow from soil can be assessed.

4.1 Indicators of Soil Quality

Key findings:
It is clear that there has been considerable progression and success in the identification and development of soil quality indicators under Defra funded projects. UK Soils Indicator Consortium (UKSIC) has provided a useful umbrella mechanism to develop broad ranging issues relevant to Defra and other partners at UK and country levels:

- The UK is now the first region in Europe, and possibly globally, to have established a time-series in national soil monitoring through a series of GB or national monitoring programs primarily Countryside Survey and National Soil Inventories that measure soil state and change.
- A Headline Indicator for soil organic matter has been established through the Government Sustainable Food and Farming Strategy. This is a major achievement.
- An agreed minimum set of soil quality indicators (MDS) has been established for inclusion in any Tier 1 broad-scale soil monitoring. This includes, soil organic carbon, soil pH, heavy metals (Cu, Zn, Ni), Olsen P, potentially mineralisable nitrogen and bulk density. This set seems adequate for providing “headline” information on the general status and trends in soil quality as required of Tier 1 broad-scale monitoring.
- All agreed indicators have been implemented in at least one soil sampling scheme between 1990 and 2008 which provides an excellent resource for further indicator development, but in general is only for the top 15 cm of soil
- There are outstanding issues regarding the information needed on the agreed list of indicators of soil quality which include: quality measures, tolerances, and reproducibility and action levels.
- The process of developing and identifying soil quality indicators (SQIs) for UK has been greatly aided by the existence of data from surveys and long-term experiments, and the trialling of potential SQIs on sites with recognised history and background data.
- There are key gaps with respect to physical and biological indicators. The latter should be resolved shortly with the publication of SQID Phase 2. The former however remains a major issue, given increasing concerns over soil compaction, erosion and drought/water stress.

Categories of indicators for soil quality

At the simplest level, SQIs can be defined from the biological, chemical and physical characteristics of soil, as proposed by the USDA (1996). The first extensive review of SQIs for the UK (SP0512) adopted a broader perspective and defined three levels of SQIs and proposed that the design of a soil monitoring network should reflect this hierarchy of soil quality indicators (see Text Box 1). The Defra review 1990-2005 (ES0127) also

Text box 1 Categories of indicators for soil quality from Loveland and Thompson (2002)

1. measured soil properties / processes linked to soil function;
2. a group of environmental properties / processes which affect a soil function; and
3. a high-level indicator which reflects how soils are functioning within a defined system

noted that soil properties can be used as indicators of soil quality e.g. pH, organic matter status, metal content, or SQIs can be surrogate indicators of soil processes which are otherwise difficult to measure e.g. erosion. Consideration has also been given to the use of modelling and mapping approaches in defining and setting limits to indicators (e.g. risk mapping for heavy metals or soil erosion, soil suitability for wastes, Agricultural Land Classification or GHG emissions from modelling). This broad perspective is a particular strength to the overall UK approach to soil quality indicators research. The following synthesis reflects this range of perspectives on indicators of soil quality.

Progression of Defra research on soil quality indicators from 1990 to 2008

Soil, in contrast to air and water, is a highly challenging medium for which to develop quality indicators. Soil quality itself is highly context dependent reflecting inherently high levels of spatial complexity and temporal heterogeneity along with a wide-ranging diversity of human uses for soil. Soil quality is a judgement of a soil's capacity to deliver desired outcomes. For example, Acton and Gregorich (1995) defined soil quality for agricultural soils as "the soil's fitness to support crop growth without resulting in soil degradation or otherwise harming the environment". Over the last 20 years, considerable effort has been expended, in the UK and globally, to the development of indicators to characterise soil quality for different uses and to establish the capacity to monitor change in soil quality and, increasingly, the consequences for soil functions. This focus on soil functions means that related indicators of soil quality can now be linked to the delivery of ecosystem goods and services.

The 19th Report of the Royal Commission for Environmental Pollution on Sustainable Use of Soil (RCEP, 1996) raised the profile of the need for targeted research into SQIs. The commissioning of this report reflected wider recognition that soil had received less attention than air or water with respect to environmental protection and regulation e.g. Howard and Hornung, 1989. The European Thematic on Soil Protection and the proposed EU Soil Framework Directive has raised awareness of the need to protect the vital functions of soil. The definition of these soil functions has modified over time. This synthesis follows the definitions set out by the First Soil Action Plan for England (Defra, 2004) which are:

- Food and fibre production
- Environmental interaction
- Foundation for the built environment
- Support of ecological habitat and biodiversity
- Protection of cultural heritage
- Providing raw materials

Key options provided by the 19th RCEP Report (see Text box 2) were addressed in the mid 1990's through targeted activities such as the Countryside Survey Monitoring and Assessing Soil Quality project which specifically addressed the inclusion of soil biological measures (see Black et al., 2002) and the resurvey of the National Soil Inventory for England and Wales to investigate changes in soil chemical and physical properties within arable/ley grassland (SP0115), permanent (managed) grassland (SP0118) and subsequently other land uses (see Bellamy et al., 2005). Information from these and others surveys, along with long-term experiments, has proved invaluable in the development of SQIs within UK, as outlined below.

Text box 2. RCEP (1996) Recommendations relating to SQIs

- R7 "To complement the monitoring of air and water quality, we recommend the setting-up of a national soil quality monitoring scheme, for which responsibility should lie with central government"
- R89 "We recommend the inclusion in future surveys of biological measures of soil quality".

Prior to 1996, although there was considerable Defra research relevant to SQIs, this was not carried out with specific relevance to soil monitoring but rather was focussed on key issues such as soil erosion, atmospheric deposition of pollutants and critical loads, sustainability of agricultural soils, heavy metals contamination and eutrophication. This research has provided a significant evidence base for the subsequent developments of soil quality indicators, particularly in relation to specific soil functions and pressures. The Environment Agency led project on the "identification and development of a set of national indicators for soil quality" (SP0512, Loveland and Thompson, 2002) was the first project specifically tasked with addressing SQIs for national soil monitoring. Loveland and colleagues evaluated 67 potential indicators of soil quality from literature reviews, available data and expert knowledge. Nine functional indicators were highlighted for key relevance to monitoring and soil functions. Table 4.1 lists these indicators and summarises, from the report, the key issues regarding their significance and outstanding requirements. There was also one awareness indicator, based on reviewing internet webpage statistics. This now seems particularly progressive given current EU-level activities, some 20 years later, on raising public and political awareness of the value of soils to society.

The UK Soil Indicators Consortium was formed in 2003 from various Government agencies and departments across the UK to take forward the outputs from SP0512 'Identification and development of a set of national indicators for soil quality'. Defra was the lead partner in coordinating and organising UKSIC. The consortium was tasked with working collectively to:

- Identify the indicators that should be built into a UK soil monitoring scheme
- Develop a scheme that meets both multiple national and European requirements
- Suggest the best mechanisms for funding and undertaking this monitoring

This consortium has been the major driving force for a series of commissioned projects funded by Defra and other UKSIC partners to further develop SQIs for soil monitoring across the UK. This “umbrella” approach established a single stakeholder / end-user forum for the discussion and prioritisation of research requirements. In so doing, the consortium was able to support and fund a broad range of SQI topics in a coordinated manner which has helped to produce a relatively comprehensive assessment of SQIs. This synthesis reflects the significant contribution that UKSIC has made to SQI development since 2003. It should be borne in mind that Defra contributions to this research are not always obvious where UKSIC projects part- or solely funded by other partner organisations from the consortium and reference has been made to these projects to obtain a fuller picture of Defra supported research in this area.

With specific reference to SQIs, the consortium set an objective to develop a set of policy relevant and scientifically robust indicators of soil quality that would cover all of the functions of soil; pick up significant changes in soil quality in a timely manner; meet the different requirements of the member organisations (making best use of collected data) and make use of existing research into indicators being supported by the member organisations. The Consortium adopted a staged approach to further work on indicators and monitoring.

Table 4.1. Summary of the nine functional indicators proposed by Loveland and Thompson (2002) SP0512.

Indicator	Soil function	Summary of report commentary on relevance and wider issues
Total above-ground biomass production	Food and fibre production	The production of food, fibre, timber and livestock products will remain a paramount function of large areas of UK soils into the foreseeable future. Although it is not always straightforward to relate yields of these products directly to soils, any significant change in output would indicate a need for further investigation. In many cases, such variation would be explained readily by known climatic, political, market or other factors. However, where this was not the case - and this might be more true of longer-term change - then more detailed consideration of the role of the soil resource would be needed. This indicator thus performs as a high-level, overall signal of the functioning of the whole soil system.
Total below-ground soil organic carbon	Food and fibre production/ Habitats and biodiversity.	There is a general acceptance that soil organic carbon is an important indicator of a number of soil functions and related processes. The potential list of interactions with soil carbon is very large. However, understanding of many of the processes that are influenced by soil organic carbon content (and the forms in which it occurs) is often poor or simplistic - even at a qualitative level. There are also considerable practical difficulties in determining below-ground carbon stores; agreement about the depth of soil to be assessed, what constitutes ‘soil organic carbon’, the methods of measurement etc. are lacking at the national level. However, these difficulties should not detract from the potential for making this below-ground soil organic carbon a target indicator. Any initial assessments are bound to be crude, but the very act of making them will lead to some convergence of views about the ways in which the questions will and should be dealt with, and they will identify the priorities for further improvement in the assessment.
Topsoil pH	Environmental interaction	An assessment of soil pH is of profound importance. The interaction of the soil with substances added to it, e.g. from the atmosphere, wastes, fertilisers etc, and the outputs from soils, e.g. emissions to atmosphere, leaching to waters etc. are influenced strongly by soil acidity or alkalinity of the soil. The pH status of soils has implications for habitat diversity, crop yields, water quality and other issues. There is a thus great need for the optimum and acceptable range of soil pH to be established for a wide range of soil systems in relation to all soil functions. The magnitude of soil pH change over time can, when considered alongside ancillary soil information such as clay content, be used to assess other soil functions such as buffering capacity.
Buffering capacity	Environmental interaction	Buffering capacity is a measure of the ability of the soil to resist change. Although applied mostly to soil acidification, buffering could equally well be cast in terms of the soil’s ability to adsorb additions of agro-chemicals or substances deriving from waste or atmospheric deposition. Semi-quantitative assessments of buffering capacity can be made on from soil properties e.g. clay content, cation-exchange capacity and pH. Direct measurements are lacking for most UK soils. Research would be required into methods and their interpretation in a number of contexts.
Keystone species	Habitat and Biodiversity	Although some aspects of soil-habitat-species (macro- and micro-; faunal and floral) are known, much remains unknown. This is particularly true about those species which indicate whether a soil system is functioning well. There is a strong need to establish which are keystone species, what they tell us about the robustness of the functioning of the soil ecosystem in which they are found. This indicator will require considerable research.
Soil microbial diversity	Habitat and Biodiversity	Given the evidence that soil micro-flora and fauna are heavily implicated in soil processes, a start should be made on the development of an indicator that could reflect this role. It is argued that an overall measurement of, for example, substrate utilisation or diversity, e.g. DNA-analysis, would be a useful starting point. Not enough data exist and therefore requires further research is needed.
Soil surface condition	Providing a platform	The condition of the soil surface affects profoundly the function of the soil in relation to the built environment and also impinges on run-off potential and flood risk, sediment transport, nutrient transport / eutrophication risk, infiltration characteristics and aquifer recharge. The difference between an ‘acceptable’ soil surface condition, or what processes give rise to an acceptable soil surface, are not well-understood. Gross damage is usually obvious, but can still be difficult to measure. However, the consequences of damage can be severe and difficult to remediate. Work is required to assess ways in which soil surface condition can be measured and ways in which these measurements can be expressed in a meaningful way in terms of soil functions.
Extent and depth of ploughing	Protection of cultural heritage	In effect, this is two indicators in one. Because of the number and diversity of cultural remains at shallow depths within UK soils, many see tillage as the biggest single threat to their continued existence. This reflects what new areas of land are being tilled (and so what remains are threatened) and what is the magnitude of the threat, i.e. how deeply (and frequently) is the land tilled. The principle of the indicator is a powerful one, but it needs to be backed up by considerably better data and will require further research.
Area of land taken for mineral workings	Providing raw materials	Extraction of mineral resources always leads to considerable soil disturbance. Some impacts might be reversed during restoration, the lost soil might be replaced with some other function of value, e.g. a wetland habitat, or there can be permanent soil loss under buildings. It is important to know both the overall extent of such change and which soils are being affected and which therefore which functions are reduced. This is especially true where there is potential for the loss of rare soil ecosystems and associated habitats. It is questionable, in practice, whether the soil function is much considered in these issues.

Stage one of the UKSIC approach to future work involved a policy shift of initial indicators (details of options and gaps from the individual UKSIC reports is provided in Note 1 at the rear of this document). The 67 indicators from (SP0512) were sifted informally by the UKSIC partners for their relevance to policy areas using the criteria of relevance, sensitivity, discrimination and signal-to-noise ratio, efficiency and cost and the integrative nature of indicators. The policy areas reviewed are listed on the Defra UKSIC website as: Soil Protection, Reporting state of natural heritage, Conditions of notified features on designated site, Landscape and natural beauty (indicators of countryside change), climate change, BAP action plans, Agri-environment protection, Environmental impact assessment, Contamination/Pollution prevention, Water Framework Directive/Diffuse Water Pollution, Sustainable Land Use, EU Thematic Strategy on Soil Protection, Natural Resource Protection, Animal Health and Welfare, Flood risk monitoring and Protection of cultural heritage. Of the 67 potential indicators, a reduced number were found to be most relevant to “the soil’s interaction with the environment”. These were divided into chemical, biological, physical and ‘other’ categories (Table 4.2).

Table 4.2. Proposed indicators of soil quality identified from the UKSIC policy sift

Category	Proposed Indicators Shaded = sub-set for detailed review; * in bold*= final indicators prioritised for a Minimum Dataset (MDS)
Chemical	***SOC (reported as soil organic matter or SOM)***
	***Top soil pH (water and $CaCl^2$)**
	cation exchange capacity (CEC) to 1 m depth
	total N
	Olsen P
	anion adsorption capacity in topsoil
	base saturation
	heavy metals (Cu, Zn, Ni)
	organic micropollutants (Persistent Organic Pollutants - POPs)
	concentrations of other potential pollutant elements
Biological	microbial biomass carbon/SOC
	soil biomass
	mineralisable N
	Biolog score
	DNA-based microbial diversity index and enzyme assays
Physical	integrated air capacity to 1 m depth
	number of locations with erosion features
	topsoil surface condition
	aggregate stability
	bulk density
	topsoil plastic limit to a depth of 1 m
	macroporosity
	time to ponding
	water dispersible clay
Other	catchment hydrograph
	surface water turbidity
	biological status of rivers with and without sewage treatment works
	number of eutrophication incidents per year

Stage 2 involved scientific robustness testing. Potential indicators were tested to determine relevance, measurability and interpretability with respect to individual soil functions. Each project considered the MDS indicators from Stage 1 but also addressed other indicators considered relevant from literature reviews and expert knowledge. The research was led by various UKSIC partner organisations, with report publications reflecting this. Defra maintained a key role in all aspects of this stage, irrespective of lead contractor. In parallel, the EU-funded ENVASSO project (ENVironmental ASessment of Soil for mOnitoring; Kibblewhite et al., 2008) was evaluating SQIs to support the requirement of the proposed Soil Framework Directive, with a focus on indicators relevant to soil threats. This project established a formal link to Defra through ENVASSO-UK. The indicators proposed by this project are listed in Table 4.3. A short summary of the main options and knowledge gaps from the individual UKSIC indicator reports can be found in Notes 1.

Stages 3 - Monitoring scheme. The UKSIC objective was to develop an agreed set of policy relevant and scientifically robust indicators into a UK wide soil monitoring scheme, making as much use of existing schemes as possible. SP08011 reviewed the availability of existing data on UKSIC indicators from current and historical soil sampling schemes. This highlighted a lack of baseline data on soil physical properties. The "Design a UK Soil Monitoring Network" project (SP0558) worked with the UKSIC partners to establish an agreed list of indicators for Tier 1 i.e., broad / national scale monitoring. Thirteen indicators were agreed by UKSIC (see Table 4.3) for inclusion in any / all UK soil monitoring schemes, with scope for individual countries to include further indicators (c.f. Aalders et al., 2009 for Scotland). Of these 13 indicators, the majority are chemical based (11) with no higher level or integrative indicators. The design project further consulted and worked with the UKSIC partners to prioritise "canary"[1] indicators with which to design and evaluate monitoring schemes, as it was impractical to consider all indicators with equal priority. Canary indicators are those identified as critical to current monitoring objectives. Soil organic carbon and soil pH were agreed by UKSIC as definite canaries with total Cu and total Zn as subsequent priorities for specific land use interests. There was no consensus on the remaining indicators as critical canaries for a range of reasons. This project has set out the procedures for the agreed indicators e.g. soil sampling, analytical methods, sample archiving, data management, statistical analyses, interpretation and reporting. Information is summarised for each indicator in a series of indicator checklist tables (see Table 4.4 as an example for soil organic carbon). The project has highlighted that there are key knowledge gaps regarding the agreed set of indicators which would constrain the usefulness of data arising from monitoring. The shaded areas in Table 4.4 illustrate the gaps for the SFFS Headline Indicator for soil organic matter. The gaps are mainly associated with the need for information on:

- Quality measures i.e. what form of information is required from the indicator e.g. descriptive statistics, exceedance over a threshold, change from previous samplings.
- Tolerances i.e. what level of uncertainty is acceptable.
- Action levels i.e. establishing when a difference or change in an indicator is unacceptable or undesired (e.g. prompt values).
- Reproducibility of analytical methods.

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[1] Canary indicators are those identified as critical to current monitoring objectives and therefore, an option for a monitoring network must be suitable for these priority indicators (i.e. able to determine status and detect change with adequate precision) if the design option is to be considered for Tier 1 monitoring. For further details see, Black et al., 2009 (SP0558)

Table 4.3. List of soil quality indicators obtained from reports to UKSIC and their relevance to individual soil functions and threats. Adapted from LQ09. A = UKSIC indicators selected for the Minimum Dataset (MDS); R = recommended primary indicators[1]; S = recommended but not taken forward[1]; O = recommended for further research[1]; b = biological indicators prioritised for each function[2]; B = recommended by consensus in SQID expert workshop; E = indicators relevant to functions/threats as identified by ENVASSO; RT = from robustness testing reports; EA = EA (2006 and workshop note); DS = from LQ09

Full list of UKSIC Soil Quality Indicators	**Indicator category**		**functions of soil**										**EU threats to soil**								
		SOM: headline indicator (RT)	UKSIC indicators (DS)	Food & fibre production (EA)	Food & fibre (RT)	Environmental interactions	Support for habitat & biodiversity (EA)	Provision of raw materials	Cultural heritage & archaeology (RT)	Platform: *Built environment*	Resistance and resilience of soils	Biological indicators[2]	decline in SOM[6]	soil contamination	soil erosion	soil compaction	landslides	soil salinisation	decline in soil biodiversity[4,5]	sealing	desertification
soil organic matter content/SOC	Chemical	H	A	R		R	R		R		R		E								E
labile carbon					R																
clay content					R																
extractable Mg			A	R																	
extractable K			A	R			R														
total Cd			A	R										E							
C/N ratio			A				R						E								
available Cu						S								E							
available Ni						S								E							
available Zn						S								E							
Olsen P			A	R	R	R	R														
soil pH			A	R	R	R	R		R		R			E				E			
total Cu			A			R								E							
total N			A			R															
total Ni			A			R								E							
total Zn			A			R								E							
buffering capacity											R										
soil redox									O					E		E		E			
aggregate stability	Physical			R							R				E	E					E
soil structure											R										
soil moisture at 1 m depth				R																	E
bulk density[4]			A	R		R					R		E			E					
plough depth									O												
soil texture											R										
water-table depth and variability									O												E
ammonia oxidisers/denitrifiers	Biological			b		b	b					O							E		
Archaea diversity						b	b					O							E		
potentially mineralisable N			A		O		R														
bacterial diversity				b		b	b					O							E		
fungal diversity				b		b	b					O							E		
methanogens/ methanotrophs						b	b					O							E		
microarthropod diversity				b		b	b					O							E		
multiple substrate induced				b		b	b					O							E		
soil respiration											R										
nematode diversity				b		b	b					O							E		
visual flora and fauna diversity				b		b	b					O							E		
microbial biomass/ soil organic					O																
respiration quotient				O																	
soil microbial biomass											R										
enzyme activities				b		b	b					O							E		
soil microbial community structure				B		B	B				R	O							E		
area & volume of deposits lost	Higher-level								O												
area of new cultivation									O												
extent of soil sealing										O											
erosion and sediment distribution									O						E		E				

1. Information derived from review reports to UK-SIC; 2. Derived from Black et al., (2006); 3. Area & volume of superficial deposits lost annually to mineral extraction & peat cutting; 4. Bulk density included as “T”; not an indicator of carbon itself but included as an essential measurement to derive carbon stock

Table 4.4 Topsoil organic matter (SFFS headline indicator). Adapted from Black et al., (2009)

Function	**Food & fibre production**		
Indicator required	**Soil organic matter (SFFS headline indicator)**		
Policy objective	To halt the decline of soil organic matter caused by agricultural practices in vulnerable soils by 2025		
Source	Defra, 2005		
Indicator assessment	To determine whether there have been significant losses in soil organic matter (SOM) caused by agricultural practices in vulnerable soils		
Assessment interval	E = start year 2008/09, report on SOM 2010/11 (approx) and again before 2025. All other administrations = 5 yr		
Domains of interest	devolved administrations and Land uses		
Indicator variable (unit)	measured values of topsoil soil organic matter content (g kg^{-1})		
Measured variable (unit)	measured values of topsoil soil carbon content (SOC %) converted using a pedotransfer function (previously SOC x 1.724)		
Indicator parameter	- mean, standard deviation and upper and lower 95% confidence limits for specified Land uses, following transformation to normal distribution - estimated change at 95% confidence since last sampling (or earlier samplings)		
Indicator quantity	status and change in the mean soil organic matter content for agricultural land uses.		
Type of result	Quantitative: Is soil organic matter content significantly different to previous estimates? Qualitative: Is soil organic matter content progressing towards the targets set for each land use?		
Quality measure (d: tolerance level)	(i) the width of a 95% confidence interval for the true mean SOM (g/kg) is 2d or less, or (ii) the width of a 95% confidence interval for true change in mean SOM g/kg) is 2d or less *(n.b. the measures required will depend on whether both status and change are required)*		
Land use (other than Land Cover classes)	arable / rotational grass	permanent managed grass	managed semi-natural grassland
Action level (mean)	progression to 50 g kg^{-1} for E&W	progression to 75 g kg^{-1} for E&W	progression to 220 g kg^{-1} for E&W
Soil depth	0-15 cm topsoil		
Sampling procedure	Direct comparison with NSI E&W requires sampling using Soil Survey for England and Wales sub-sampling by 2.5cm diameter mild steel screw auger, See the Soil Survey of England and Wales Field Handbook (Hodgson, 1976)..		
Analytical method	SOC by method comparable to LOI + Walkely Black		
Archiving	Air-dried 2 mm sieved soil sample		
Additional information	change relative to previous values (NSI E&W); probably moving to stock estimates with measurement of bulk density; data for Government Office Regions on the “would like” list and would like options and costs of inclusion. Comparable to methodology listed in Defra SFFS headline indicator Factsheet.		

Implementation of indicators of soil quality in broad-scale monitoring (SP0545, SP0115, SP0118, SP0124, SP0533, Emmett et al., 2010)

Since 1990, various schemes have included a range of the UKSIC indicators in broad-scale soil sampling initiatives; the National Soil Inventory for England and Wales (NSI_E&W), The Northern Ireland Soil Survey, G-Base, National Soil Inventory for Scotland and Countryside Survey (CS). Defra funded or co-funded both the NSI_E&W and CS and both have yielded valuable, though in one instance contrasting, information on the status and change in soil indicators, along with other soil properties and processes. The UK is now the first region in Europe, and possibly globally, to have established a time-series in national soil monitoring through Countryside Survey. Key messages from the indicators are:

- Soil pH increased significantly in the last 30 years and has been attributed to recovery from acid rain.
- Nitrogen status of soils has remained largely unchanged.
- Heavy metal concentrations (total Zn, Ni, Cd) also remain largely unchanged though there are signs of declining concentrations in cropped land use systems. Cu has however increased in British soils which may reflect land management.
- Soil carbon has declined in arable land.
- There are inconsistencies in soil carbon results from CS and NSI_E&W which may reflect sampling strategies, analytical methodologies or other factors. CS has detected no major change in SOC in other land uses while NSI_E&W has detected rather large losses. Further work to explore these differences will provide invaluable information and lessons for the future deployments of soil carbon / organic matter indicators within large-scale schemes for UK and internationally.
- An observation is that the targets for the SFFS headline indicator for soil organic matter were set using the NSI_E&W data. Until the differences between CS and NSI_E&W are resolved it is not possible to determine the success of Defra's objective to halt the decline in soil organic relative to these target values using the recent results from Countryside Survey.
- An observation is that the wealth of data generated by these schemes has yet to be interpreted in terms of degradation of soil functions. The forthcoming Integrated Assessment of Countryside Survey may provide some insight here. These recent monitoring experiences serve to illustrate that considerable effort is required to establish, retain and make accessible information regarding the identification, development and deployment of soil quality indicators. This information is not always easily accessible at present.

Outstanding issues

- Develop headline indicators for the remaining soil functions, with appropriate action levels / prompt values for different land uses.
- Analyses of existing soil data to address the remaining information gaps for the UKSIC MDS
- Explore the utility of the extent of soil sealing as an indicator of soil quality as this would address the concerns over the potential loss of soil / prime agricultural land to development.
- The various projects have, on the whole, used selection criteria to identify, review and recommend SQIs. These criteria have however differed between projects and it would seem timely to establish a universal (minimum) set of selection criteria which would be appropriate for a UK soil monitoring programme. These criteria would support the consistent evaluation of existing and novel indicators as the monitoring programme progresses.
- Establish the reproducibility of sampling and analytical procedures to be used in long-term soil monitoring. A key priority must be the establishment and adoption of analytical standards to support both inter- and intra-scheme data compatibility.
- The governance stage has yet to be completed. Therefore who undertakes the soil monitoring how a scheme would be organised and how the results should be made available is still to be decided. This has implications for further development of indicators.

Future opportunities

- Due to the fundamental nature of the MDS indicators, they could be adapted (i.e. in terms of information generated from the data) to inform on soil threats and therefore have direct alignment with the proposed EU soil monitoring programme.
- Establish and maintain a UK network of long-term "reference" sites which have known responses to key pressures. Given the general resilience of soils to change, there is a need for long-term sites where impacts from pressures have been established. These sites could be used to trial all future potential indicators of soil quality to ensure consistency of responses over both space and time, and with respect to key pressures e.g. it would be straight-forward to determine whether one indicator performed better than another. Existing long-term experimental sites and terrestrial Environmental Change Network sites are an obvious resource for this.

- Consider the incorporation of rhizobium into soil quality indicators given recent results highlighting the broad sensitivity of rhizobium to heavy metals in soils (see SP0111; SP0142) and the availability of DNA-based methods to identify these organisms.
- Establish mechanisms for access to information about and generated from soil monitoring. This might include further development of a website dedicated to UK Soil Monitoring as an access-point to relevant data and information.
- Develop approaches to disseminate the information generated by soil quality indicators to land managers and other end-users.
- The important role that soils play in supporting the delivery of ecosystem services is generating increasing demands for soil data for use in valuation (see SP08004) and other purposes. Ecosystem services research would be better supported through the identification and development of integrative indicators for which the role of soil properties and processes are quantifiable both in space and time.
- Further research to identify and develop indicators for the functions and threats related to soil structural condition and transfer / retention of water and gases (e.g. GHGs) would be of benefit.
- Move from single action levels / prompt values for SQIs towards a more strategic view which would provide information on the capacity of soils to support multiple demands from the same functional unit i.e. different values for different purposes from the same indicator.
- Further research is needed to develop indicators of soil quality that can directly provide quantitative information on the functional status of soil at a range of spatial and temporal scales (i.e. Tier 2 and Tier 3 monitoring in addition to Tier 1). This will require the development of process-based indicators, integrative indicators of soil function and the use of modelling approaches to establish status of soil functions e.g. in a similar vein to Land Capability for Agriculture / ALC or risk mapping of soil erosion (see also SP0531). Key here will be defining what constitutes a functional “unit” for soils, and the key characteristics (properties, processes and functions) associated with this unit. This is likely to be some combination of soil type and land use.

4.2 Sampling and Monitoring of Soils

Key findings:

- Soil biological properties are only just beginning to be measured at soil monitoring sites
- Of the soil threats compaction and erosion are the least well surveyed
- Current survey information can most likely be translated into the natural capital framework. Some other parameters like soil depth would be helpful additions as soil production *vs* erosion is not well understood.
- The lack of detailed information on soils at depth across England and Wales is a substantial source of uncertainty in understanding changes in soil quality and carbon stock estimates.

Soil monitoring activity across England and Wales

Defra has commissioned a number of reports that review sampling and monitoring schemes that apply to England and Wales (SP0515, LQ09, ES0127). There are a number of recent Defra supported national monitoring surveys, either currently in operation, or recently concluded. These are the Countryside Survey (CS), National Soil Inventory (NSI), the Representative Soil Sampling Scheme (RSSS) (Concluded), the Environmental Change Network (ECN); Defra and the Forestry Commission are currently helping support (30 %) an EU (70 %) funded project named ‘Biosoil’. The forest soil study and the level 2 forest monitoring scheme monitors 170 forest sites across the UK, with many sites in England and Wales. Soil fertility, carbon and many other soil and environmental changes have been examined in the long term experiments at Rothamsted and the soil and plant archive exists for future work. In addition soil erosion surveys have been undertaken. Table 4.5 provides a summary of the Defra reports written between 1990-2008 period, what they cover and examples of what the schemes have been used for.

In the period since the review of all Defra Research in agriculture and environmental protection between 1990 and 2005 (ES0127), there has been further discussion in respect of soil monitoring and which parameters should be measured. Monitoring is intended to show the magnitude, spatial and temporal extent of change. A project (SP0514) was set up to examine the problems that may be encountered with repeat sampling in the NSI scheme. Analysis suggested that there were some significant differences in some of the measured properties between samples taken at 0, 10, and 50 m from the target site. However, analysis of the sample sites suggested that these differences could be explained by factors such as topography, land-use and pedological differences. The research suggested that sampling should be as close to the original sampling point as possible and certainly no more than 30m from it. A recent study of sampling variation based on sites within the BGS G-BASE project demonstrated that short-scale (20-metre) sampling variation accounted for an order of magnitude greater variation in five soil indicator variables than subsampling and analysis (Rawlins et al., 2009). This highlights the need to ensure short-scale variation in soil indicators due to sampling is minimised by combining sufficient incremental samples (preferably 25; *pers comm*. Barry Rawlins) to form a composite sample to represent each site.

The similarities and differences in the National Soil Sampling Schemes was examined in report (SP0515; 2003) where the various National Soil Monitoring Schemes (Countryside Survey (CS), National Soil Inventory (NSI), the Representative Soil Sampling Scheme (RSSS) and the Environmental Change Network (ECN) were compared and synergies between the schemes determined. The major results are summarised as conclusions from Report SP0515 were that (i) each survey was valid and consistent with its own aims and their strengths were aimed at the target users, (ii) there was some complementarity in the datasets as the NSI, RSSS and the CS samples were taken 0-15cm and some analytical methods were similar, (iii) each scheme covered different landscape/soil/landuse combinations and their sampling designs were devised to answer the questions posed by the users, (iv) the NSI, RSSS and CS schemes are designed to give overall regional or national pictures, not field scale monitoring. Thus suggestions for future schemes included that (i) any future scheme should be appropriate for the whole of the UK and (ii) and it must reflect the needs of the users, particularly addressing the issues directly linked to monitoring (how do we monitor, what do we monitor, time intervals, sampling depths) whilst addressing the needs of policy makers in the UK and EU. The review produced in 2005 (ES0127) stated that compared to soil physical and chemical properties, there is far less information regarding soil biological properties.

Table 4.5: Summary of reports associated with Defra funded / partially funded surveys

Survey	Specific reports associated with survey	What aspects reports cover	Key survey outputs
NSI	SP0104, SP0115, SP0118, SP0121, SP0123, SP0124, SP0533, SP0545	Re-sampling of sites, statistical analysis of data	Producing guidance on heavy metal limits for sewage sludge, Examining change in organic C
ECN	CC0402, CC403, CC0405, CC0407, CC0408, ES0113	Sampling strategy, Soil survey input to ECN	Monitoring soil changes at 12 sites throughout UK
RSSS	SR0101, SR0107, SR0108, SR0109, SR0112, SR0113, SR0118, SR0123, SR0127	Statistical design, Data processing, Feasibility of adding organic C to survey	Monitoring fertility status of agricultural land in UK
Countryside Survey	WC0701 Emmett et al., 2008 Emmett et al., 2010	Countryside survey, Soils manual, 2007 Soils report	Monitoring soil parameters, especially records increase in pH as a sign of recovery from acidification.
Soil Erosion Surveys	SP0402, SP0407, SP0411, SP0413	Upland and arable erosion	Assessing soil erosion in upland and lowland U.K.

What aspects of state and change in soil do the soil surveys monitor: A central component in maintaining and protecting our soils is that of long-term monitoring of soil state and change. There are 5 fundamental surveys that can be used in measuring and monitoring state and change in soils in the UK. These are the (i) LandIS database linked to the National Soil Map (NATMAP), (ii) NSI resampling survey, (iii) Countryside survey, (iv) Representative Soil Sampling Survey and (v) the Environmental Change Network. The soil parameters measured and the surveys are described in Notes 2.

Soil Erosion Surveys: Soil erosion on arable land was re-examined (SP0407) between 2001 and 2002, after an original study undertaken between 1996-98 (NT1014). The reason for re-sampling was the extremely wet autumn and early winter of 2000/1 when 489mm rain fell in England and Wales, making the 12 months to 31 March 2001 the wettest since records began in 1766. Thus revisits were made to 270 NSI field sites, first visited between 1996-98. Analysis included (i) a replication of the

1996-98 survey protocol and (ii) an aerial photographic analysis to sites that couldn't be accessed due to the Foot and Mouth outbreak. The survey involved the assessment of soil erosion and deposition within the field by recording the dimensions (average length, width and depth) of erosion and deposition features. Fields greater than 10ha were surveyed by surveying those areas that were hydrologically contiguous (e.g. in the same intermediate slope / surface drainage system as the NSI node point). It was found that soil erosion continued on NSI sites over the duration of the study although the study was compromised by the foot and mouth outbreak. A further study was undertaken to test whether caesium-137 could be used to estimate soil erosion rates across agricultural land in England and Wales (SP0411) and a subsequent study was commissioned to document erosion rates using this method at 248 sites across England and Wales SP0413 between 2005-2008.

Soil monitoring in respect of 'Natural Capital and Ecosystems Services concept: Table 4.6 synthesises current surveys and demonstrate how they contribute to the assessment of the Natural Capital of soil. The table indicates that many of the soil properties are collected in different surveys; however, they tend to provide a snapshot in time. The more dynamic properties such as temperature and moisture are not routinely monitored by survey methods.

Table 4.6: Relationship between Soil Natural Capital (state and stock) and Soil Monitoring Schemes for England and Wales.

A. Soil Mass

Soil Natural Capital	**Linked to Defra Objective**	**Causes of Change**	**Surveys**	**Comments**
Mass – soils **Mineral stock** Soil depth , Volume / mass	Protecting and enhancing stores of soil carbon Building resilience to climate change - water storage Effective soil protection during construction and development	Long time scale – Weathering, bed rock lowering Short-medium-long time scale - Erosion through wind, precipitation or cultivation Engineering and construction	No systematic map of total soil / regolith depth is available for the UK. Most surveys stop at <1.2m NSRI NatMap database/inventory has information but often stops at 1.2m. BGS holds information on very shallow soils from G-BASE survey The CS survey of 1978 has profile information down to 15 cm. ECN will re-survey changes in soil horizons depths. Only 12 sites nationally BIOSOIL examines horizons of organic and mineral soil depth to 80cm	Is likely to be a reasonably static or very slowly changing dynamic variable. Landuse change may affect soil depth the greatest particularly if soil becomes more susceptible to erosion. However relatively little info on soil production rates. **See Note 2 (at end of report).** Academic researchers continue to measure rates of soil erosion in specific locations in Eng & Wales. Related factors – no erosion map of Eng. & Wales, although Defra has undertaken monitoring programs in the past (SP0407)
Particle size	Carbon storage, water storage	Erosion through wind, precipitation or cultivation	NSRI NatMap inventory database has original data. However, Particle size distribution (PSD could be substantially more spatially variable and NSRI sampling may not be of sufficient resolution to pick up spatial changes. BGS has high resolution PSD data for East Midland region of	Considered a static variable therefore NSRI dataset. However, research has shown that cultivation especially can coarsen soils through erosion of lighter particles**. See Note 2.**

Soil Natural Capital	**Linked to Defra Objective**	**Causes of Change**	**Surveys**	**Comments**
			England using G-BASE archive samples	
Mineralogy	Fertility – Maintenance thereof, particularly natural potassium stocks and release, clay content impacts function and resilience	Rate of soil mineral weathering	BGS has basic mineralogy data held in Soil Parent Material Map database. However it is geology based rather than measured soil data. The RSSS looks at extractable K. This links in with clay mineralogy and the ability of clay types (especially illite/smectite minerals) to buffer K availability. Long term changes in clay mineralogy examined at Rothamsted Classical Experiments by Tye et al. 2009.	Very little information re: rate of mineral weather and natural fertility replacement for Eng. & Wales. Skolkloster classes (Hodson et al. 1998) designed to assess mineral soils short term acid buffering capacity have been used to identify and map soils sensitive to acidification.
Mass – solid **Nutrient stock**	Fertility maintenance	Nutrient mining from crop production	Extractable K measured through RSSS scheme for agricultural land CS monitors soil P and mineral N. Biosoil monitors C & N as well as Ca, Mg, K, H, & Al. Rothamsted Classical experiments monitor N, extractable cations, particularly K.	
Mass – solid **Organic Carbon**	Protecting and enhancing stores of soil carbon Building resilience to climate change - water storage	Landuse change, cultivation practice, clay content. Possible climate change response via bacterial Q_{10} relationships	Both NSRI and the Countryside survey have undertaken the resampling of SOC. A survey priority Biosoil monitors C & N Rothamsted Classical Experiments have monitored long-term changes in C. Biosoil mionitors change in Forest soils C	
Mass – solid **Organisms**	Protecting and enhancing stores of soil carbon Building resilience to climate change - water storage Determine impact of pollutants on biodiversity	Landuse change, cultivation practice, soil physico-chemical properties, climate change	CS records state and change of selected broad invertebrate taxa and more specifically mites, springtails and collembola	
Mass – liquid **Soil water content**	Protecting and enhancing stores of soil carbon Building resilience to climate change - water storage	Climate change, land use and management change	NSRI Natmap has information relating to soil series soil water content at different suctions in its inventory.	
Mass – Soil air **Soil gas**	Protecting and enhancing stores of soil carbon	Compaction changes in bulk density, changes in moisture	No survey of soil gas composition undertaken. CS has information on	

Soil Natural Capital	**Linked to Defra Objective**	**Causes of Change**	**Surveys**	**Comments**
	Building resilience to climate change - water storage	regime	bulk density from which porosity is determined. NSRI have bulk density values for soil series and horizons in the NATMAP	

B: Energy

Soil Natural Capital	Linked to Defra Objective	Causes of Change	Surveys	Comments
Thermal Energy Soil temperature	Organic C, Soil Moisture, Bio-diversity, Release of nutrients Also important for engineering aspects for the future e.g. ground source heat pumps.	Climate change, changes in moisture regime from drainage/wetting.	Of the stated surveys only ECN includes soil temperature monitoring in the UK. The Met Office has a comprehensive soil temperature monitoring network with its weather stations.	Will be one of the major changes with climate change. The MET office has soil temperature maps (0-30cm) averaged over 30 years for each month and season.
Biomass energy Organic carbon	Building resilience in soils	Landuse change, cultivation practice, clay content. Possible climate change response via bacterial Q_{10} relationships	Both NSRI resampling and Countryside survey have resampled SOC in the past. A likely survey priority for the future. Rothamsted Classical Experiments have monitored long-term changes in C	

C: Organization and Entropy

Soil Natural Capital	Linked to Defra Objective	Causes of Change	Surveys	Comments
Physicochemical structure Aggregate %	Building resilience to climate change - water storage	Change in carbon status or wetting and drying regime	NSI NATMAP survey would include this information at the time of sampling.	This is a factor that may change due to changing carbon % and cultivation techniques, especially in the top soil
% clay	Building resilience to climate change - water storage	Erosion, cultivation	NSI NATMAP survey would include this information at the time of sampling. BGS has more detailed PSD information for the soils of Eastern England only.	No continued monitoring
Biotic structure Biological population Organisation biodiversity	Protecting and enhancing stores of soil carbon Building resilience to climate change - water storage Determine impact of pollutants on biodiversity	Pollution, climate change	The CS monitors soil invertebrates and makes measures of biodiversity.	Reports results according to Broad Habitat, aggregate vegetation class and soil organic matter
Spatial-temporal Structure Landscape metrics	Monitoring and understanding landscape processes	Erosion	NSI survey contains soil boundary information based on surveyor interpretation	

Scale: The current UK soil monitoring schemes were set up by different research organisations for different purposes as outlined in SP0515. A conclusion of this report was that the schemes were well designed to allow statistical analysis of (i) spatial variation of soil properties for the appropriate scale or that (ii) they were designed to monitor change (CS and RSSS on a rolling 5 year cycle). Table 4.7 outlines the scales addressed in terms of those appropriate to the ecosystems approach.

Table 4.7. Monitoring of soil temperature based on the 4 Defra soil monitoring schemes.

Monitoring scheme	National	Regional	Local
Representative Soil Sampling Scheme	Yes	Yes	Yes
Land Information System	Yes	Yes	Yes
Countryside Survey	Yes		
Environmental Change Network	Yes (Sparse)		12 locations

Thus the surveys were considered to be representative of a range of different landscape/soil/land use combinations and were designed to answer specific questions. The CS and NSI schemes are not designed to give a specific field or farm scale answer to soil temporal change but are designed to give an overall impression of regional or national trends. However, the ECN will be able to provide high resolution temporal change at the 12 specific locations.

Do the surveys provide sufficient information on dynamic soil change characteristics such as erosion, organic C and compaction? NSI (Bellamy, 2005) and CS (2007) (Emmett et al., 2010) have focused on determination of change in soil organic carbon; CS also determines change of P, N, pH, soil invertebrates, and some pollutants including heavy metals. Change in terms of erosion and compaction is not routinely monitored by surveys. Defra report SP0402 reported on the quantification and causes of upland soil erosion at the national scale. A large part of the study consisted of (i) systematic measurements of eroded area and volume at a statistically robust set of field sites (n=399), (ii) the use of aerial photographs and (iii) a review of published and unpublished literature. The field sites were predominantly NSI sites (n=372) and part of the original soil survey inventory. Additional sites came from the Countryside Survey 2000 (n=27). The survey examined the length, width and depth of discrete erosion features found with a radius of 10 or 50 m from the node point of the NSI 5x5 km grid. The area and volume of eroded soil was then calculated. The amount of redeposited soil was also determined by measuring the width and length of areas of deposition and the depth of redeposited soil. Erosion in upland soils measured in 1999 was estimated to cover an area of 24, 566 ha and 0.248km3 in upland England and Wales, of which there was large scale blanket bog erosion. Of this 18 025 ha and 0.242km^3 was attributed to water erosion, whilst biotic (humans and animals) accounted for 6541 ha and 0.041 km^3. However, wind erosion was negligible. Some limitations of this study were highlighted by Warburton et al., (2003), specifically i) inadequate definition of the field survey methods, ii) a lack of appreciation of the geomorphological context of the results, and iii) no linking of erosion loss to timescale. In report SP0407, results are presented of a re-survey of the upland sites. Results suggested that further soil erosion was found on almost every field site. On average it was suggested that erosion increased annually by 0.25m^2 on each upland site and by a volume of 0.37m^3. Again sheep and water were considered to be the dominant erosive processes. Given that we do not know soil depth, and the rate of regeneration of soil from weathering it is difficult to quantify a mass balance of soil loss vs production.

How well do the monitoring schemes inform us about the key threats in the strategy? Organic matter decline: With respect to monitoring soil carbon on a regional scale, the surveys have been able to record changes, although interpretation of why change (or lack of it) has occurred has been more problematic. There are issues with upland soils (peats) and calculating total carbon stocks. These include bulk density measurements as well as peat depth. National Parks and Areas of Outstanding Natural Beauty appear to be trying to develop peat depth databases (e.g. North Pennines). Bulk density is measured in CS for every carbon measurement but not in NSI data. This is a potential source of uncertainty in carbon stock estimation.

Compaction: In the UKSIC suggestions for soil monitoring, compaction monitoring involve the use of bulk density in detecting compaction in the top 30 cm, either from cultivation or livestock poaching. Thus the measurement of compaction in the top soil has been suggested in Science Report SC030265 to be through the taking of bulk density samples. The Countryside Survey is the only extensive survey to monitor bulk density (ECN does but this is restricted to a few sites), using cores 15cm deep by 5cm diameter (Emmett et al., 2008).

Current compaction monitoring does not take into account sub-soil compaction caused by agricultural vehicles and cultivation. This is important for crop rooting, water infiltration and retention. It may be a reasonable suggestion that compaction surveys be established along the lines of the erosion sites, where penetrometer surveys could be undertaken around node sites of the NSI survey.

Erosion: Soil erosion should also be considered along with the depth of soil and soil production rates in assessing the sustainability of soil management (i.e does soil production keep pace with soil loss. At present few values have been published for the UK with regard to soil production. One example is by Riggins et al. (In Press) who used cosmogenic radionuclides (^{26}Al, ^{10}Be) and found that granite bedrock lowering was between 10-20 m/My (metres per million years) with maximum soil production occurring when the soil depth was 0.3m. Soil depth is a measurement of the current soil resource; there is little information on variation in soil depth at the national scale. One study by Tye *et al*. (In press) examined the depth of soil across the Sherwood Sandstone outcrop in Nottinghamshire. Results from analysing 350 boreholes across the outcrop show that median soil thickness is 1.5 m whilst the mean value is 1.8m.

How often do we need to measure stock / state in support of soil policy? The definition of ‘stock’ within the NC/ES concept includes many properties that have been measured once in the NATMAP inventory. This particularly relates to properties such as particle size distribution (psd) which are assumed to be relatively static. However, work published by Jolivet *et al* (2001) and Lobe *et al*. (2001) suggest a coarsening of top soil with cultivation is occurring as fines are removed by wind, so that perhaps soils should be considered more dynamic than they often are.

There are obvious financial considerations that influence the frequency that monitoring can be undertaken. However, in Report SP0544, the frequency of sampling and performance of soil monitoring schemes was addressed with the development of a statistical tool. The tool addressed temporal and spatial variation within surveys. Performance criteria include (i) objectives of the monitoring scheme, (ii) the scale at which the survey is to take place (e.g. field, uniform regional, Non-uniform regional), (iii) confidence level of detection of change, (iv) detectable level of change, (v) rate of change, (vi) measurement error and (vii) sampling error. Table 4.8 gives an example of the output from the tool for soil carbon where the detectable level of change is shown for different grid sizes when soil carbon is assumed to change at either 0.1 or 0.15% per year. This analysis indicates that for national capability resurveys should be conducted less than 10 years apart.

Table 4.8: Output of Performance model developed under Project SP0544 for frequency of sampling for different grid sizes to detect changes in soil carbon

		Years between sampling	
Grid Size	Detectable level of change (%)	Rate of change 0.1 % per year	Rate of Change 0.15 % per year
5km	0.3532	4	3
10km	0.7066	8	5
16km	1.1308	12	8
25km	1.7671	18	12

Outstanding Issues

- Although the compaction and erosion of soils are major areas of concern, the depth and regularity of surveys have not been considered to the same degree when compared to the development of the soil quality indicators. More-over, the issue of soil production rates needs addressing since this is needed to assess stock change; otherwise we have only half the picture; i.e. high soil erosion rates in an area of high soil production maybe of less concern than high erosion rates in areas of very low soil production.
- The discrepancies in the changes of soil carbon between the NSI and CS requires further work

Future opportunities

- Co-located soil erosion and production rates would facilitate the understanding of the long term sustainability of soil management. This is particularly important for agricultural soils which are typically more prone to erosion by water, wind and tillage and soil loss by co-extraction with root vegetables.

- Monitoring of bulk density and soil compaction would be beneficial, especially for clay-rich soil types prone to compaction. Monitoring as an aid to reducing compaction in soils has other benefits; improving drainage and the potential to reduce generation of N_2O, a greenhouse gas emitted from the soil.
- Current soil monitoring networks do not include biological indicators; serious consideration should be given to their inclusion.
- With the inclusion of many of the Minimum Dataset of Soil Quality Indicators within the different monitoring networks, consideration should be give to combining them as a National Monitoring network.
- The soil monitoring networks have given the UK a sound knowledge base on which to continue building; individual surveys should continue to monitor what they originally set out to achieve. This would be a major contribution towards the monitoring desired by the proposed EU soil monitoring program.
- Web-based dissemination of survey results need to be considered so that information is available to stakeholders and land managers.

References

Defra projects:

CC0402 Soil survey input to ECN
CC0403 Soil survey input to the whole of the network (previously CC0402)
CC0404 Environmental Protection Division (ECN)
CC0405 Sampling strategy for ECN protocols
CC0407 Soil survey, sampling and analysis for ECN
CC0408 Environmental Change Network
Defra, 2004. Soil action plan for England
ES0113 UK Environmental change network
ES0127 Defra research in agriculture and environmental protection 1990-2005; summary and analysis
NT1014 A systematic approach to national budgets of phosphorus loss through soil erosion and surface runoff at National Soil Inventory nodes
PB13297 Safeguarding our soils a strategy for England
SP0104 To use National Soil Inventory to produce guidance on heavy metal limits for sewage sludge
SP0111 Effects of sewage sludge applications on soil microbial activity and the implications for soil fertility
SP0115 Resampling of selected soils from the National Soil Inventory sites
SP0118 Resampling of permanent grassland sites from the National Soil Inventory
SP0121 Scoping study for the mathematical analysis of national soil inventory data
SP0123 Chemical analysis of resampled permanent grassland sites from the National Soil Inventory
SP0124 Statistical analysis of NSI data
SP0142 Long term metal experiments: statistical review of findings to date and definition of future experimental programme
SP0402 Research on the quantification and causes of upland erosion.
SP0407 Arable and upland NSI erosion resurvey
SP0411 Documenting soil erosion rates on agricultural land in England and Wales
SP0413 Documenting soil erosion rates on agricultural land in England and Wales - Part 2
SP0512 Identification and development of a set of national indicators for soil quality (P5A(00)01)
SP0514 Sampling strategies and soil monitoring
SP0515 Comparability of soil properties derived from data sources.
SP0531 Novel methods for spatial prediction of soil functions within landscapes
SP0533 Initial assessment of projected trends of SOC in English arable soils
SP0544 Development of performance criteria for soil monitoring schemes
SP0545 Spatial analysis of change in organic carbon and ph using re-sampled National Soil Inventory data across the whole of England and Wales
SP0558 Design of a UK Soil Monitoring Scheme
SP08004 Economic valuation of soil functions: Phase 1 - method development
SP08011 National Soil Monitoring Network: Review and Assessment Study SP0123 Chemical analysis of resampled permanent grassland sites from the National Soil Inventory

SR0101 To provide representative estimates of current nutrient and pH status of soils in England and Wales
SR0107 Representative soil sampling scheme - feasibility of adding organic matter measurements
SR0108 Representative soil sampling scheme - feasibility of adding soil organic matter measurements
SR0109 Statistical design and analysis for the representative soil sampling scheme
SR0112 Representative Soil Sampling Scheme(VLAEM) (Continuation of SR0108)
SR0113 Data processing for Representative Soil Sampling Scheme
SR0118 Representative soil sampling scheme (RSSS)
SR0123 Representative soil sampling scheme (RSSS)
SR0127 Representative Soil Sampling Scheme (RSSS)
WC0701 Countryside Survey 2007

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5) Evaluate work done on the identification and quantification of capital.

The focus in this section is on how the research undertaken for Defra over the last 18 years has contributed to advancing our knowledge and understanding of the measurement, monitoring, modelling and/or assessment of the soil Natural Capital stocks identified.

5.1 SOIL MASS:

The soil mass consists of a solid, liquid and gas phase. Each of these are a form of soil NC stock and potentially a resource for protection. The provision of ES is often related to the state of this NC stock. Each of these phases, solid, liquid and gas, are in combination the building blocks of a soil. A soil is like a three legged stool, limit or remove one leg and the stool will topple over; similarly for a soil, remove one of the phases and the soil ecosystem will degrade. Considering the soil mass as a NC asset should assist in safeguarding our soils for the future by leading to an improved understanding of how to manage soils better; and help to recognise their value within ES.

5.1.1 Solid

5.1.1.1 Soil mineral stock

The soil mineral stock forms the granular matrix constituting the soil body and the mineral component of the soil NC. The proportions of sand, silt and clay determine the distribution of pore sizes controlling water and gas retention, whilst determining the size of habitat for the soil biota. Soil surface area increases as particle size becomes smaller, so that 1 gram of clay mineral can have a surface area the size of a tennis court. Nutrients, vital to plant growth are retained at the particle surface. Both Defra and the Welsh Assembly Government (WAG) have recognized the need for better protection of agricultural soil stocks; in particular that the soil mineral stock is under threat from erosion by wind and water (SSSE 2; WSAP 3.4). The need to protect soil stocks from urban development has also been recognized (SSSE 6; WSAP 3.2 and 3.6). The consequences of soil loss are lost production, and reduction in water quality as well as the silting up of drainage systems, water courses and dams. By understanding the soil mineral stock as a NC resource it may be possible to evaluate the impact that erosion has on the size of this stock. However, there are no studies thus far that explicitly and systematically assess soil mineral stock. Studies on erosion have attempted to quantify rates of soil loss from uplands and lowlands, but these are not assessed within the context of a diminishing soil stock. As soil stock is determined by the balance between soil production (weathering) and soil loss (erosion), both of these fluxes need to be quantified.

Key findings:

- There is little direct information to assess how the rates of soil loss (erosion) are balanced by the rates of soil formation (weathering) across different land classes and uses. Weathering rates need to be determined, in order to develop a soil mass balance, which would help in the assessment of carbon and erosion.
- Quantifying changes in soil depth is critical for determining long term changes in the soil stock.
- Quantification of soil bulk density, stone content and depth will allow the conversion of soil texture data (measured by the Soil Survey) into soil stock.

A number of reports have been commissioned by Defra reviewing sampling and monitoring schemes for soils that apply to England and Wales and touch on soil mineral/textural stocks (SP0515, LQ09, ES0127). The National Soil Inventory (LandIS) contains NATMAP, the national soil map with national scale information on the distribution of soil textural properties (see Table 4.5 for list of associated reports). NATMAP contains texture data on 6127 points located on a 5 km grid across England and Wales; soil information is generally constrained to 1.2 m or less.

Measurements of soil bulk density and soil depth in conjunction with soil textural information (% sand, silt, clay) will enable the estimation of stock of every textural class and how each is affected by erosion. For example, preferential erosion of fines (silts and clays) has direct impacts on soil function and fertility through nutrient losses, and on soil bulk density through modification of texture (coarsening). As the clay fraction is the most chemically active mineral component of soil, most chemicals (i.e. nutrients, pesticides, pollutants) preferentially adsorb onto silt and clay surfaces. Fines also affect water retention in soils and therefore also affect the flow and transport of water and gases. Therefore quantifying changes in the soil stock and texture is important for understanding hydrological and ecosystem function. Additional information on stone content is necessary for discerning effects on erosion and soil stock, as stone content has been shown to affect erosion.

Studies on soil erosion need to be paralleled by studies on soil formation. A quantification of the spatial variability in rates of weathering is needed in order to estimate net soil production or loss (i.e. an increase or decrease in soil stock). Weathering rates are slow relative to erosion rates so observations in the field will not yield useful results over a short time scale. However, controlled laboratory experiments on soil profiles can be done and there is research in the EU led by scientists in the UK attempting to understand these processes across Europe (e.g. SoilTrEC project, see http://eusoils.jrc.ec.europa.eu/projects/soiltrec/). Weathering rates exhibit large variations depending on rock type, topography, tectonic activity and climate regimes. For example, long-term chemical weathering rates on granitic sites covering diverse climatic regimes have been found to span a range of 0–173 t $km^{-2}year^{-1}$ (Riebe et al., 2004). Therefore, establishing rates of weathering for sites undergoing extreme erosion is important for evaluating the long term changes in soil stock.

5.1.1.2 Soil nutrient stock

The soil nutrient stock forms the basis of the nutrient store for the terrestrial ecosystem, both natural and man-managed. It ensures that soils can fulfil functions vital to the economy, such as the provision of food and fibre, and to the environment, such as the maintenance of forest and grassland that regulate the hydrological cycle and biodiversity. The nutrient store consists of materials found in the soil solution or adsorbed on mineral or organic surfaces, termed available, and those that form part of the mineral or organic structure and are occluded or combined until released into a plant available form. From plant biomass, the nutrients may move to animal biomass and higher trophic levels. Alternatively nutrients maybe leached from the soil in soluble or particulate form by water draining through the profile or lost in gaseous form e.g. through denitrification or nitrification. The distribution of a nutrient between the various soil structural components differs between the various nutrients.

Key findings:

- The databases of NSI (National Soil Inventory) and RSSS (Representative Soil Sampling Scheme) are platforms on which stocks of nutrients and their trends can be based. Significant Defra work has been carried out in the review period towards the methodology of “scaling-up” to convert the data into absolute stocks that can be measured, monitored and related to nutrient budgets. Further work on scaling-up appears desirable.
- The growth of organic farming has been an important stimulus to research into nutrient dynamics in soil, so that management methods may be adjusted if necessary. In setting the future nutrient research agenda, it appears desirable first to assess whether organic farming will continue to grow as it has done. If so, there may be a need for the current methods of assessing soil nutrients to be reassessed or recalibrated to the needs of organic farming.
- Most research targeted at nutrients has been done on N and P. However, there is no indication that of all the macro- and micro-nutrients, one or more are at particular risk from soil degradation in the UK.
- Most nutrients are being monitored by two pools each, a “plant-available” pool with a relatively fast turnover and a “reserve” that changes only on a years-to-centuries timescale and this seems appropriate.

What are the important nutrients?

All nutrients are important in that life as we know it ceases if one becomes totally absent. Sixteen elements are recognised as essential to plant life and another five for animal life. C, H and O are supplied by air and water and constitute most of the bulk structure of living organisms. The other elements may be considered as nutrients, are largely provided by the soil, and for convenience are divided into macronutrients and micronutrients.

Each of the macronutrients (N, P, S, Ca, K and Mg) typically constitutes about 0.1% to 3.0% of plant dry matter, and crops make substantial demands on those nutrient stocks of the soil. Offtakes of N, P and K are such that annual additional inputs of these nutrients are normally needed for economic production. The PLANET software (ADAS, 2010) developed by ADAS with Defra support, (ES0124, IF0141, IF0171, KT0113, KT0120) provides a computerised method of applying the recommendations of Defra's 'Fertiliser Manual (RB209)' (8th edition, December 2010) for N, P and K, and also Mg and S. The development of this software has therefore made a significant contribution to soil nutrient protection by helping to avoid depletion. In most UK soils, the reserves of Ca appear sufficient that enough is available without the use of specific additional inputs. Although, this may not be the case for repeated conifer forestry production cycles in areas with naturally low Ca content bedrock, but in this case Ca deficiency can be avoided by sympathetic harvesting techniques (stem only rather than whole tree) and supplements of Ca phosphate fertiliser.

The micronutrients are typically < 10 ppm as-opposed-to >1000 ppm for macronutrients (above). Complete agreement on a definitive list of micronutrients has not been agreed, for plants B, Cl, Cu, Fe, Co (for N fixation) Mn, Mo, Na, Ni, Zn are proposed, in addition Li, I, Se, Cr, V, Si, F, As and Sn are needed for animals (Alloway 2008). Animal life requires Co, Cr, I, Na and Se, and evidence has been put forward that Ni, Si, Sn and V can also be beneficial (Mertz 1974). Soils must therefore supply sufficient of all these elements for transmission up the food chain. In England and Wales, the normal recycling of crop residues, soil mineral dissolution and inputs as components of fertilizers supply most micronutrient needs along with atmospheric deposition. In England and Wales, deficiencies only occur on a localised basis. Soils and crops liable to deficiency are by now reasonably well established, as are deficiency symptoms and diagnostic tests, meaning that any change should be detected. Problems are diagnosed and remedied on a case-by-case basis by independent agricultural advisors and laboratories. During the period under review, there has been no relevant Defra research directed to the assessment of micronutrient deficiencies in soil, although it may have be funded elsewhere. Research in this area has been reviewed for Europe by Sinclair and Edwards (2008). On the other hand, it must be noted that Cu, Mn, Mo and Zn are also classed as "heavy metals" and are toxic if present in excess, a topic dealt with separately (Section 8.4.2).

Evaluation of the nutrient stocks- general issues

The national database: England and Wales possess a comprehensive dataset in the form of the National Soils Inventory (NSI) held by the National Soil Research Institute at Cranfield University. The data were measured in the period 1978 to 1983 and form a "baseline" survey that is attributed to 1983. It is based on soils found at 5691 points on a 5-km grid, and the topsoil attributes include most of the nutrient elements, *ie* Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, P, Se and Zn, in most cases measured both as extractable components and a near-total assessment by *aqua-regia* digestion. The micronutrients B, Cl and I were not measured, nor N. In principle, this forms the basis of an inventory of the natural capitals of the nutrients measured. Using the NSI, McGrath and Loveland (1992) compiled an atlas which depicts regional variations in topsoil nutrient concentrations as measured, but not the stocks in terms of masses.

Work of the Soil Protection Programme in 1990-2008 has enhanced the value of the NSI with follow-up studies. Various projects provided new statistical interpretation of the data (SP0124, SP0506, SP0520). NSI grassland sites were resampled in 1994-6 and significant changes in soil nutrient concentrations identified (SP0506). Some other sites including non-arable ones were resampled in 1998-2000, and although only soil organic C and pH were measured (SP0545), the SOC contains most of the N stock. CS has added to the knowledge base with N, P and trace element stocks being potentially determinable (Emmett et al., 2010). Impacts of erosion with reference to nutrient loss in eroded sediments were assessed for upland soils (SP0407).

Scaling-up in space and time: A broad picture of nutrient dynamics at larger scales, i.e. catchments, river basins, regions and nationally, aligned to an understanding of ecosystem services, requires information to be summarised and aggregated systematically to larger and longer levels of space and time. To estimate the amounts of nutrients on regional and national scales from the NSI's concentration data requires multiplication of the measured concentration by the appropriate quantity of that soil considering both area and depth. The NSI provides a grid of point measurements which must be converted into values applicable over mapped areas. Spatial variability of a nutrient's concentration may be high within the 5km grid of the NSI, depending on the localised impact of land management. Conclusions of Defra's statistical studies appear to differ. SP0124 concluded that a coarser 10km grid would be sufficient to show the spatial pattern of many properties. On the other hand, SP0520 concluded that most soil chemical properties can only be mapped from a sample grid finer than 5km and that local spatial variability may be different to the spatial variability across the country as a whole, and suggested that sampling schemes should be adapted to local conditions. Given this difference of conclusions, it is suggested that further research is needed to quantify representative stocks of nutrients.

For all nutrients, there is a component that is available, which requires a universally agreed and accepted method for determination, to plant roots during a growing season and a "back-up" reserve that is not immediately available, but provides a store that is relevant to long-term assessment on the years-to-centuries timescale. The available component of each nutrient must be sufficient for the required plant growth, but to reduce losses, via water or air, not excessive. It therefore appears necessary to assess stocks of each nutrient in two ways: the readily available stock and the long-term stock. Future soil monitoring must therefore measure the relevant components or NC of each nutrient for the appropriate management timescale. Since different nutrients have different chemistries, each of the most important trio (N, P, and K) is discussed separately below, and tentative NC classifications are offered according to the scheme of Robinson et al. (2009) in Tables 5.1, 5.2 and 5.3. These are initial suggestions offered as a basis for discussion.

Monitoring: The need for a robust evidence base to underpin policies to protect soil carbon has been recognised (SSSE, Executive Summary, PB13297) and recognition is made that soils change slowly. The same applies to the long-term stocks of nutrients.

As well as issues of spatial and temporal variability, the reliable detection of change in soil properties is a significant technical challenge. Changes that are small in relation to the total nutrient stock may nevertheless be important in themselves or as precursors of greater change, and must be measured against a background of considerable spatial variability as well as analytical variability. Changes might be measured by either resampling the same locations over years or by a sequence of randomised samplings (SP0520). Projects SP0124 and SP0520 gave options regarding spatial and temporal monitoring for future sampling in the NSI which is a very large database that, for reasons of effort and cost, can be resampled only occasionally.

Separately from the NSI, Defra has executed a programme of frequent (annual) monitoring of a limited set of assessments (pH, extractable P, K and Mg) with repeat sampling at a relatively few (180) selected arable and grassland farms under the Representative Soil Sampling Scheme (RSSS) projects (SR0118, SR0123, SR0127, SS0133). They started in 1969 and effectively monitored change in the selected nutrients, broken down by region and cropping systems. In addition, CS (Emmett et al., 2010) is now providing important information on stocks and changes.

Defra's Soil Protection research programme: The soil protection theme in 1990-2009 comprised 112 projects. Projects involving the measurement of nutrients as a component of their activity have dealt with the use manures (SP0129, SP0501, SP0508, SP0516); sludges (SP0109, SP0125); fertilizers (SP0504, SP0505, SP0508, SP0518); monitoring and quality indicators (SP0123, SP0124, SP0512; SP0514; SP0520). Although sewage sludge is applied to land for the purposes of recycling and increasing nutrient supply, sponsored work has been aimed mainly at assessing effects of metals introduced.

Evaluation of stocks *per-se* has not been addressed directly. One project (SP0508) was explicitly concerned with long-term effects of manure and N fertilizer. However, the authors of some projects have recognised the existence of long-term dynamics outside the possibility of research within the allotted project timescale, and identified them as relatively unknown factors for which the projects could not provide definitive answers.

The measurement of soil available nutrients as a soil quality indicator appears an obvious necessity from the perspective of those concerned with agricultural and forestry (including energy crops) production and fertilization research. However, starting from a "blank-sheet" approach and first principles, as in SP0512 ("Identification and development of a set of national indicators for soil quality"), the role of nutrient assessment in soil is seen to compete with alternatives such as using measurements of nutrients in crop biomass and nutrient budgets and many other potential indicators of soil health and quality. Although soil nutrients did not make it to SP0512's list of "headline indicators" of soil quality (Table 12.1), measurements concerning nutrients in soil comprised two out of 11 indicators of soil quality for a proposed minimum dataset of physical, chemical and biological indicators for soil quality (Table 11.1)

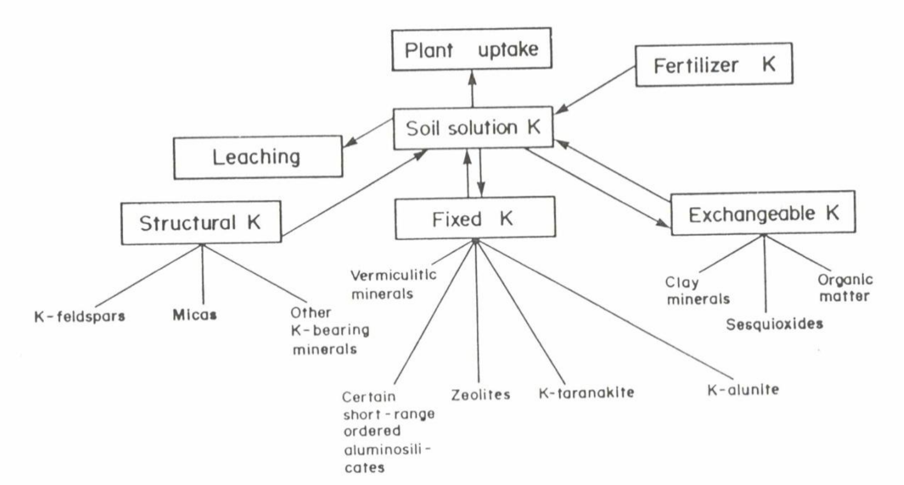
Regarding the different nutrients, work related to management techniques was dominated by N (SP0501, SP0504, SP0508, SP0518) and P (SP0505), with K and micronutrients involved only on a minor or incidental basis.

Natural Capital of the individual nutrients in soil

Potassium, classification of the K capital

Mass: The quantities of K required by plants are second to the quantities of N, but K is discussed first because its management is more straightforward. K in soil exists only as the inorganic K^+ cation, either in solution, on surfaces or within minerals, and the chemistry of soil K is relatively well-understood in that there are many chemically well-defined phases. For practical purposes, physically meaningful pools of K exist (i) in solution, (ii) exchangeably adsorbed by the soil CEC provided by minerals and organic matter, (iii) as a slowly exchangeable component within illite minerals and (iv) the original source in bulk mineral particles (Figure 5.1).

Figure 5.1 Interrelationships between the various forms of soil K (Sparks and Huang 1985).



In UK conditions, the K extractable by 1M ammonium nitrate corresponds well to the exchangeable and soil solution K pools that provide most of the available K in a subsequent growing season, although in some soils, a part of the slowly-exchangeable K is released. For the purposes of assessing the NC of K, measurements of near-total K (normally by digestion in *aqua-regia*) and exchangeable K (by ammonium nitrate) appear sufficient to describe the long- and short-term components of the K stock (Table 5.1). Typical ranges for the amounts of these two stocks in UK soils are indicated in Figure 5.2.

Figure 5.2. Principal pools of K within UK soils. Approximate contents of total and extractable K (kg/ha) in the 0-15cm soil horizon are estimated from the concentrations of the 25th to 75th percentiles of the NSI data.

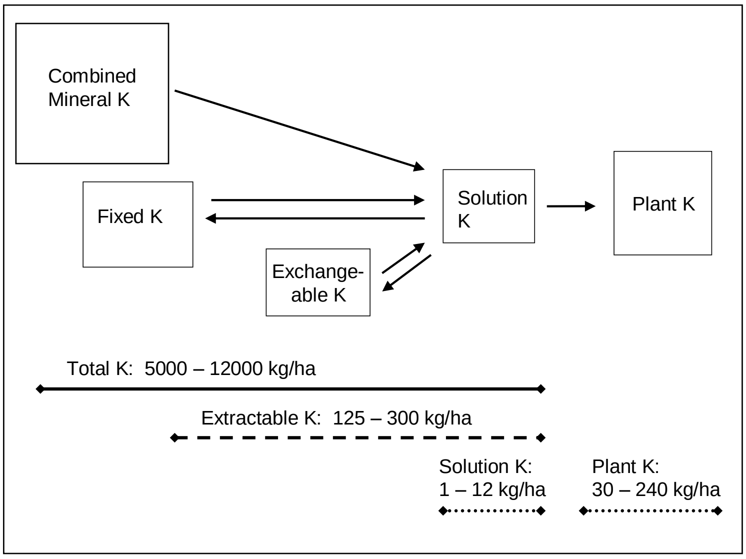


Table 5.1 Soil Potassium Natural Capital	
Mass	*Related ecosystem services*
Combined K	Long-term fertility maintenance
Extractable K	Crop production
Energy	*No clear involvement of K*
Organisation	*K masses involved*
Long-range (nation, region) >100m; > 1 year	Combined K
Medium-range (region, basin) 10m - 1 km; 1 month – 1 year	Extractable K, Combined K
Farm level	Extractable K

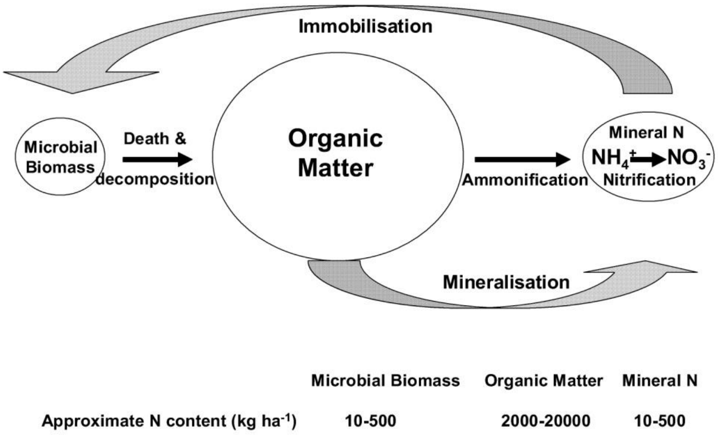
State of knowledge of the evaluation of the K stocks: Stocks of K at national, regional and local levels could in principle be estimated from the NSI data. The major challenge to accurate quantification is probably the geostatistical scaling-up. As noted above, the conclusions regarding sampling density and regions appear to differ between Defra SP project reports, suggesting that this is a subject for further research.

Progress towards improvement of the regime for monitoring K stocks: Soil extractable K corresponds well in size and dynamics with the K that is taken up by annual crops. Therefore, the RSSS projects provide a firm basis for the monitoring of the soil available K status under farming since 1969 (SR0118, SR0123, SR0127, SS0133) based on annual resampling at a limited number of sites from 1969 onwards. In contrast to that relatively limited sampling basis, some other projects (SP0506, SP0123) have looked at longer intervals (about 13 years) and a large number of sites using the NSI data.

Understanding of the degradation threats to the K stocks: Most soils possess a good buffer capacity to store and supply K to crops. The principles of monitoring exchangeable K and applying maintenance or remedial fertilizer doses appear to be managed effectively at present, through existing publications; the ‘Fertiliser Manual (RB209)' and the associated PLANET software (ADAS, 2010). An important development is the continued increase in “organic” farming practices. In organic farming, addition of nutrients and remediation of deficiencies may be more challenging than in conventional crop nutrition, because the substantial inputs of nutrients come through recycled organic materials which supply all nutrients together in ratios determined by their origins, whereas it is easy to supply N, P, K etc independently in conventional agriculture. Crop nutrition under organic farming systems has been studied under Defra’s “Organic Farming” Theme (OF0114, OF0126T, OF0145, OF0164, OF0180). This work constitutes a contribution towards understanding and avoidance of possible degradation or imbalance in K stocks. As examples, OF0145 noted that under a stockless organic arable rotation, there was a slow but progressive decline in measured soil extractable K, while OF0180 found that both positive and negative trends in soil K of fields could be identified over 4 years, although there was no overall trend for the self-sufficient organic dairy farming system. A further threat that has not been considered in Defra soils research to date is that of forestry, growth and harvesting.

Nitrogen, Classification of the N capital

Figure 5.3 Principal pools of N in soil and the processes that cycle N between them (ES0127).



Mass: The review (ES0127) of Defra projects from 1990 to 2005 provides an overview of UK soil N pools and processes (Figure 5.3). Almost all of the soil N capital is combined with soil organic matter, completely unlike the situation for K. The organic C:N ratio of surface soil is relatively constant, typically in the range 1:9 to 1:11. Thus decomposition of the soil organic NC is always accompanied by mineralization of N, and formation of soil organic matter accompanied by immobilization of N. Alone among the macronutrients, N undergoes interchange between soil and atmosphere, and most of the immediately available N exists in solution, resulting in a more dynamic system than for other nutrients.

The microbial biomass N is small in comparison with organic matter and important because it mediates most biochemical activity in the soil. However it is not a direct source of the N for the loss processes and uptake by plants. Although typically only 0.5 to 2.5% of the total N capital the mineral N component of N is fully soluble. It is the component that directly provides food for plants and is susceptible to losses through leaching and gaseous evolution.

Organisation: Different organisations apply to the different mass stocks of N (Table 5.2). Significant changes in the main stock of soil N can be detected only on a years-to-centuries timescale because it is an integral part of soil organic matter. At the long ranges of space and time, watershed/ landscape/regional space levels and time spans of a year and more, the changes in soil organic N are strongly relevant. The changes in quantity and distribution determine the medium-long term soil fertility patterns and reserves of N that determine crop productivity. These changes are essential to the understanding and management of soils in relation to climate change and national policy.

On the other hand, short-range variations (< approx 5mm) and short-term fluctuations (< approx 1 hour) in the energy, air and water status of a soil have substantial effects on the dynamic mineral N pool. The distribution and balance of forms of N, nitrate, ammonium and microbial N are affected by aggregate structure providing niches for biochemical reactions for organic N mineralisation and immobilisation, and the generation of N_2O (a “greenhouse gas”), NH_3 and N_2 gases. In conjunction with the dynamics of the soil water capital, these concentrations determine the amounts of N immediately available to plants and liable to loss via leaching and gaseous evolution.

Table 5.2 Soil Nitrogen Natural Capital

Mass	*Related ecosystem services / diservices*
Organic N	Fertility maintenance, climate change offset
Mineral N	N leaching and gaseous emission
Microbial N	Soil microbiological health and thus regulation of soil organic matter turnover, recycling of plant and animal residues and the processing/detoxifying of anthropogenic organic biochemicals.
Energy	*No clear involvement of N*
Organisation	*N masses involved*
Long-range (nation, region) >100m; > 1 year	Organic N
Medium-range (region, basin) 10m - 1 km; 1 hour – 1 month	Organic N, Mineral N
Farm level, field level	Mineral N
Short-range <1m; 1 min. – 1 day	Mineral N, Gases, Microbial N

State of knowledge of the evaluation of the N stocks: The UK total soil N stock for 0-15 cm can be estimated from the latest Countryside Survey (CS) results for topsoil %N concentration for GB (Emmett et al., 2010). From CS data, the total-N stock (0-15 cm) in each country in 2007 can be calculated from the mean soil total N density (kg/ha) for 0-15 cm across all Broad Habitats multiplied by the total habitat area. This gives estimated stocks (0-15 cm) for England of 67 TgN, for Wales of 13 TgN and a total for England and Wales of 80 TgN. Soil mineralisable-N was also measured by CS in 2007 to provide an index of the amount of nitrogen available to plants. From these data the mineralisable-N stock (0-15 cm) is 0.2 TgN for England and Wales, 400 times smaller than the total-N stock. The NSI did not measure N in any form because soil organic N is closely correlated with soil organic C. An additional approximate assessment is possible from the soil organic matter stock. The median SOC was 3.6 % and the land area of England and Wales is 151 123 km^2 (Oxford Reference Online, 2010). The C:N ratio of soil organic matter in arable soils is normally in the range 11:1 and 9:1 (Rowell, 1993), and assuming a typical value of 10:1, this gives a soil organic N stock of approximately 102 Tg for 0-15cm soil. An alternative estimate can be made from published data of Smith et al. (2000), who estimated soil organic C in UK arable land (0-30cm) at 562 Tg, with the comment that this was about half of the previous estimates. Again assuming a C:N ratio of soil organic matter of 10:1, and assuming a typical value of 10:1, this gives a soil organic N stock of approximately 56 Tg, for the UK and 0-30 cm.

The CS value for N stock falls between the estimated N stocks from NSI and Smith et al (2000). The total habitat area for England and Wales estimated from CS was 148375 km^2 which is only slightly smaller than the Oxford Reference value. The mean C:N ratio for 0-15 cm measured by CS across all Broad Habitat types in Great Britain in 2007 was 16.0. Using this value and the total mean C stock (0-15 cm) for England and Wales from CS gives an estimated organic nitrogen stock of 60 TgN.

Perhaps the conclusion here is that although N is the most important single nutrient in the ecosystem, and changes in the N stocks are being assessed via soil organic C measurement, quantification of the overall stock is rather imprecise at present, something which Countryside Survey will address to some extent.

To improve the above estimates, more representative assessments of soil C:N ratio could be obtained from the literature and Defra literature, eg. the range 8.8 to 13.1 was found in some UK grasslands (BD1429). The C:N ratio of a soil can be changed in the long-term by N-deficient or N-surplus land management. Defra research has not assessed this possibility for building additional N stocks over that provided by SOM enhancement. A further important aspect will be the concurrent understanding of the rate at which N transformations occur.

Progress towards improvement of regime for monitoring N stocks: N stocks have several distinct components of greatly different dynamics. Long-term monitoring of N stocks in soil for national and regional soil fertility should be through monitoring organic C since organic matter contains the medium-to-long term N stock, though CS and NSI have yet to agree on the stock and change. SP0124 addressed issues of spatial and temporal variation regarding the NSI, with a suggestion that monitoring should could take place at 10-year intervals and on a 10-km grid a major cost saving over the NSI 5km grid. Given that significant changes in soil organic matter and organic N are likely only at intervals of 10 years or more, the coarse sampling appears appropriate to assess underlying trends in the N capital.

Monitoring for mineral N on a short time-scale appears highly desirable to predict available N supply for crops and potentially leachable N. Defra has continued to fund approaches to this (NT2501). However, long- and short-term assessment and prediction of N losses is complex because the losses are the aggregate of short-term events in spatially variable land and in both the nitrogen and water cycles. As stated in the comprehensive review ES0127 with regard to water pollution: “although initially nitrate leaching was perceived as a problem of the chemistry and biology of the nitrogen cycle it was quickly realised that soil structure and water flow patterns were significant controlling factors (SR0121)”. Simulation modelling to integrate the biology and hydrology would improve assessment and prediction of N losses; but to gain more accurate models, N measurements need to be coupled with broad classes of C and microbial quality, not just C:N ratios.

Since the dynamics of soil mineral N are at the heart of monitoring and understanding the N cycle, much more intensive measurement of it is desirable but its measurement is labour intensive. Recognising this problem, funding has been put into development of more rapid methods (AR0910). There is no remote sensing technique available and for now, no early prospect of monitoring mineral N on a routine basis at a national or regional scale, only on the basis of selected sites.

Understanding of the degradation threats to the N stocks: Because of the obvious importance of the costs, economic and environmental, of N fertilization, Defra has funded a major soil research programme on N, which is comprehensively reviewed (ES0127). Studies have been made at the field level of inputs, outputs and losses (e.g. NT1833), and the process level. Inputs of N through deposition from the atmosphere contribute significantly to the available N in soil to the extent of about 50 kg N/ha per year in SE England (SP0202). Atmospheric N deposition adds to the N stocks, but because a large part is acidic it is also a degradation threat to soil cation stocks (SP0202) and thus the performance of soil as a nutrient supply.

At the field scale, all removals of N represent degradation threats. Degradation of a nutrient stock occurs when outputs and off-takes exceed inputs for the system under study. The compilation of nutrient budgets at various scales informs on this possibility and the methodology and benchmarks for farm-scale budgets of N and P have been researched (ES0124), and N budgets used to help assess sustainability e.g. in organic dairy farming (OF0180).

Phosphorus, Classification of the P capital

Mass: Key features of soil P stocks are (i) that the unavailable reserves of soil P are distributed between soil organic matter and inorganic minerals that are derived from the soil’s parent rock material, and (ii) most inorganic phosphate is very strongly adsorbed to the soil’s mineral surfaces (Figure 5.4). Because of the latter property, its concentration in soil solution is low at any time, and therefore it shows restricted availability both as a plant food and for leaching loss. The concept of a distinction between available and unavailable, for plant uptake, forms of soil P has been put to practical use in the form of an index of plant-available P in soil, which in the UK is P extracted by a sodium bicarbonate solution known as the Olsen reagent. This is measured routinely in agricultural soils. The two stocks of total and Olsen-P appear natural and complementary ways of describing the soil P stocks, although it is recognized that the Olsen-P stock is defined by its method of measurement rather than being a chemically distinct entity in the soil. The National Soil Inventory contains comprehensive data on both total P and Olsen-P, thus describing the two obvious major soil P stocks.

Organisation

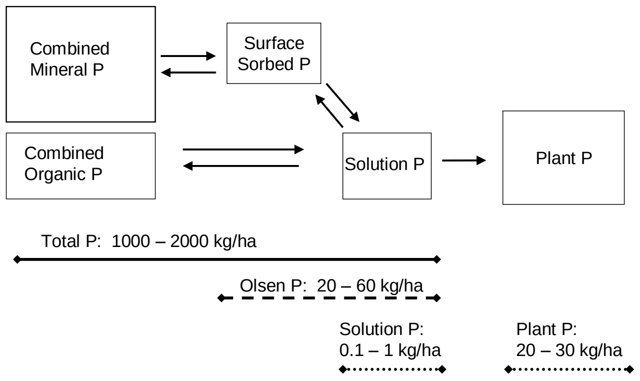


Figure 5.4. Principal pools and processes cycling P within soil. Approximate contents of total P and Olsen-P (kg/ha) are estimated from the 25th to 75th percentiles of the NSI data.

Temporal: P is distributed between organic, combined inorganic and surface sorbed phases, each with different timescales for change. Combined inorganic minerals dissolve very slowly on the timescale relevant to practical land management, while the organic component in soil organic matter contains an important P reserve that can be built or drawn upon significantly on a years to decades timescale. Soil solution P remains at a low concentration and shows restricted availability both as a plant food and for leaching loss, so the available P, including sorbed and exchangeable components does not fluctuate widely on a day-to-day and week-to-week timescale. However, the relationships between sorbed and solution P have been shown to affect the susceptibility of P to diffuse in solution and run-off sediments in conjunction with hydrological dynamics. On the weeks-to-months timescale, changes in available P are relevant to diffuse pollution with P.

Spatial: Very small scale variation (<~1m) has low relevance to the wider ecosystem services. The dynamics of P at the surface and aggregate structural level are determined by water films and the physico-chemical structure of soil surfaces, but not by aeration and there are no gaseous loss pathways. Diffuse loss and availability processes interact with soil minerals and hydrology at the field and landscape level.

State of knowledge of the evaluation of the P stocks: The two soil P forms measured by the NSI correspond reasonably with the practically-oriented assessments of P natural capital suggested. Olsen-P corresponds with the available P on a weeks-to-years timescale, while the “total” P measured by *aqua-regia* digestion includes the main reserve of P. The utility of Olsen-P for UK conditions was established in the 1950s to 1960s, and it is used confidently in conventional UK farming. Defra work in 1990-2008 has not reassessed the applicability of the method although the rise in organic farming may require some reassessment of the method (OF0114). This arises from the use of diverse P sources, especially organic ones, as the worlds’ stocks of high-quality phosphate rock for mineral fertilizer dwindle. *Aqua-regia* digestion does not recover all of soil P as the definitive methods using sodium carbonate fusion or HF but it certainly reveals all of the P that might become available at the hundreds-of-years timescale and is accepted as a convenient measure of “total” P in the UK. The principal problem in scaling up Olsen-P and Total-P data to quantitative stocks is that of spatial variability, to convert the grid of point measurements into values applicable over mapped areas as discussed in the general observations.

Progress towards improvement of the regime for monitoring P stocks: The measurement of Olsen-P in the NSI, RSSS and CS datasets provides a large monitoring database at national, regional, farm and field scales. However, under organic farming, the larger inputs and stocks of P in organic compounds mean that the soil organic P pools are a significant source of available P, which Olsen-P does not assess. Soil organic P pools are not at present routinely assessed and Olsen-P may be under-representing available P for organic farming (OF0114). The organic P chemistry of organically farmed soils is diverse. In relatively inorganic P limited soils, organic P species make a variable but significant contribution to the plant available P pool; Olsen P is not very sensitive to this variation. It is possible that assessment including a component of organic P may be desirable in the future.

Understanding of the degradation threats to the P stocks: Defra research has made substantial progress in this understanding in the review period. The diffuse loss of P through erosion of sediments has come to be understood as an important contributor to water pollution. Crop offtake and sediment erosion are by far the major routes for P loss from soil and thus the main degradation threats. A substantial Defra research programme was therefore conducted in the period 1994-2003 (NT1012, NT1015, NT1016, NT1023, NT 1024, NT1026, NT1027, NT1028, NT1041, NT1043, NT1044 NT1046) and various soil P fractions and properties measured, such as Olsen-P, $CaCl_2$-extractable-P, properties of P sorption isotherms and Equilibrium P concentration (EPCo) and particulate-P. Olsen-P has been suggested (Table 5.3) as a good natural capital to be quantified and monitored. But if management of P diffuse pollution becomes a higher management priority than P for crop nutrition, then alternative measures of the soil extractable P might be better suited as stocks to be assessed for scaling up to catchment and regional scales to meet national priorities. It is noted that upland soils are at particular risk and the threat is likely to increase with climate change (SP0407). P budgets complement the monitoring of soil stocks just as they do for other macronutrients. P budgets have been applied at the farm level, particularly to improve the assessment of organic farming systems (OF0114, OF0180),

Table 5.3 Soil Phosphorus Natural Capital

Mass	*Related ecosystem services*
Combined P (Total P + Olsen P)	Fertility maintenance, Diffuse P pollution
Available P (Olsen P)	Crop production, Diffuse P pollution
Energy	*No clear involvement of P*
Organisation	*P masses involved*
Long-range (nation, region) >100m; > 1 year	Combined P
Medium-range (region, basin) 10m - 1 km; 1 hour – 1 month	Available P
Farm level	Available P

Micronutrients

Work directly relating to micronutrients in soil has not been commissioned in the review period, except as an aspect of the core activities to develop the NSI. However, some potentially toxic contaminant metals are also micronutrients, leading to some spin-off results. As a by-product of work on contamination from sludge, the NH_4NO_3 soil extraction method was shown to be a good monitor of bioavailable Zn which gave yield increases in some cases, but it was less effective for Cu (SP0109, SP0125). Animals require micronutrients which may become concentrated via excreta in the soil of intensive production systems such as poultry and pigs and studies on this (SP0129) reveal dynamics of micronutrients such as Cu and Zn.

5.1.1.3 Soil organic matter, and carbon stock

Defra is committed to protecting and enhancing soil carbon stores by protecting current stores and by improving understanding of how to increase levels of soil carbon. Given the cost, and the need to reduce greenhouse gas emissions, understanding this organic matter carbon stock is of importance for policy development. By understanding the soil organic matter carbon stock as a NC resource it may be possible to evaluate changes in the magnitude of this stock that may impact climate change, and better determine agricultural soil quality which is linked to organic matter levels.

Key findings:

- Current estimates of soil carbon stock for UK soils vary depending on assumptions and methodologies used.
- Major uncertainties exist: soil mapping uncertainties include, depth of soil in particular peats, and bulk density values at depth below topsoil.

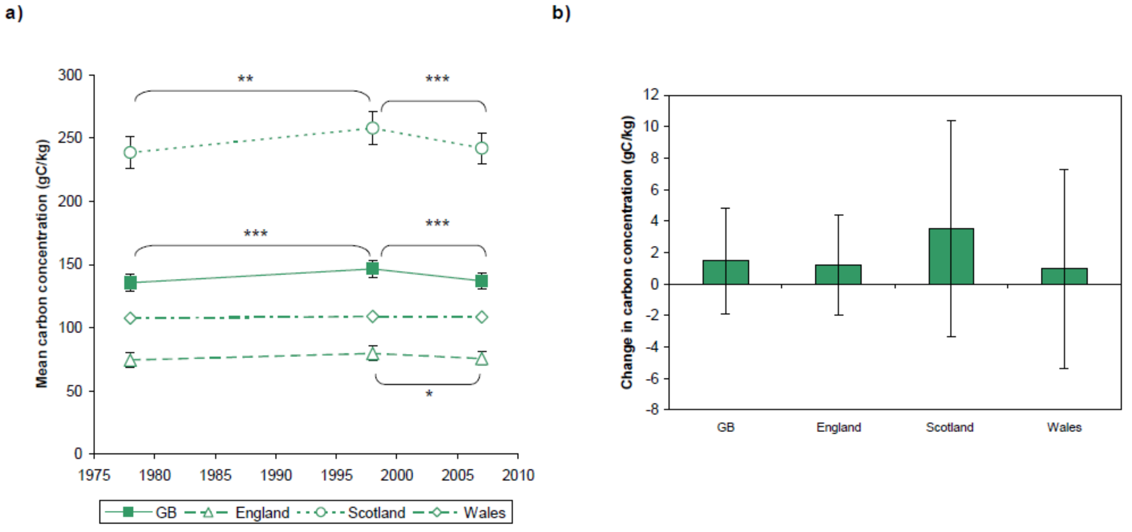
Stores of soil carbon in the form of organic matter are important from agricultural and forestry perspectives, as soil carbon in the form of organic matter has been demonstrated to play a key role in enhancing soil structure and in improving water and nutrient retention. From the environmental perspective UK soils are estimated to store more than 10 billion tonnes of carbon. The loss of this store, in the form of CO_2 to the atmosphere, would be equivalent to more than 57 times the UK's greenhouse gas emissions for 2007 (PB13297, 3.1). Organic matter decline due to cultivation has been estimated to cost ~£82 million per year by the Environment Agency (PB13297).

The most frequently cited estimate of UK soil carbon stock is that of Bradley et al. (2005) recently updated for organic soils by Smith et al. (2007). However, estimates of soil carbon reserves are heavily reliant on the quality of soil maps (degree of ground truthing, map scale, classification type) and on algorithms describing carbon density in soil (Frogbrook et al. 2009). Consequently, estimates of national soil carbon storage in a recent estimate of uncertainties surrounding the Welsh soil carbon stock indicated give a range of 340-530 Mt carbon if different mapping approaches and datasets were used (Malik 2006).

Change in soil carbon quantities is included as part of the UK GHG emission inventory which are prepared to internationally agreed guidelines prepared by the Intergovernmental panel on climate change (IPCC). These guidelines are used to ensure that emission estimates are consistently reported internationally for compliance with the Kyoto Protocol. The Land Use, Land Change and Forestry Inventory, prepared by CEH (e.g. Mobbs and Milne, 2005), is based on estimates of emissions from the changes in carbon quantities in soils and biomass when the use of specific land areas is changed (e.g. arable land changing to forest). In addition, for forest land use remaining as forest land, the C-Flow model (CEH Edinburgh) is used to estimate changes in carbon content of soil and biomass to provide an estimate of CO_2 emissions and sinks. But for other land uses which have remained unchanged for many decades and where soil carbon levels have reached equilibrium, the net CO_2 emissions from soils and biomass are assumed to be zero because the overall system is hypothetically in equilibrium - except "liming". Changes in soil carbon take many years to reach equilibrium. Carbon losses are assumed to occur over 50-150 years, while carbon gains are assumed to occur over 100-300 years. Emissions and removals for any one year include estimates of the continuing loss or uptake of carbon as a result of land use change in previous years. Monitoring work to detect change in carbon stock provides a potentially valuable cross-check with these essentially modelled and activity based estimates.

The Sustainable Farming and Food Strategy (SFFS) for England and Wales considers topsoil SOC as a headline indicator for the better use of the soil resource (SP0546). The Food, 2030 report indicates that SOC is declining, with the caveat that the sampling is infrequent. Trends in topsoil organic carbon (SOC) stocks have been estimated at the national and regional levels by the National Soil Inventory (NSI) (SP0521, SP0533, SP0545) and by the Countryside Survey (Emmett et al., 2010). NSI used a grid based mapping approach with a resolution of 5km, sampled to a depth of 15cm. The survey was first conducted between 1978 and 1983 and then a subset of sites were re-sampled to try and detect changes in SOC (SP0115, SP0118, SP0521) The re-sampling results (SP0521, SP0545) suggested losses of SOC across England and Wales in most habitats although there were gains in soils of small organic matter content. Carbon was estimated to be lost at a rate of 0.6% per annum over the survey period relative to the existing SOC content (Bellamy et al., 2005).

Figure 5.5 Change in soil C concentration (0-15cm) for GB and individual countries (a) over time and (b) net change between 1978 and 2007. Standard errors are indicated. Significant differences (*** p<0.001, * p<0.01, * p<0.05) are shown between the years bracketed.



Concurrently, the Countryside Survey (Emmett et al., 2010), an ecosystem survey including soils, based on a stratified random sampling scheme based on land class reported no significant change in soil carbon (0-15 cm) for England or Wales between 1978 and 2007 (Figure 5.5) (Emmett et al., 2010). The reported research could not confirm the loss of soil carbon reported by the Bellamy et al., (2005). However, both approaches found that there was the loss of SOC (0-15cm) from the intensively managed Arable and Horticulture Broad Habitat / Crops and Weeds Aggregate Vegetation Class. There are a range of differences between the approaches in addition to sampling design including number of samples, relocation variation, analytical, methods and statistical analysis. Full details of these two studies are presented in the review of soil monitoring networks carried out for a wide range of agencies including Defra (SNIFFER LQ09) In a comparison of the two programs the Countryside Survey estimate for carbon stock for England and Wales was 954 Tg in soils (0-15cm) (Emmett et al. 2010), in contrast to the estimate of 864 Tg for England and Wales estimated by Bellamy et al. (2005) based on the NSI data. One possible contributory factor to this difference was a new conversion factor for determining SOC concentration from LOI using 0.55 for CS compared to the factor of 0.5 used by Bellamy et al. (2005) Another difference is the difference in bulk density factors used. Estimates for the NSI were calculated using a pedotransfer function first reported by Howard et al., (1995) whilst CS based on measured bulk density in 2007. The only other significant evidence of change in SOC concentration was reported by Kirby et al., (2005) for British woodlands. Kirkby et al. (2005) sampled, 1648 plots randomly located in 103 woods, first in 1971 and again in 2000-2003; their findings suggest no significant change in SOC over 30 years, topsoil C concentration remaining at ~88 g C kg^{-1} (slight increase of +0.38% over 30 years; ~+0.01% y^{-1}). Project LQ09 gave a review of soil monitoring schemes in the UK, it identified 24 schemes out of 27 that contained the SOC indicator, which reports carbon concentration; however, many of these schemes do not contain bulk density which limit their application in determining change in carbon stocks.

Discussion continues with regard to methodologies employed and the results obtained. In the wider literature, national scale EU monitoring programs have been reviewed by Kibblewhite et al. (2008), Morvan et al. (2008) and Schils et al. (2008). Lack of bulk density measurements are a common criticism levelled at these programs, as well as insufficient sample numbers, and lack of repeated explanatory measurements. Countryside Survey, in 2007, has endeavoured to address the issue of bulk density although there is still a major weakness in sampling of topsoil only. Recent research advances in methods that may support further national scale SOC stock estimates include, the use of airborne geophysics. Spatial analysis of geophysical data, collected over N. Ireland, showed a strong negative relationship between the airborne radiometric potassium signal and soil organic carbon sampled on a 2 x 2 km grid; as the mineral content of the soil declined the SOC content increased (Young et al., 2007).

All major organisations currently involved in soil monitoring recently contributed to a report to the Environment Agency (SC060073/SR) considering how future UK soil monitoring would best deliver the requirements required by a range of stakeholders which focussed on soil carbon to a large extent. Much of the work was focussed on the sampling design and a design-based stratified random approach was found to be more suitable for assessing change and status of soil carbon relative to grid and optimised-grid based approaches. Other recommendations from the report were sampling to depth, inclusion of bulk density and development of Standard Operating Procedures. Finally, integration with a network of measurement sites for carbon flux measurements and improved measurement of change in soil depth, particularly peat depth, would be valuable.

5.1.1.4 Soil organisms

The soil biomass is composed from a wide range of different organisms including bacteria, fungi, protozoa, nematodes, mites, springtails, enchytraeids and earthworms. Moreover, several other groups also spend part of their life cycle as larvae in soil such as beetles and flies. One gram of soil may support ten thousand protozoa, ten million bacteria and five kilometres of fungal mycelia. In turn, microbial organisms dominate the soil biomass. The microbial biomass of the plough layer in unfertilised arable plots at Rothamsted was estimated as equivalent to around 100 sheep per hectare (Brookes, 2001). The soil microbial biomass is widely recognised as the key agent in soil organic matter breakdown and recycling of plant nutrients. However, the larger meso- and macro-fauna also play an important role by regulating microbial populations, breaking down litter and in the physical alteration of soil properties. Without the activity of these organisms soil remains as a weathered mineral material containing recalcitrant organic detritus. Clearly, the organisms in the soil form the engine that drives dynamic soil processes.

The activity of the soil biomass is central to the multi-functional nature of soil and the provision of supporting (nutrient cycling; soil formation; primary production), regulating (climate regulation; disease regulation; filtering, buffering and transforming pollutants) and provisioning (genetic resources) ecosystem services. Equally, the soil biomass provides diagnostic indicators of soil health. In turn, assessing the quantity or NC stock of soil biomass is of great importance in terms of the soil protection strategies.

Baseline data on the stock of organisms provide a powerful gauge against which future changes in soil properties and threats to their function, including climate change, may be quantified. This links closely with the assessment of current soil quality indicators (Section 4.1). Regular measurements over time can provide evidence as to whether the soil biomass stock is in decline. Given the range of services associated with the soil biomass we can also assess whether it matters if the soil biomass stock declines i.e. has the functional capacity also declined. The diversity of the soil biomass stock is considered as a component of 'Biotic structure' later in the section.

Key findings:

- Countryside Survey has been instrumental in the enumeration of soil invertebrate communities at GB scale for the first time in 1998 and highlights broad differences between environmental zones and habitats.
- Evidence of increased soil invertebrate abundance from 1998 to 2007 in all habitats except arable was indicated by the Countryside Survey.
- Long-term sludge experiments indicate that addition of zinc-rich and copper-rich sewage sludge (resulting in soil concentrations that would exceed statutory limits under operational practice) have a negative impact on microbial and invertebrate populations.

The soil component of the Countryside Survey undertaken in 1998 (also known as CS2000; Environment Agency 2002) represented the first British national-scale assessment of soil communities (Table 5.4). CS2000 produced a baseline dataset of invertebrate group level community composition across all major soil groups and habitats of GB. It showed how populations of culturable heterotrophic bacteria, oribatid mites and springtails varied across the major environmental zones, vegetation classes and soil types (Black et al., 2003). The sampling of soil invertebrates was repeated as part of the Countryside Survey in 2007 (Emmett et al. 2010) and thus became the only project to have assessed the stock of soil organisms at the GB scale over time. The repeat sampling demonstrated that abundance of invertebrates in 2007 was greater than in 1998 under all vegetation classes except Crops and Weeds, and that these differences were due largely to greater mite populations. While a single repeat sampling campaign such as Countryside Survey cannot determine unequivocally whether change in soil populations is underway it is noted that this kind of long-term and large-scale dataset is essential to understand potential drivers of change. Further analysis is needed to tease out the relative roles of changes in soil chemistry, land management, weather, climate and natural population variation in influencing the soil invertebrate community changes; some of the key large scale monitoring programs are listed in Table 5.4.

Table 5.4. Key large-scale soil monitoring projects in GB and details of their spatial and temporal coverage.

	Key project	Spatial coverage	Temporal coverage
1	Countryside Survey	National - England, Scotland & Wales can be reported separately. - Covers agricultural and semi-natural habitats.	Every 8 or 9 years.
2	Long-term heavy metal experiments	Local to Regional - Expanded to 9 sites on different soil types.	Biennial.
3	Environmental Change Network	Local to National - 12 sites distributed across GB	Every 5 years

Priority biological indicators were identified in the first phase of SQID (SP0529) as potential candidate indicators for a national soil monitoring scheme and they included soil microbial biomass characterised from Phospholipid Fatty Acid (PLFA) profiles and nematode communities. The total PLFA content is indicative of the total viable microbial biomass and it is now widely used to study soil microbial communities. Individual PLFAs can also be used to gauge the relative abundance of bacteria and fungi. Evidence suggests PLFAs can be used to discriminate land use, soil type, management and pollution effects. However, it was highlighted in SP0529 that there has been no systematic study of PLFAs in the full range of soil types that might be covered by a soil monitoring exercise. Likewise, the wider literature indicates the high potential of nematode populations to monitor the impact of environmental pressures on soil. The second phase of the SQID project (SP0534) examined a wider range of soil organisms from a small subset of the Countryside Survey locations and is due to report this year. Its aims were to establish standard operating procedures for the priority biological indicators, compare the ability of priority indicators to discriminate between a range of soil-land use combinations, test the sensitivity of priority indicators to distinct environmental pressures, and to determine the degree of surrogacy between these biological indicators. Clearly, the outcomes of SP0534 will have a major bearing on how the stock of soil biomass is assessed, and which groups of soil organisms are assessed as NC, in future monitoring schemes.

Once appropriate indicators of soil biomass have been identified, national baseline datasets will become crucial in defining expected or target values and ranges. Studies relevant to assessing the stock of soil biomass in the wider literature are both spatially and temporally disparate. Any attempt to synthesise the wider literature in this respect will therefore be limited by the associated variability. Systematic assessments of soil organisms undertaken by a number of other European nations could be useful to provide these expected or target values against which to compare changes. In particular, the Netherlands have a well established soil biological monitoring programme (see Rutgers et al. 2009). This consists of around 300 locations in a random stratified design comprising combinations of land use and soil type which are covered over a six-year sampling cycle. This scheme now has average values for the biomass and abundance of a wide range of soil organisms derived from 10 years of measurements.

Having a thorough knowledge of the stock of soil organisms means that the impacts of degradation threats on soil biomass and the functions it performs can be better understood. IF0117 examined the scientific literature to assess the impact of crop management practices on soil microbiota, focusing on crop rotations, tillage and soil amendments. The report highlights that with increased intensity of land use changes to crop management practices will be necessary, and this is most likely to be in the form of shorter rotations or even continuous culture of arable and biofuel crops. Evidence suggests that this can have a negative impact on crop health, yield and agro-ecosystem function as a result of effects on soil microbial populations.

The second phase of the SQID project (SP0534) has also utilised the long-term sewage sludge and heavy metals experiments to look at the response of the different priority biological indicators to pollution. These studies, funded by Defra and partners (UKWIR, EA and WAG), were initially set-up in response to recommendations from an independent scientific committee on ‘Rules for Sewage Sludge Applications to Agricultural Land’ in 1993. Their aim is to assess the long-term fate, behaviour and impact of metals introduced into the soil through application of sewage sludge and they are important to better understand suitable application rates for different soil types. Chapter 3 in ES0127 provides a comprehensive overview of phase I and II of this long-term series of Defra projects and their main findings. Findings from phase III (SP0130) indicate that the size and activity of microbial populations have a generally negative relationship with increasing concentrations of zinc and copper in sludge. Sludge amendments at one of the experimental sites have also been shown to influence soil invertebrates with nematode and enchytraeid abundance reduced in the high-zinc treatment and earthworm abundance reduced in both low and high copper treatments (Creamer et al. 2008). SP0534 will soon report further on the response of PLFAs, nematodes and micro-arthropods from a greater number of the experimental sites.

Defra is committed to supporting future research into the impact of climate change on soil, soil functions and soil threats (Section 4, PB13297). Improved understanding of how climate change will affect the stock of our soil organisms and their functions is much needed, and will inform strategies to adapt to such changes. Data from the Countryside Survey may go some way toward providing evidence of climate change effects on the soil biomass but lacks temporal resolution. The national scale and sheer number of locations in CS means that more intensive temporal monitoring across time is simply not possible. Expanding CS to include any priority indicators identified and tested in Defra projects is more feasible but it would clearly require additional resources. The Environmental Change Network (ECN) comprises only 12 terrestrial sites, although recent unpublished analysis demonstrates that the plant communities represented span much of the range covered by CS as a whole. The key strength of the ECN, however, is that the main drivers of environmental change, i.e. climate, atmospheric pollution and land use are all monitored locally, in addition to above-ground components of the ecosystem, thereby providing a powerful explanatory context for observed biological changes. The network has recently provided evidence of potential climate-related effects on aboveground organisms (Morecroft et al., 2009) and noted for example that the direction of change in beetle and butterfly abundance over the last two decades differs between sites in the north/west and south/east of GB. While the ECN monitors a number of bulk soil properties every 5 years, and also provides 2 weekly monitoring of soil solution chemistry it currently lacks any monitoring of soil organisms. Over the past two years, however, interest has been expressed from a range of soil scientists to develop soil biological monitoring and research across the network. Clearly, there is scope, and widespread scientific interest, in developing monitoring of soil organisms at these sites, as an integral part of a wider programme to determine the influence of variation and change in climate, air pollution and land management on soil properties and function.

5.1.2 Liquid: Soil water content stock

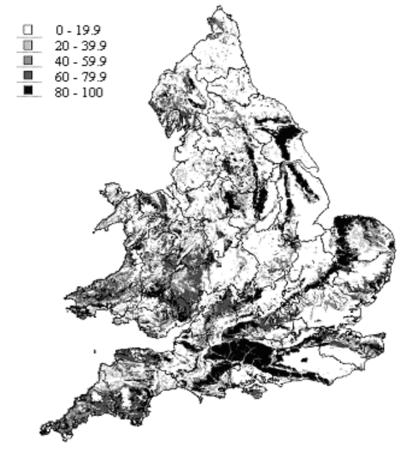
Soil moisture is critical to plant growth and forms the water pool that sustains life, moreover, it controls microbial activity which in turn controls and regulates soil biogeochemical cycling, especially respiration and carbon fluxes. The capacity of the soil to absorb moisture also controls the partitioning of rainfall arriving at the soil surface between infiltration and runoff which regulates flooding. Unlike soil carbon, soil moisture is highly dynamic, varying weekly or even daily, depending on weather conditions locally and regionally. In this sense, the NC stock of soil water is less readily interpreted. Defra has committed to building the resilience of soils to a changing climate (PB13297, chapter 4) which is expected to produce hotter, drier summers and warmer wetter winters. This means a higher expectation of soil moisture limitation and drought, as well as more potential flooding in winter. Defra has supported research on soil moisture with regard to drainage, flooding and the assessment of the soil moisture reservoir with regard to plant growth. By understanding the soil moisture NC stock it may be possible to evaluate the plant available water resource, soil respiration and carbon flux, aquifer recharge and the impact of climate change on soil function.

Key findings:

- There is no consistent spatio-temporal monitoring of soil moisture across scales.
- Measurement methods are emerging that integrate spatial areas ~0.5km^2 (COSMOS)
- Models are too compartmentalized to predict complex interactions, and emergent behaviours, that might result from climate change.

Measurement of soil moisture content

Figure 5.6 Percentage of soils that are of Wetness Class I (well drained) when not drained. 1km^2 grid. Old MAFF Division boundaries also shown. From (ES0111)



Soil moisture is not routinely measured at national, regional or local scales in the UK, but is modelled using the Joint UK Land Environment Simulator (JULES) for Met Office applications. Some of the automatic weather stations at ECN sites measure soil water potential using gypsum blocks which is converted to moisture but the 12 ECN sites are spatially sparse. A snapshot of soil water content at national and regional scales is provided by (ES0111), which reports a database of agricultural drainage. The report is based on data from the 1960's but highlights the proportion of soils in England and Wales that are in wetness class 1 (Fig 5.6), which means they drain well naturally. The large areas of white (Fig 5.6) indicate broad areas of England and Wales that are subject to too much water. Measurement of soil water has typically been carried out using in situ instrumentation. This has the advantage of local accuracy, but is difficult to extrapolate or interpolate to regional scale in a highly spatially varying soil environment. More recent advances in instrumentation, such as COSMOS (Zreda et al., 2005), allow determination of areal average soil water content over larger areas (~0.5 km^2).

With regard to point measurement (10 cm scale) Defra has funded research on the use of capacitance soil water sensors (SR0121). This project compared the capacitance probes (CP) with neutron probe (NP) (Standard method) and gravimetric sampling (Grav) (Standard method). Agreement between NP and Grav was r^2=0.88, where as the CP and Grav was only r^2=0.42 which was attributed to stones and the small sampling volume of the capacitance sensor. Research in the wider literature has indicated that high frequency time domain methods are the best alternative to the neutron probe (Anon 2008); especially the new time domain transmission sensors (Blonquist et al., 2005). Potential opportunity exists for exploiting some of the new technology and developing wireless networks of sensors. There is no evidence of a consistent monitoring of soil moisture across scales in a coordinated manner in England and Wales, with only the 12 ECN sites having limited moisture information. This is likely to be an impediment to future modelling efforts, for which soil moisture is likely to be an important state variable for understanding the impacts of climate change.

A 2004 report for Defra (Wood et al., 2004) considers 'the use of remote sensing to deliver soil monitoring' national and regional scale soil moisture is addressed in section 2.3 on radar techniques. The report indicates active microwave methods are feasible but sensitive to relief and surface roughness, whilst passive microwave has not yet been fully explored. This is in broad agreement with the wider literature (Robinson et al., 2008). However, in the USA for example the Natural Resource Conservation Service (NRCS) is deploying Soil Climate Analysis Network (SCAN) stations around the USA to improve spatio-temporal monitoring of soil moisture, temperature and solution electrical conductivity (http://www.wcc.nrcs.usda.gov/scan/). This network essentially consists of weather stations with soil sensors. Given that low-cost (£100, as compared to traditional time domain reflectometry ~£10,000), multi-parameter soil moisture/temperature sensors are now available (Blonquist et al., 2005) this becomes more economically feasible. Linking soil measurements to ECN sites might be one path forward. Future soil moisture monitoring methods that have been reported include GPS receivers (Larson et al., 2008) and COSMOS sensors (Zreda et al., 2005). These perhaps offer the most potential for providing ground based measurements suitable for assessing model estimates from MOSES, JULES or related models (more details are presented about these two models in the below section on spatial interpolation of soil moisture). The sampling volume of a COSMOS sensor is ~0.5 km^2, but research is needed to determine how these sensors integrate soil moisture measurement over this area.

Measurement of soil water retention and transmission properties

The evolution of soil water content over time depends on the water retention and transmission properties of the soil. These soil characteristics are also critical to the choice of suitable land use, and water management for agriculture and other purposes. Water characteristics of soils can be determined from the land information system developed through Defra support (SR0102, SR0105, SR0117, SR0119, SR0122, SR0124, SR0126, SR0129, LE0304, LE0306, LE0309).

Spatial interpolation of soil moisture

National-scale estimates of soil moisture content are required for various purposes, notably maintaining agricultural productivity. In the absence of a dense network of continuous soil water measurements, soil water content at regional scale must be estimated by modelling. Models based on the physics of the system rather than statistics are driven by estimated precipitation and energy measurements as inputs to the soil, and using these, together with soil water retention properties and plant cover, evapotranspiration runoff, groundwater recharge and soil moisture are estimated. While these estimates have the disadvantage being model-based, a problem with interpolation from fine scale field measurements is their large spatial variability at a small scale. Larger scale direct estimation of soil moisture would overcome this problem. At present in the UK, the Met Office MORECS model is the only nationwide service giving temporal model-based assessments of rainfall, evaporation and soil moisture; the resolution of MORECS is 40 km squares which is of limited use for soil protection work. The underlying MOSES model has the potential to offer 2km grid square scale which would be suitable for national soil protection work. MOSES is essentially an atmospheric model with a crude land-phase attached. The JULES model has been developed from MOSES to improve the land phase representation of the energy and water budget. JULES has been applied at a 1km square scale for the United Kingdom, but its main focus is the energy and water budgets rather than soil moisture estimation *per se*, and further development of the model is needed to investigate and improve the reliability of the soil moisture estimates. Nevertheless, in the longer term it is likely that models like JULES will provide progressively improving model estimates of soil moisture where direct measurements are not available, but these models still require ground based data to check they are on track.

Soil moisture change over time

Modelling is essential to estimate possible future change in soil moisture. Climate change projections given by the UKCIP09 scenarios indicate higher winter rainfall and lower summer rainfall. This would have a major effect on soil water regimes. Therefore monitoring and prediction of soil moisture across scales is important, not only for understanding ‘soil change’ but for understanding impacts on other important soil processes. The 2003 Defra funded report (EPG 1/1/158) reviewing climate change indicators highlighted soil moisture as an important indicator. This review stated, “*This indicator is unlikely to be sustainable in the absence of targeted funding to support its updating. The preferred datasets are held by the Met Office. Discussions should be initiated with the Met Office to determine how best to derive a regional soil moisture index for future usage. Their MOSES system appears to have considerable potential.*” Subsequently JULES has been developed from MOSES, but requires improvement in its treatment of the landsurface to improve soil moisture determination. Soil moisture was also considered an indicator in the search for indicators of soil function. Soil moisture at 1m depth was considered (P5-053/2/TR); though it did not make it into the final prioritisation of indicators for soil function, which emphasises soil biology and chemistry (Defra, 2010). LQ09 identifies that national monitoring schemes contain limited soil physical information.

Soil water management

Soil resilience is the ability of the soil to recover functional and structural stability following disturbance and is aided by clay mineral content, organic matter content and biodiversity. A consequence of resilience is a soil water regime which allows continued soil function. So improving soil structure increasing soil water holding capacity may build resilience, while the consequent higher moisture storage is an outcome of resilience-building. Nevertheless, landscape resilience (going beyond soil resilience) can be influenced by soil water management. Until recent times, one of the main focuses of soil water management was the drainage of land for improved agricultural productivity. To this end, field drainage systems were installed in heavier soils and wetlands were drained by systems of ditches, sluices and pumps. This has led to declines in the area of wetlands in the UK which are now recognised as a threat to biodiversity in particular. Many formerly reclaimed farmlands now have their water levels managed so as to promote the re-development of wetlands with their associated flora and fauna. This water level management generates landscape resilience. Defra has invested significantly in research into the management of these revived wetlands. A review of restoration of blanket bogs (BD1241) indicates that wildfire is now the major risk to these environments with risk from afforestation and grazing etc. reducing. 'Grip' blocking (BD1322) or the infilling of drainage ditches is identified as the key management strategy of interest. Efforts to link wetland management to the ecosystems approach have been initiated by the Wildfowl & Wetlands Trust at their Otmoor protected area (NR0112).

5.1.3 Gas: Soil oxygen and gas stocks

Soil gas stocks are contained in the non-water filled pore space of the soil. The primary gases of interest in this pore space are oxygen (O_2), and carbon dioxide (CO_2), however, methane and nitrous oxide are also of major interest with regard to greenhouse gas production. Ensuring sufficient soil oxygen concentration is critical for healthy plant growth and production functions, whilst CO_2, methane and nitrous oxide are all important greenhouse gasses whose concentrations and emissions to the atmosphere have environmental implications. Defra is committed to protecting soils from degradation threats in both agricultural and urban settings. Compaction is an important threat to gas stocks, both the reduction in O_2 and the generation of nitrous oxides. Defra has supported research on soil compaction; and has also supported work on gas emissions from soils. By understanding the gas stocks, it may be possible to evaluate how degradation, for instance by compaction may change oxygen availability to plants; or conversely how management strategies impact greenhouse gas production and emission.

Key findings:

- No routine monitoring of soil gas composition is conducted in the UK as the technology is still emerging for routine insitu soil gas measurement.

Soil porosity (void space) can be determined from soil bulk density; the proportion of this pore space filled with gas can be determined (if the soil water content is known) simply by subtracting the proportion of moisture filled pore space from the total pore space. Knowing the air filled porosity will not provide any information on the type of gases present which can be important for determining greenhouse gas emissions and oxygen supply to plants. Research in the USA suggests that root growth requires oxygen diffusion rates of 0.20 µg cm^2 (Stolzy and Letey, 1964). It wasn't until recently that low cost soil sensors capable of monitoring soil gases insitu with a data logging capability were developed. Sensors currently available include the SO-110 (Apogee Instruments inc., Logan UT), for monitoring O_2, and the GMM-220 for monitoring CO_2 (Vaisala, Helsinki, Finland); methane and nitrous oxide still require measurement by chamber extraction and lab analysis. Recent research in the wider literature describes the application of these types of sensors (Turcu et al., 2005). Given that only recent advances in sensor technology now permit measurement no routine monitoring of soil gases is conducted in the UK. Bulk density data, from which porosity could be determined, is collected at a coarse national scale with the Countryside Survey (Emmett et al., 2010) and for soil series as part of the NSRI NATMAP data (LE0306) contained in LandIS.

5.2 SOIL ENERGY

5.2.1 Temperature: Thermal energy

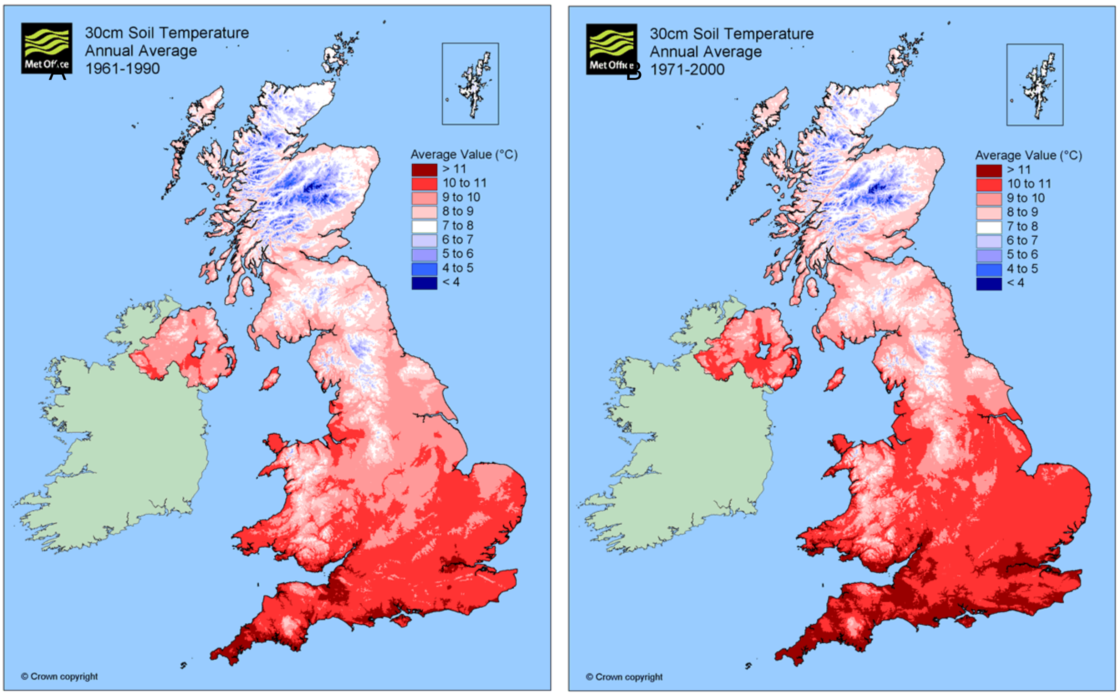
Soil temperature is an important control and regulator of both microbial activity and the rate of chemical reactions that contribute to the soils biogeochemical cycling processes. Both land use and climate changes have important implications with regard to mean annual soil temperatures and biogeochemical cycling in soils. Defra and WAG recognised the need to build resilience into soils in order to allow for adaptation to climate change (PB13297; WSAP, 2009). Changes in soil temperature may lead to alteration in the speed at which biogeochemical reactions occur impacting many processes ranging from nitrogen mineralization, microbial respiration to pollutant degradation. By understanding how soil temperature changes will impact soil processes it will better help us to understand how to build resilience into our soils in order to help adapt to climate change.

Key findings:

- National monitoring of soil temperature is conducted by the Met Office, Environmental Change Network (ECN) sites also have sparse monitoring.
- Average annual soil temperatures for 0-30cm are increasing, especially across England.
- There is a need to determine if soil temperature is an important soil indicator for soil resilience to climate change

At the national scale soil temperature data is collected by the Met Office who have records extending more than 100 years. The 'Land Surface Stations data (1900-2000)' and the 'MIDAS Land Surface Stations data (1853-current)' (Met Office 2011) provide a valuable source for soil and air temperature for the UK; Figure 5.7 shows the UK annual average soil temperatures for the top 30cm of soil, and indicates and increase in the temperature stock markedly across England for the two averages. Defra supports the Environmental Change Network (ECN) site located at Drayton (CC0404; IF0140; IF0185), and has supported some data management (NR0116). Comparison of soil monitoring data, including ECN, is presented in report, SP0515, but focuses largely on other soil properties. The ECN has 12 terrestrial sites that include soil monitoring across the UK, with 7 in England and 1 in Wales, that measure meteorology, flora, fauna and soils and landuse. Soil temperature is monitored hourly at 10 and 30 cm depth as part of the automatic weather stations. The data provides high temporal resolution data that is spatially sparse. Table 5.5 shows which of the Defra supported soil monitoring schemes records soil temperature at national, regional and local scales.

Figure 5.7. The 30cm annual average soil temperatures for A) 1961-1990 and B) 1971-2000. The averages indicate a warming of soils especially across England. (http://www.metoffice.gov.uk/climate/uk/averages/ukmapavge.html).



Soil monitoring is very much tailored to the collection of soil static properties, such as texture, for inventory rather than the collection of high temporal resolution 'dynamic' soils data. Given the efforts to create land surface models for the UK, such as JULES (Blyth et al., 2010), which predict heat and water dynamics, collection of baseline 'dynamic' soils data is of growing importance. In order to understand the impact of climate change we need to develop a better understanding of soil moisture and temperature. For instance, Seneviratne et al. (2006) have indicated a strong link between heat-wave development and persistence in Europe that has been responsible for many deaths, and a decrease in soil moisture. Soil temperature and moisture will be important parameters for identifying climate change impacts on soil, and exploration of the Met Office soil temperature data sets could be an important contribution to our understanding of climate change for soils on anthropogenic time scales.

Table 5.5. Databases and monitoring of soil temperature based on 6 Defra data collections or soil monitoring schemes, with data collected by the Met Office for comparison.

Monitoring scheme	National	Regional	Local
Representative Soil Sampling Scheme	-	-	-
Countryside Survey	-	-	-
Environmental Change Network	Yes (Sparse)	-	-
Geochemical Baseline Survey of the Environment	-	-	-
Databases			
Land Information System	-	-	-
Multi-Agency Geographic Information for the Countryside (MAGIC)	-	-	-
Other			
Met office data	Yes	Yes	

Concern over climate change has refocused research efforts to confront the challenge of predicting, monitoring and adapting to ‘change’. Defra has supported a scoping study (SP0538) to outline the expected impacts of climate change on soil function. Given that surface temperatures are predicted to increase, and the close relationship between soil temperature and surface temperature, it is expected that soil function will be affected. The report indicates that along with soil moisture, temperature is a key control and modifier of soil processes, controlling the rates of reaction and microbial activity. Warmer soil will accelerate soil processes leading to more rapid organic matter decomposition and quicker release of nutrients, though the final emergent behaviour will depend on the interplay between soil temperature increase and soil drying. Important consequences of increasing soil temperatures identified in (SP0538) include, increased fire risk in peat soils, rising DOC affecting river water quality, increased soil chemical activity which may increase nutrient availability and may enhance chemical weathering of structures, and increased soil respiration and oxidation, which will likely increase carbon emissions.

A further scoping study (CC0378) has been supported focusing on the impact of climate change on nutrient pollution from agriculture. Of the 15 models considered only 6 were identified as being suitable for climate change studies, 1 of these required soil temperature as an input, whilst 3 others use air temperature. Findings of the modelling using ANIMO and SWAP, using UKCIP02 and HadRM3 climate change scenarios, indicated the important interplay between temperature and soil moisture. Higher temperatures led to increased nutrient flux but this was moderated by lower soil moisture and reduced discharge. The scoping study highlights the importance of understanding soil processes, particularly the interplay between soil moisture, temperature and bio-geochemistry to predict soil response to change. It is clear from the report that a major assumption in predicting soil response to climate change is that changes in soil temperature follow changes in surface temperature. Given that soil temperature is also affected by soil moisture, it would be good to determine if this assumption is valid for a changing climate, perhaps using the Met Office (2011) data. We need to understand how important monitoring of soil temperature is as a soil indicator. Soil temperature was not considered a soil indicator by the UK soil indicator consortium (SP0512, P5-053/2/TR) though it is highlighted along with soil moisture as an indicator of soil biological condition by Doran and Parkin (1996) to which SP0512 refers.

CC0378 also highlights a number of studies in the wider literature that have tried to examine the response of soil nutrients to increased soil temperature. The study by Ineson et al. (1998) found soil solution nitrate varied considerably. They suggested that additional nutrient release was masked by increased plant uptake. Other studies in the wider literature have examined the impact of soil temperature change on organic matter pools. Increased respiration increases CO_2 flux (Trumbore et al., 1996; Fang and Moncrieff, 2001). Whilst Freeman et al (2001) have attributed increased exodus of peatland DOC to warmer temperatures. Other researchers have investigated the mechanistic relationship between moisture and temperature on CO_2 flux (Lomander et al., 1998), finding increased temperature and moisture, resulting in an increase in CO_2 flux. Schjonning et al. (2003) demonstrated that CO_2 flux and nitrification have moisture dependent envelopes in soils; the magnitude of which are likely to increase with increasing temperature. Meta-analysis of 32 ecosystem warming studies research sites indicated increased CO_2 flux, increased nitrification and increased plant uptake from warming (Rustad et al., 2001), they concluded, “With the exception of aboveground plant productivity, which showed a greater positive response to warming in colder ecosystems, the magnitude of the response of these three processes to experimental warming was not generally significantly related to the geographic, climatic, or environmental variables evaluated in this analysis. This underscores the need to understand the relative importance of specific factors (such as temperature, moisture, vegetation type, successional status, land-use history, etc.) at different spatial and temporal scales, and suggests that caution should be applied in "scaling up" responses from the plot and site level to the landscape and biome level." The implications of the highlighted research for Defra are that there is both a need to further understand mechanisms, through the interplay of different state variables, or natural capital stocks, and greater effort is needed to develop regional and national scale models incorporating soil temperature and its impact on soil processes.

5.2.2 Biomass: Chemical energy

Biomass is biological material derived from living, or recently living organisms. Biomass forms the primary energy source for microbial activity in the soil and is derived from carbon used to construct biomass that is absorbed from the atmosphere as carbon dioxide (CO_2) by plant life, using energy from the sun. Decline in soil organic matter may fundamentally alter the availability of this energy source. Defra has committed to protecting and enhancing soil carbon stores (PB13297), which can be viewed as a surrogate measure of biomass, by protecting our current carbon stores and by improving our understanding of how to increase levels of soil carbon we will protect this energy source in the soil and therefore the main driver for biogeochemical cycling. By knowing the soil biomass NC stock as indicated by soil carbon levels, an indication of the available energy source for microbes for maintaining biogeochemical cycling is obtained. This has many important additional consequences such as soil structure development, erosion prevention and climate change mitigation. Given that carbon is considered a surrogate measure of biomass, the reader is referred to the previous NC summary for, "*Soil organic matter, and carbon stock."* (5.1.1.3)

5.3 SOIL ORGANIZATION

The organisation of soils leads to important soil functional capabilities that arise as emergent behaviour through complex processes and interactions. Emphasis is often placed on physico-chemical structure because of its important role in the regulation of gas and water fluxes. For instance the emergent property of aggregation regulates water retention properties amongst others. Protection of soil structure is important to many aspects of the soil protection strategies and is highlighted in the WSAP (2009); as is the protection of soil biodiversity and habitat structure (PB13297; WSAP, 2009). The connectivity of soils across the landscape influences soil processes, and the flow of water and transport of materials. Spatio-temporal structure, connectivity and change form an important aspect of soil monitoring.

5.3.1 Physico-chemical structure

The physico-chemical structure of soils regulates its ability to retain water, and controls flow and transport of water and materials through the soil at landscape scales. In addition, at the pore scale, the structure acts as a habitat, providing niches with differing environmental conditions in which soil fauna and flora function. Defra is committed to protecting soils from degradation threats in both agricultural and urban settings. Compaction is one threat to soil structure, but loss of soil carbon is also intimately linked with maintaining soil structure. By understanding how to best maintain soil physico-chemical structure it will better help us to improve our soil quality and maintain soil function and the ecosystem services that can be derived from the soil.

Key findings:

- Soil structure is a notoriously difficult concept to describe quantitatively, and none of the surrogate measurements made to indicate changes in structure, are entirely satisfactory.
- There are currently no nationally applicable datasets relating to aggregate stability across all land use and soil types, and most aggregate stability experimentation to date has focused on arable systems, though there's increasing focus on peatlands.
- Threshold values of SOC, below which soil structure is likely to have adverse effects on soil quality, are likely to be soil and climate specific. In the absence of site specific information, threshold values of SOC using crop models and pedotransfer functions relating soil structure to SOC for specific soils.

The ability of soils to fulfil different functions and provide ES is strongly influenced by soil structure. The most important functions include supporting root growth and crop development, receiving storing and transmitting water, cycling carbon and nutrients and diminishing and dispersal of agricultural and other chemicals. Soil structure also has a major influence on soil strength and workability with a well structured soil being considered to be relatively strong when wet (i.e. resistant to slumping, capping and dispersion) but relatively weak when dry (i.e. facilitating easier tillage and root penetration) in comparison with a poorly structured soil. The ability of soils to resist external stresses from weather, from cropping and other management practices varies from soil to soil. Indeed, soil structure can be very sensitive to human activity. The extent of the soil structural change resulting from these activities can be considered over time scales ranging from hours to centuries (Kay, 1990) and size scales ranging from microns to metres. This makes it rather difficult to measure and monitor. However, the maintenance of a good soil structure is critical for soil sustainability. Field experience and decades of research have given rise to a multitude of empirical methods to describe different aspects of soil structure. These techniques are often narrowly focused covering only limited temporal or spatial scales and on soils subject to a single specific internal or external stress. However, irrespective of the temporal or spatial scale at which the measurement is made, each of the resulting characteristics reflects one of four general aspects of soil structure; (i) form, (ii) stability, (iii) resiliency and (iv) vulnerability.

Structural form

The structural form (sometimes known as soil architecture) is defined as a heterogeneous arrangement of solids and voids. In the solid phase of a well-structured soil, clay particles may be flocculated into stable domains; these domains may be clustered into micro-aggregates; the micro-aggregates may be built up into aggregates. Primary particles larger than clay particles (silts, sands and stones) become incorporated into the hierarchy at the appropriate scale. Between this solid phase, and influenced by their size and form, is a system of pores. The characteristics of macro-pores (pore size distributions, pore continuity and stability) are important in determining the aeration, infiltration, drainage and the leaching of agricultural chemicals. For example water available to plants is generally stored in intermediate sized pores in the size range 30 µm to 0.2 µm. These pore spaces are also a habitat for soil micro-organisms and changes in pore properties induced by mechanical stresses and strains can have a marked effect on microbial activity (SP0303, SP0305). Thus soil structure is often described as having an hierarchical organisation with compound particles at one scale, or order aggregating together to form larger compound particles at the next hierarchical scale and so on; however, not all hierarchical orders exist in all soils (Dexter, 1988). Loss of a particular hierarchical order often leads to the destruction of all higher structural orders. Fractal and pore scale modelling has been widely used to describe hierarchical self-similar or self-affine soil structures.

Numerous processes continuously act together in the aggregation and stabilisation process (See review in SP0305). Some primary factors are clay flocculation, wet-dry/freeze-thaw cycles, the compressive and drying action of roots and the action of earthworms. Inorganic stabilizing agents include mainly clays, cations such as Ca^{2+}, Fe^{3+}, and Al^{3+}, oxides and hydroxides of Fe and Al and Ca and Mg carbonates. Organic stabilizing agents can be considered in three main groups (Amezketa, 1999): (1) transient binding agents are decomposed rapidly by microorganisms and include microbial and plant derived polysaccharides; (2) temporary binding agents are roots, hyphae and some fungi; (3) persistent binding agents consist of resistant aromatic humic material associated with metal cations and strongly sorbed polymers, which are derived from the resistant fragments of roots, hyphae, bacteria cells and colonies.

Direct measures of soil micro-structural form include the use of CT and X-ray tomography. 3D pore scale representations are obtained. These measures are used to observe microstructure and observe micro-faunal habitats (see for example Young et al 2008). These techniques are currently very costly requiring considerable computational resources and are only used in the study of soil micro-structures. At a similar scale, but in two dimensions direct observations of structural features by electron microscopy and optical scanning of impregnated soil thin sections provides measures of structural form including porosity, pore size distribution, continuity or tortuosity of the pore system, pore orientation and shape. Direct measures of seedbed macro-structure (mm to cm scale) have been made from resin impregnated blocks (Watts & Dexter, 1994).

Indirect measures of pore size distributions are routinely made by determining soil water retention characteristics. In an inert porous medium the volume of water retained at a given suction should be equivalent to the volume of pores having diameters (µm) smaller than, 300 s^{-1}, where s is the suction in kPa. Conversely, pores having larger diameters will be air-filled. Soil water retention characteristic are measured in the laboratory in soil drying experiments and are thereafter assumed to be an intrinsic property of soil (see for example LandIS NATMAP HORIZON Hydraulics database). However, this is an oversimplification; Gregory et al. (2010a) have shown that the effect of changes to soil structure caused by soil deformation, shrinkage or compaction on the water release characteristic can be as great as the effect of soil type. They propose a new model for a water release characteristic which takes into account the effect of damage to soil structure with a single fitted parameter. Gregory (2010b) have explained how in-situ tension infiltration can be used in a simple way to give a rapid estimate of the extent of macro-pore structure in a soil and also a characteristic pore size to define the capillary network. With this approach they have shown that soil management affects the amount and continuity of macro-pores in soil. This technique can be rather labour intensive although automatic tension infiltration apparatus shows considerable promise (Sprongova et al 2009). Air permeability and gas diffusion measurements are used to determine soil structure. The application of gas movement measurements to tillage and compaction studies allows assessment of short-term effects such as seedbed aeration, and long-term effects such as such as the build up of structures under zero tillage and recovery from compaction (Ball et al., 1988). New approaches based on acoustic/seismic soil-sensing technology form the basis of a new engineering technique for *in situ,* non-invasive monitoring of soil structure in support of sustainable agriculture are being studied. The penetration of sound through a soil surface from acoustic sources above it is controlled primarily by its structure; air permeability, porosity, tortuosity and the presence of near-surface layering (R.Whalley personal communication). Electrical resistivity tomography (ERT) is a geophysical investigation tool that is a relatively rapid method used to investigate soil structure and other physical features of soil. The method produces either 2D or 3D images interpreted electrical resistivity from the measurement of apparent resistivity. The technique is sensitive at characterising soil cracks and other structural features (at mm and cm scales) that form for example, during shrinking and swelling (Samouelian et al 2005). A vulnerability index was proposed (SP0305) based on the normalised differences between the bulk and aggregate shear strength. Well structured soils are expected to have a high aggregate strength relative to bulk strength and vice versa. Strength measurements of this type provide insights into the vulnerability of soils to structure breakdown under natural weathering processes, but the exact mechanisms are more complex than simple shear of bonds within the aggregate.

Field assessments of topsoil structure can be obtained from detailed profile descriptions are held in the LandIS database. In general, these descriptions of soil structure in the field follow a purely observational route with no linkage to the function. Soil survey techniques tend to consider the highest order of the hierarchy: the macro-structure with descriptions which refer to the size and conformity of the aggregates without trying to quantify the macro-pore distribution. A qualitative system of structural assessment developed by Peerlkamp (1967) which involves visual examination of a spade full of soil from about ten different points in a field, has been tested and results show that differences in soil structure can be readily distinguished by unskilled operators. Variation between operators is not great and the order of differences between different soils similar (SP0305, Batey, 1975). An ‘ST’ number is given to the soil based on a consideration of aggregate development, cohesion of soil particles, aggregate porosity and root development. The assumption is that medium or finer crumb structure, low cohesion, good porosity and absence of surface capping provide a good medium for root development.

Structural stability

The ability of soil structure to persist under the influence of different stresses is defined as its stability (Dexter, 1988) and is a measure of the strength of internal bonds within an aggregate when subjected to either internal or external stresses. A change in aggregate stability over time represents a change in the fundamental factors affecting soil structure. More indirectly, a change in aggregate stability will infer a change in other physical parameters such as macroporosity, hydraulic conductivity and water release curve and might also infer a change in chemical and biological parameters such as SOC and mineralisable N. Also, if aggregate stability deteriorates there is a greater risk of capping, overland flow and erosion of surface soil. On drying soils with unstable structures become increasingly strong and less friable (SP0303).

Measures of structural stability: The aim of aggregate stability tests is to give a reliable description and ranking of behaviour of soils under the effect of different management practices or environmental conditions. One of the biggest problems in assessing soil aggregate stability is the vast number of techniques developed to look at particular stresses. When comparing the stability of soil structures, it is necessary that the disruptive forces be standardised if the measurement is to have any practical significance, forces causing disintegration should be quantifiable, repeatable and related to those in the field. The forces applied may include impact, shearing, abrasion during sieving and forces due to the entry of water into aggregated structures. A number of methods have been used to express the resulting size distribution of aggregates, notably variations in mean weight diameter (MWD), a statistical method of reducing a size distribution of aggregates by a single number (Van Bavel, 1949), Another method used following wet sieving is the amount of water stable aggregates (WSA). This is the weight of aggregates remaining intact and above a certain threshold size compared to the fraction of soil above that size prior to the test. The amount of dispersible clay or clay and silt combined and microaggregates < 100 µm (likely to block pores) are also used as indicators of soil stability. Terminology is a further source of confusion. Tests to determine the stability of macroaggregates are often termed aggregate stability tests, whereas tests to determine the stability of microaggregates are termed clay dispersion tests. As indicated above, the disruptive forces or energy applied to the soil prior to this assessment can be by wet or dry sieving, shaking in water, falling weights to simulate tillage (SP0303), and wetting slowly or rapidly (slaking) (SP0519, SP0530) and raindrop impact tests. Although repeatable, the energy used to disrupt soil structure is seldom quantified. The use of numerous different methodologies and variations on methodologies has made comparison of data difficult (SP0306).

Aggregate stability was short listed as a potential component of the minimum data set MDS soil quality indicators for the UK,(Environment Agency, 2006) The authors of the report state that there are many shortcomings in current aggregate stability methodologies but if a single aggregate stability method was decided upon it might be worthy of consideration for the MDS, not least because the quasi-permanent nature of soil aggregates may be a more sensitive indicator of soil physical quality than the more ephemeral properties of soil bulk density or macroporosity. However, there is little data on temporal or spatial variation in stability and time of sampling, which in managed soils for example, may be particularly important. If a single, reliable method of aggregate stability was adopted for the MDS it could provide an extremely useful indicator of erosive and crusting potential of the soil, which is otherwise measured in the field using resource-intensive rainfall simulation apparatus. The authors of the report (Environment Agency, 2006) recommend the dispersion ratio (DR) method be adopted as a UK standard. DR method measures the proportion of total silt and clay which is dispersed as a result of slaking and mild applied forces and is said to be most useful for assessing field situations where damaged and undamaged areas occur within the same soil type. It is said to be universally applicable and can be used to measure the general stability of soils under different management conditions (ADAS, 1977). DR is calculated by expressing the ratio of silt plus clay contents obtained by mild dispersion in distilled water (M) and drastic dispersion in sodium hexametaphosphate solution (D) where DR = M/D*100. Small numbers <5 represent very stable well aggregated structures not easily broken down while larger numbers >31 represent unstable soils easily reduced to their primary particles of silt and clay. However, it is noted that the practical significance of the results must be interpreted in relation to soil type, drainage, and climate and field experience. There are seven broad stability categories, of the DR index, sufficient to indicate improving or deteriorating trends within each category (Table 5.6). It should be noted that there is no differentiating between broad soil types in the DR because consideration of soil type is integrated within the DR method.

Table 5.6. Dispersion ratios and corresponding interpretation (after Environment Agency, 2006)

Dispersion ratio	Interpretation
<5	Very stable
6-10	Stable
11-15	Fairly stable
16-25	Somewhat unstable
26-30	Unstable
>31	Very unstable

There are currently no nationally applicable datasets relating to aggregate stability across all land use and soil types, and most aggregate stability experimentation to date has focused on arable systems. However, if use of a robust, consistent and interpretable method such as the DR method was agreed then the measure would add value to existing national soil monitoring schemes.

Pressures on soil aggregate stability: Foremost among the many management practices that influence soil structure are; (i) tillage and (ii) practices that deplete organic matter in the soil. There is a strong interaction between climate and soil management practices (SP0305). Mechanical factors (tillage and poaching) have implications for soil disaggregation, especially in conditions of high soil moisture. For example, SP0303 found increased loss of stability as soil consistency changed from friable to plastic and the degree of destabilisation increased markedly with increasing tillage intensity. Soils with low clay content and low organic carbon were more susceptible to a loss in aggregate stability during tillage. Tillage effects can be countered to a degree by long-term and regular manure amendments, aiding greater longevity of macro-aggregates. However, soil physical properties including aggregate stability were surprisingly little improved following long-term additions of organic and mineral fertilisers on a number on English soils (SP0530). Growing of grass leys on arable soils results in a slow build up in aggregate stability (SP0519) but this is rapidly lost when the ley is ploughed out. Conservation and zero tillage, controlled traffic, organic rotations helped increase stability in arable soils. The effects of cultivation depth on soil properties related to stability (especially SOC) are likely to affect any soil monitoring schemes over time (ES0127, SP0513 and SP0517).

Micro-organisms have long been implicated in mediating soil structural stability, in particular fungi that may form and stabilise aggregates. Evidence suggests that tillage can have an influence over the degree to which certain microbes influence soil structural parameters. For instance, ploughing soil leads not only to the disruption of the soil mass, but also to the breaking up of fungal hyphae. Direct drilling, on the other hand, maintains structural integrity and fungal hyphae to a greater extent. Ergosterol, a phospholipid only found in live fungi, has been used as an indicator of soil bio-physical condition. The rationale to choose fungi over any other microbial community was firstly, the ease, reproducibility and accuracy of the measurement when confined to one soil type; secondly, the fact that tillage has been shown to have the largest immediate effect on fungal populations. Levels of viable fungi in the management regimes were ranked consistently as *Grass = Direct Drilled* **>>** *Ploughed*. Over two growing seasons it was clear that, at no stage, did the levels of fungi in the ploughed soil catch up with the other soils. In short, the legacy of the ploughing, at the scale of the fungal population, remains throughout the growing season (SP0305).

Soil structural stability and organic matter: SP0306 reviewed the relationship between structural stability and SOC and report limited evidence from the literature that thresholds of SOC below which there are dramatic changes in stability. The reviewers report that if thresholds exist, they differ significantly between soil types; even though the amounts of SOC are known to differ between, for example, soil textural groups. Modelling of SOC behaviour using the ROTH-C and the CENTURY models, showed trends towards 1.5% SOC in soils with less than 18% clay and 2.3% SOC where more than 18% clay as equilibria reached over periods of 100 years with continuous arable cultivation (SP0306). Soils in eastern England were identified in which SOM returns from cropping will not reverse downwards trend in SOC leading to a point where they fall below the stability threshold. The need for methods to assess the content, status and effects of active SOC on stability were discussed in SP0310 and used in SP0510. The light-fraction organic matter is partly governed by the fungal biomass of the topsoil, and both of these turnover in the soil fairly rapidly and are influenced by tillage practices. For this reason, more frequent additions of fresh or labile organic matter such as green and farm yard manures will be more effective in maintaining high levels of both parameters. SP0519 and SP0306 showed that at sites where different land-uses were prevalent it was possible to assess the change in stability of soil with SOC content. On these sites there appeared to be a critical change point in most soils such that at OC levels above the change point soils were stable and the stability changed little. At SOC contents less than the critical value stability declined dramatically. These change points differed between soils and differed depending on the measure of stability (external stress) being tested. Within a fairly broad range of soils the change points could be related to clay and fine silt content of the soil. Almost all samples taken from the top 2.5 cm of land could be fitted with the same relationships but the deeper soils behaved differently. SP0519 also showed that the destabilising effects of the individual stability tests are ranked: fast wetting (most destructive) > mechanical energy > slow wetting (least destructive). Aggregates broken down most by rapid wetting were from arable, light and medium soils (<0.35 g/g clay) and those with low soil organic carbon (<15 g/kg). All aggregates classified as very unstable (MWD <0.4 mm) or unstable (MWD 0.8 < 0.4 mm) fall within this envelope. Virtually all grassland soils regardless of their SOC or clay content were categorised as either stable (MWD 2.0 < 1.3 mm) or very stable (MWD > 2.0 mm) in all three tests. Threshold values of SOC, below which soil structure is likely to have adverse effects on soil quality, are likely to be soil and climate specific. In the absence of site specific information, crop models and pedotransfer functions designed to predict crop yield from soil and climatic conditions may be used in conjunction with models linking soil structure and SOC contents to identify threshold values of SOC.

Mapping UK soil structural condition

Soil structure is a notoriously difficult concept to describe quantitatively, and none of the surrogate measurements made to indicate changes in structure, are entirely satisfactory. No one technique covers the four general aspects of soil structure; (i) form, (ii) stability, (iii) resiliency and (iv) vulnerability. Project SP0519 has highlighted critical thresholds for soil texture (% clay) and SOC, below which soil can be considered unstable or highly unstable and at risk of erosion. These thresholds (<35% clay, <1.5% SOC) have been used in a map to plot the areas with the highest potential risk of erosion. This project has also highlighted that arable sites are at greater risk of erosion compared with grassland sites which are generally not. Hence, all arable sites have been assigned a higher risk score than grassland sites. The % clay threshold, SOC threshold and arable land use, shows a clear distinction between the higher erosion risk in arable areas that predominate in the east of the country, and a lower risk for grassland areas which are found extensively in the west. Following validation against observed recorded erosion features, this approach correctly identifies 96% of sites as being as risk from erosion, whereas only 4% with observed erosion had not been classed as being at risk. This represents a clear improvement in the accuracy of erosion risk prediction, compared with the previous methodologies. However, it must be noted, that these findings are based on only a limited number of observations of recorded erosion features. To validate this approach further, more extensive coverage of recent erosion occurrence would be required, as well as testing of the validity of selecting the three criteria to reflect erosion risk (organic carbon, clay content and land use).

Maps of the structural stability of top soils in England and Wales have been produced as part of SP0305 (see A Guide to better Soil Structure leaflet). These are based on the premise that stable soils tend to have high clay content, high calcium carbonate content, favourable organic matter content, favourable drainage and favourable biological activity. Unstable soils are fine sands or silts, with poor drainage, low organic matter content and on sodium-rich clays. Management and weather related factors will affect the extent of deterioration of a soil's structure. Similarly, a map has been produced of UK arable and managed grassland topsoils according to their 'structural regeneration' or resilience has been derived (SP0305, A Guide to better Soil Structure leaflet). It applies to soils that may have suffered compaction damage by machinery or livestock. In this case structural resilience can be defined as the tendency of a soil to revert naturally to their former porosity, density and strength after compaction. The recovery of a compacted soil is greatly influenced by swelling and shrinkage in soils with sufficient clay contents and by frost action. In areas where soil freezing in winter is only slight or absent, the effects of wheeled traffic are likely to persist for several years.

5.3.2 Biotic structure

Biotic structure concerns the taxonomic and functional biodiversity present in the soil and the organisation of populations in terms of food webs. The soil contains a vast biodiversity with thousands of microbial taxa and hundreds of invertebrate taxa likely to be found in a square metre of soil. Due to variation in size, life-history, environmental tolerances and behaviour these different taxa have different effects on soil properties and processes. It is therefore the sum of interactions between these diverse organisms and their soil habitat that largely determines soil function. Given that biotic structure is intimately linked to properties of the soil habitat assessment of its NC is key to understanding how soils may respond to environmental pressures and change.

Nevertheless, many soil taxa may perform similar roles thereby imbuing soil biotic structure with redundancy in respect to its functional capacity. This is important as it means that soil could maintain its functional capacity in the face of environmental change, and therefore, more diverse soil systems may be more resilient to environmental pressures. In addition, diverse soil communities act as a reservoir for genetic diversity that may have future pharmaceutical and biotechnological applications.

It is also clear that the vast range of taxa that inhabit the soil do not act alone but are enmeshed in the structure of food webs. Certain taxa or functional groups may act as keystone organisms within a 'healthy' or functioning food web. This means that their removal could have an impact which cascades through the rest of the food web with consequences for soil processes. As highlighted in SP0512 such changes in the structure of the food web can lead to changes in the rate of nutrient cycling, with effects on crop yields, plant competition and vegetation composition.

Much of what has been discussed as relevant to Defra's soil protection strategy for assessing the NC stock of soil biomass (5.1.1.4) also follows for soil biotic structure. Therefore understanding the state of the biotic structure is linked to the same specific objectives and policy requirements in soil strategies.

In particular the WSAP (2009) also recognises and highlights the role of soil in supporting biodiversity and the importance of this vast biodiversity in maintaining soils multi-functionality. Protecting soils from habitat degradation is important and has been recognised in the soil protection strategies in order to prevent decline of biodiversity. It is appreciated that the diversity of the stock is of great importance for soil function, in particular the biogeochemical cycling that occurs in soils. Defra has therefore identified the need to examine the vulnerability and resilience of soil biotic structure to pollutants. Through the creation of a national baseline dataset of soil biotic structure and subsequent monitoring it may be possible to evaluate soil quality improvement or degradation. This will enable a better understanding of the flow of ES derived from the biodiversity and complex food webs within the soil.

Key findings:

- The number of broad invertebrate taxa was greater in the Countryside Survey in 2007 compared to 1998 in all vegetation classes.
- Microbial diversity was examined at GB scale for first time in Countryside survey in 2007.
- Long-term sludge experiments show that addition of zinc-rich and copper-rich sewage sludge (resulting in soil concentrations that would exceed statutory limits under operational practice) negatively impact microbial and invertebrate diversity.
- Currently there are no Defra biodiversity indicators representing soil biotic structure.

As discussed in section 5.1.1.4, soil biomass CS2000 (Environment Agency 2002) was the first assessment of soil communities at a GB scale, and, it is one of only several such programmes to have undertaken a national scale survey of soil biodiversity in Europe (e.g. Rutgers et al. 2009). The aim of the soil invertebrate diversity measurements conducted in CS2000 was not to sample and identify all invertebrate diversity within soil. Soil diversity has not even been characterised and quantified fully for a single site and therefore at such a scale it is impossible to provide a full assessment of the soil diversity (SP0512). Instead, it aimed to produce a baseline dataset of invertebrates across all major soil groups and habitats of Great Britain. CS was also unique in that assessment of soil diversity was spatially integrated with other soil, vegetation and land use measurements. Analysis detected significant differences in invertebrate diversity between environmental zones, vegetation classes and soil types (Environment Agency 2002; Black et al. 2003). These diversity patterns were evident at both the broad (number of invertebrate orders) and specific (e.g. Oribatid mites) taxonomic levels. The broad differences in soil diversity and food web structure between habitats are generally well understood from the wider literature. However, it is less clear how these factors may interact with other environmental pressures (e.g. climate change) to influence the temporal variability of soil biotic structure.

The re-sampling of invertebrates in CS2007 provided an opportunity to examine whether patterns of biotic structure were consistent across time and, in addition to providing continued soil monitoring efforts at a GB scale, it was also in a position to address the key policy question asking whether there was any evidence to indicate a loss of soil biodiversity as stated by the EU (Emmett et al. 2010). CS2007 reported statistically significant reductions in the number of soil invertebrate broad taxa recorded and Shannons diversity index across a range of habitats. While the reductions in diversity are small they are not inconsistent with reported declines in soil biodiversity. Ongoing work on the identification of oribatid mites from CS2007 will provide the ability to examine whether species-level invertebrate diversity has changed between surveys and this will be the first such assessment done at the national scale in GB. A NERC-funded study attached to CS2007 provided another scientific landmark in the first assessment of microbial diversity and composition at a GB scale (Griffiths, 2010).

As components of 'biotic structure' both soil diversity and food web structure cover many other groups of soil organisms for which no national baseline datasets exist and therefore no expected values have been derived. A comprehensive soil biodiversity inventory would require a wide range of sampling techniques and would be a massive undertaking. 'Rolling out' a national-scale sampling to include a representative measures of biotic structure, such as those identified as priority indicators in SP0534, may be more feasible. Furthermore, given the difficulty in quantifying the diversity of soil organisms the application of molecular methods could rapidly increase our capability to monitor the status and change of soil diversity across a national monitoring network (SP08012). This is currently being addressed in SP0534 in testing a number of molecular methods for assessing diversity in microbial and nematode communities. Again, the variety and distribution of the ECN sites, together with the range of abiotic and above-ground biotic variables already monitored at them, provides a potential platform for the regular monitoring of soil biodiversity across the range of organisms that cannot be achieved in other large-scale surveys. In the past year, for example, baseline surveys of soil pH, and soil microbial and above ground plant diversity have been carried out by CEH researchers at two ECN sites with the aim of establishing links between soil chemistry and below- and above-ground biodiversity, and developing protocols for soil microbiological monitoring.

Clearly long-term and large-scale studies are invaluable in determining the impacts of climate change on soil biotic structure. Emmett et al. (2010) found changes in the relative abundance of different groups of decomposers with an increase in oribatid mite but not springtail populations between the 1998 and 2007 surveys. The concomitant increasing trend of average temperature during this period suggests that climate-related effects may influence the composition of decomposers and further analysis will be undertaken to explore this possible mechanism. AC0304 was a scoping study to look at the potential interaction of climate change with the impact of agri-environment schemes on biodiversity. The report indicated that it was likely climate change would have an impact on soil microbes but that knowledge was limited in terms of the significance of changes in microbial diversity and in the techniques available to monitor microbial diversity. It also makes the general point that soil biodiversity is under-represented in studies looking at the value of agri-environment schemes and emphasises the need for baseline data in relation to them.

It is also important to understand how pollutants derived from both industrial and agricultural sources may impact upon soil biotic structure. The Integrated Assessment of CS2007 provided evidence that declines in sulphur deposition has led to a reversal of soil acidification, which can be seen in the trends reported in Emmett et al. (2010). More recently, reductions in taxa richness and diversity indices of soil invertebrates under sewage sludge amendments with high zinc and copper concentrations have been reported (Creamer et al. 2008). As CS2007 is the only point at which microbial diversity has been assessed at the GB scale, links between microbes and changes in pollutant deposition cannot be properly explored. However, even in the early phase of the long-term heavy metals experiments reductions in rhizobial diversity with increasing heavy metal concentrations were highlighted (SP0110, SP0112). This indicates that microbial diversity will respond relatively quickly to such environmental pressures.

SP08012 conducted an extensive literature review to examine current understanding of the impacts of a wide range of agricultural management practices on soil biodiversity and its role in the maintenance of biological processes and ecosystem services in agricultural systems. Though understanding of the relationship between soil biodiversity and soil functions is still not complete SP0812 found that there was robust evidence for the following conclusions:

- More species are needed to ensure a stable supply of ecosystem goods and services as spatial and temporal variability increases, which typically occurs as longer time periods and larger areas are considered.
- Having a range of species that respond differently to different environmental perturbations can stabilise ecosystem process rates in response to disturbances and variation in abiotic conditions.
- Using practices that maintain a diversity of organisms of different functional effect and functional response types will help preserve a range of management options.
- Long-term experiments are needed to be able to assess temporal stability, as well as experimental perturbations to assess response to and recovery from a variety of disturbances.

Several of these were reiterated in the IF0117 report which assessed the influence of crop management practices on soil microbes. IF0117 asserted that maintaining soil microbial diversity may be important for agricultural ecosystem functions and that further research on understanding functional diversity of soil and rhizosphere microorganisms is needed. SP0512 also highlighted that it may be more important to maintain functional diversity and keystone species rather than maximise biodiversity to prevent the degradation of soil ecosystem services. It may be that species-level diversity effects in the soil are unlikely to be observed due to functional redundancy. However, it could be crucial in that soil diversity *per se* may be closely linked to the resilience of soils and their functions and service provision. Recent work has shown that resilience of microbial communities to heavy metal stress may depend on both biotic structure and soil structure (Griffiths et al. 2008). In turn, soils containing greater biodiversity may buffer or protect potential ecosystem services delivered by soils against environmental pressures. SP08012 highlighted that more work on the relationships between diversity, resistance and resilience following disturbance is needed for agricultural systems.

Consequently, it will be important that future research identifies practices which protect and, maintain or enhance, soil biodiversity. AC0304 asked whether environmental stewardship schemes could be successful to mitigate against the effects of climate change soil microorganisms. IF0122 examined the potential for the use of legumes to improve biodiversity in grassland system and found that soil microbial diversity was enhanced in multispecies grass/legume mixtures, presumably through the creation of an array of root types and root exudates. IF0117 indicated the general negative impacts that shortening arable rotations and continuous cropping may have on microbial communities. Further pertinent research on how changes in land use between set-aside and cropping impacts upon microbial community structure and diversity is being conducted for IF0138 and is due to finish in 2011.

5.3.3 Spatio-temporal structure:

Soil forms a continuum across most of the landscape and acts as the interphase between the biosphere and atmosphere above ground, and the geosphere below ground. The connectivity of the structure is important for determining how water, gas and materials move through the landscape, both vertically and laterally. Urbanization and the development of infrastructure alters this connectivity. Defra has supported soil surveys which attempt to show the spatial structure of soils across the landscape. Understanding soil ‘state and change’ is intimately linked with monitoring and by understanding the connectivity of soils across the landscape, we will be able to better understand the impact of policy decision making with regard to the impacts of anthropogenic activity (transport infrastructure development and construction and surface sealing), on soil connectivity, and how this may impact soil processes and function.

Key findings:

- Remote sensing and proximal sensing techniques, including airborne and vehicle-borne geophysical methods are opening up new ways to map soils, but are still mostly in the proof of application stage.
- Airborne geophysical data has been shown to be particularly valuable in refining the prediction of soil parent material.
- The potential for airborne radiometric data to enhance mapping of soil texture – a dominant factor in determining soil erosion – has not been assessed for England and Wales, despite the availability of high-resolution datasets.

Improved digital soil maps using remote and proximal soil sensing techniques

In Defra project ES0127 one of the main points that arose from the review of ‘Soil Resource Protection and Monitoring’ was that existing soil maps of 70 % of England and Wales were too generalised and lacked adequate resolution for many of the tasks demanded of them. Report SR0120 revealed that only 25% of soils across England and Wales are mapped at 1:25000 or 1:50000 scale. It was considered that due to financial constraints, mathematical or technical solutions may be the only viable options for improving map resolution. It is important when considering Digital Soil Mapping (DSM) to differentiate between the mapping of soil properties (e.g. soil texture, soil organic carbon) and soil units (e.g. soil series). The former typically involves the use of primary measurements of soil properties at specific locations with less expensive, secondary covariates which are correlated with the primary property. A range of geostatistical techniques are often used to make improved estimates of the primary soil property using the more spatially intensive, secondary covariates. In the case of the latter, computer aided classification techniques are often used to allocate pixels to particular soil types based on the secondary datasets. Here we first focus on the types of data which are most the most promising for improving digital soil mapping and the recent advances in geostatistical techniques which might be applied.

Geophysics, Remote Sensing and Soil Survey

SR0120 was developed to look at new methods of predictive, digital soil mapping (DSM) of soil series where trial areas were examined in Melbourne in Derbyshire and Harold Hill in Essex. A wide range of data can be used for digital soil mapping (McBratney et al., 2003) including digital elevation or terrain models; airborne geophysical survey data such as gamma-ray; magnetics and very low frequency electro-magnetic data; satellite data such as that from the Landsat Thematic Mapper (soil information about soils and geology being obtained from three band combinations); or hyperspectral data from airborne or satellite-based sensors. Conclusions from the report SR0120 were that in some landscapes accurate (80-90 %) soil series predictions were obtained. One of the project outcomes was that high resolution (HiRES) airborne geophysical data has been shown to be particularly valuable in refining the prediction of soil parent material.

Remote sensing approaches: Other than terrain derived indices to aid soil mapping, the two most common secondary covariates used in DSM are airborne geophysical survey data and hyperspectral data. The BGS has gathered high-resolution airborne geophysical datasets for certain areas of the UK, including large parts of Central England, the Isle of Wight, and Anglesey and parts of North Wales. In addition an airborne geophysical survey of the whole of Northern Ireland was undertaken in 2005 and 2006. This data has been used for mapping soil properties, some of which are in the list of UKSIC quality indicators including soil K (Haskard et al. 2010); K, U and Th (Rawlins et al., 2007), Cs137 (Rawlins et al. 2010); and soil organic carbon (Rawlins et al. 2009). A major advantage of radiometric survey data – which comprises estimates of natural radiation emitted from the top 30 cm of the soil – is it can be used in both vegetated and non-vegetated landscapes. The potential for airborne radiometric data to enhance mapping of soil texture – a dominant factor in determining soil erosion – has not been assessed for England and Wales, despite the availability of high-resolution datasets.

Recent advances in the quality and spatial resolution of hyperspectral remote-sensed data from both airborne and satellite-based carriers provide opportunities to substantially enhance DSM of both properties and soil units at 1:50,000 scale across arable landscapes (see for example Selige et al., 2006). Hyperspectral data, the availability of which will increase dramatically following launch of the EnMap satellite in 2012 can be used to improve estimates of topsoil texture and topsoil organic carbon concentrations and may aid estimation of other useful parameters (e.g. bulk density, mineralogy including inorganic carbon content). Recent research undertaken by the BGS has shown that the strength of relationships between soil texture and near infrared spectra are strongly related to parent material type across England– stronger relationships are observed for transported parent materials compared to soils developed directly from intact bedrock. This suggests that application of hyperspectral remote sensing to aid DSM across England would be enhanced by using the 1:50,000 scale parent material map of the UK (Lawley and Smith, 2008). Unpublished research by the BGS using soil texture estimates at 6000 sites (1 site every 2 square kilometres) across part of central England has shown that terrain features are not helpful in constraining estimates of soil texture fractions at the regional scale which has been applied elsewhere (Behrens et al., 2010); this may only be possible using other remotely covariates such as hyperspectral or radiometric data.

Proximal sensing approaches: The most promising proximal sensing technologies include visible and near infrared spectroscopy and electrical resistivity for enhanced DSM. For example, Tye et al. (in press) reported on the spatial structure of soils and sediments of river terraces of the River Trent using an Automated Resistivity Profiling (ARP) instrument towed behind a quad-bike. This was capable of mapping resistivity at a rate in excess of 40 ha d^{-1}; the resistivity can then be used to estimate soil property data such as soil texture fractions (Banton et al., 1997). This system measured resistivity at depths of 0.5, 1 and 2m and demonstrated the potential for substantial spatial heterogeneity of soil properties over sand and gravel terrace deposits, similar mapping has been reported elsewhere (Abdu et al., 2009). On-the-go infrared sensors have been developed to determine soil properties and these can be used to optimise soil fertiliser application rates (Maleki et al., 2007). Both technologies have the capacity to aid production of high-resolution (metre scale) maps of soil properties.

Geostatistics

Digital soil mapping relies heavily on geostatistical techniques which provide estimates of the values of soil properties at unsampled locations, and importantly, the uncertainty associated with these estimates. Geostatisticians have developed numerical techniques which aim to reduce the uncertainties associated with these estimates. In recent years there have been improvements through incorporating secondary data as fixed effects into geostatistical models and the application of optimal techniques for fitting variograms – the central tool of geostatistics – to soil data (e.g. Lark and Cullis, 2004). The assumption in geostatistics of stationarity in the covariance (i.e. the variance of the random variable is the same at any two locations) is not usually plausible when applied to properties of the soil. This assumption does not apply to data, but rather to a random function of which it is assumed that the data are a realization. Recent work by Lark and co-workers has shown that when this assumption is relaxed, the uncertainties associated with estimates based on sites where properties have been measured (an approach referred to as cross-validation) are closer to the real uncertainties than when this assumption is applied in the analysis (Lark, 2009; Haskard et al., 2010). Such approaches offer improvements in what Lagacherie and McBratney (2007) refer to as Soil Inference Systems; dynamic approaches to DSM in which data and methods are continually updated to produce bespoke outputs which can be oriented towards policy requirements.

Summary

There is considerable potential with new soil sensing technologies and DSM techniques which utilise recent advances in geostatistics to substantially improve the resolution and quality of fundamental soil properties and soil unit maps at 1:50,000 scale across England and Wales. This initiative would be part of a broader dynamic, soil inference system. In the first instance, it would be cost-effective to review which remote sensing technologies and other covariates would be best deployed across the different soilscapes. It would also be pertinent to consider which of the latest geostatistical techniques should be implemented to map specific soil properties and their uncertainties

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6) Evaluate work contributing to the identification and quantification of soil ecosystem services

The ES framework helps us to understand the flow of goods and services derived from soils that benefit society. Currently information on soil ES is very limited and as a term it means different things to different people. In this section of the report, with regard to soils, it is defined as: "the conditions and processes through which soils, and the organisms that make them up, sustain and fulfil human life. They maintain soil function and biodiversity and provide *ecosystem goods* such as pharmaceuticals and fuel" altered from Daily (1997); conversely disservices are those that reduce human sustainability. By using this contextual framework it is hoped to improve the link between scientific understanding and policy development and decision making.

Key findings:

- No accepted framework for soil natural capital and ecosystem services has been agreed upon.
- Soils and sediments are underrepresented in terms of indicators devoted to them in comparison with air, water and biota.
- Knowledge gaps exist with regard to soil indicators that specifically monitor threats, and those that assess the delivery of ecosystem services.

Defra has adopted the **ecosystems approach** and has published 'Securing a healthy natural environment: An action plan for embedding an ecosystems approach' (PB12853). This has been followed by the report, 'Delivering a healthy natural environment' which outlines progress to date (PB13385). PB12853 identified the following priority areas with regard to ecosystem services:

1. Priority area 1: Promoting joined-up working within Defra and the Defra network to deliver environmental outcomes more effectively.

2. Priority area 2: Identifying opportunities for mainstreaming an ecosystems approach.

3. Priority area 3: Using case studies that demonstrate the benefits of taking an ecosystems approach.

4. Priority area 4: Developing ways of valuing ecosystem services.

5. Priority area 5: Developing a robust evidence base.

The framework considers 3 essential scales, **National**, **Regional** and **Local**. Table 6.1 considers how these administrative scales link to scales at which soils would generally be studied.

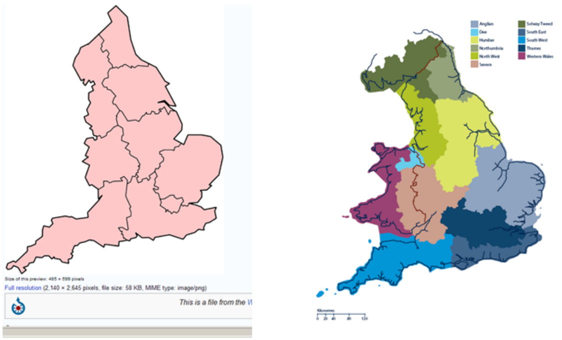
Table 6.1. Administrative units in England and Wales for the implementation of ecosystem services, with comparative scales at which soils are studied.

Scale	Administrative units	Soils study unit equivalents
National	Country / Britain / UK	Country / Britain / UK
Regional	Government Offices / Regional assemblies	Basin
Local	Local Government	Watershed
		Farm

National scales are stable; and administrative and soil study units are complementary. Regional administrative units are subject to change but in terms of scale are roughly equivalent to river basin scale. One contribution to joined-up working is to recognize that the Regional scale is equivalent to the Environment Agencies attempts to divide England and Wales into River Basin Management Units (GEHO1205BJWO-E-P). River basins and watersheds can be appropriate biophysical boundaries for studying soil NC and ES, as water is the major conveyor of energy and mass through the soil system. Local Government in England and Wales is complex and subject to change. In Wales there are 22 unitary authorities and England is divided into 6 Metropolitan Counties, 28 Shire Counties and 1 administrative area. These administrative units vary in scale, but may be equated to watershed scale.

A comparison of regional administrative and river basin units (Figure 6.1.) indicates there is some broad agreement between administrative and biophysical boundaries; at the local scale there is little agreement between administrative boundaries and watershed boundaries. Although administrative boundaries and biophysical boundaries do not need to match, it is important that clear understanding and communication, with regard to the management of locations within biophysical boundaries, is clearly transmitted. An important scale for soils, and their management, is the farm scale, which is not explicitly considered within the framework of the ecosystem report (PB12853), but should be considered in policy development at all scales.

Figure 6.1 English Government Office Regions and the Welsh assembly, River basin districts devised by the EA.



English regions

river basin districts

Case studies are an important way to highlight and demonstrate the way forward in terms of the use and implementation of ecosystem services. Studies highlighted in the ecosystem report (PB12853) with some reference to soils include, ‘Black Country living landscape’ (Regional scale); and ‘Wicken Fen’ (Local scale) which includes peat restoration. Under actions to mainstream the ecosystems approach the report (PB12853) calls for, ‘development of a framework of action for the management and restoration of peat soils based on the delivery of ecosystem services’ (SP0572).

Valuation of ecosystem services has been addressed in the report, ‘An introductory guide to valuing ecosystem services’ (PB12852); and in the earlier report, ‘Valuing England’s terrestrial ecosystem services’ (NR0108). More detailed evaluation of methods for valuing ES with regard to soils can be found in Section 9 of this report. However, NR0108 clearly identifies that there is a knowledge gap in our understanding of the biophysical relationships between some aspects of the ecosystem and how the final benefits are realised; this was found to be particularly true for regulating services, water purification and waste treatment; where hydrological/biogeochemical models are not sufficiently well developed to predict responses under multiple conditions at national and regional levels. In terms of valuation it also emphasizes the need to value supporting services, the category into which important soil functions fall, and suggests developing a biophysical model for supporting services to inform decisions regarding the other services accruing from them (NR0108).

Soils research has developed a broad evidence base for soil processes over the past ~100 years, but has had ‘inventory and land evaluation’ as the primary drivers at national levels, which tend to focus on ‘static soil properties’ such as soil texture. Given that national priorities are transitioning to understanding the impacts of climate and land-use change, and protecting and safeguarding the environment through the use of the ecosystems approach, the soils evidence base must be examined within this context. Understanding ‘change’ requires a greater emphasis on more dynamic soil properties and processes, such as soil water and organic matter. As yet there is no broadly accepted framework for identifying and evaluating the ES, or NC, of soils. In the wider literature Daily et al. (1997) proposed a soil ecosystem services framework (Table 3.2), and Robinson et al. (2009) proposed a soil NC framework (Table 3.1). More recently Dominate et al., 2010a proposed a combined NC/ES framework, which has been discussed in the literature (Robinson and Lebron, 2010; Dominate et al., 2010b). Debate is growing as to how best to develop a framework that links the wealth of soils data into and NC/ES framework from which valuation can be conducted in a consistent way. Within the context of the ecosystems report (PB12853) soil formation, nutrient cycling and water cycling fall in the supporting services category, which though vital to all other services, is not viewed as directly benefitting human society. As a result greater emphasis is often placed on those services, provisioning, regulating and cultural, that directly benefit society. Although soils contribute to many of these, the lack of specificity can mean that soils are overlooked when water and air are emphasized.

Perhaps the most current classification is that proposed by Andrews et al., (2004) who expanded the soil ES proposed by Daily et al. (1997) into six categories (Table 6.2).

Table 6.2 Six soil function (Ecosystem Service) categories proposed by Andrews et al. (2004).

Nutrient cycling
Water relations
Physical stability and support
Filtering and buffering
Resistance and resilience
Biodiversity and habitat

Indicators and targets form an important method of monitoring and implementing policy with regard to the natural environment. Targets and indicators have been reviewed with respect to the ecosystems approach (NR0119). The report found that in general, current state indicators do provide a good overview of the natural environment, with the exception of soils and sediments which are the most underrepresented in terms of indicators devoted to them in comparison with air, water and biota; with most of the indicators focusing on agricultural and woodland soils. In addition, there are knowledge gaps with regard to indicators that specifically monitor threats/pressures and those that assess the delivery of ecosystem services. In the suggested indicators for England, soils are only mentioned in regard to soil organic matter levels that affect the regulating of erosion; supporting services are not considered in the context of the report.

Setting targets for the state of soil NC or the delivery of soil ES is complex. Focusing solely on ES is perhaps more challenging in the context of soils, whilst values for soil NC stocks and their changes may be more easily developed considering current knowledge. It is also the soil stocks which are often important, for instance the amount of carbon stored in soil, or the nutrient and water stocks available on an annual basis to sustain a healthy ecosystem.

References

Defra projects:

NR0108 Valuing England's terrestrial ecosystem services
NR0119 Reviewing targets and indicators for the ecosystem approach
PB12852 An introductory guide to valuing ecosystem services
PB12853 Securing a healthy natural environment: An action plan for embedding an ecosystems approach
PB13385 Delivering a healthy natural environment' which outlines progress to date
SP0572 Ecosystem Services of Peat - Phase 1

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7) Impact of Climate Change on Soils, Soil Function and Threats to Soil Protection

The European Union has identified 8 major threats to the soil resource, erosion, organic matter decline, compaction, salinisation, landslides, contamination, sealing, biodiversity decline (http://ec.europa.eu/environment/soil/pdf/soillight.pdf). Of these, the SSSE (PB13297) and WSAP (2009) highlighted, soil erosion by wind and rain, compaction and organic matter decline as the most pressing threats in England and Wales, along with soil pollution. All of these threats will be impacted by a changing climate, the focus of this section. Defra is working towards meeting the challenge of climate change and its impact on soil function, and the threats to soil function, by building soil resilience. By improving our understanding of how climate change will affect our soils, stakeholders and businesses will be better able to adapt quickly and responsively to climate change and its impact on soil threats.

Key findings:

- Lack of measurement based spatio-temporal monitoring network for soils that goes to depth and includes measurements relating to soil water status changes.
- Models for predicting the impact of climate change on biodiversity have not been developed.
- Soil physical properties and behaviour are not well represented by soil indicators.
- There is a lack of integrated soil threat models at any scale; and understanding of how the physical, chemical and biological properties and processes interact.
- Small scale long-term experimental work on climate change is funded in sensitive upland organic soils.

It is a priority to understand the impacts of climate change, whilst as far as possible developing adaptation strategies to handle the change. With regard to climate change, predictions for the UK have been presented by UKCIP (www.ukcip.org.uk). It is predicted that the UK will see a general increase in temperature with temperatures being 2-3.5 ˚C warmer on average by 2080. Change in climate may also result in:

- warmer wetter winters
- warmer drier summers
- more frequent heavy rainfall events
- more frequent very wet periods in winter and spring
- more heatwaves
- less snow and frost.

It is also expected that regional differences in climate will be increased, with larger increases in amounts of rainfall in the north and greater rises in temperature in the south (Stockdale and Palmer, 2009). Data from the Met Office for soil temperature (Figure 5.7) indicates that soils are warming in the upper 30cm, especially across England.

Soil resilience, defined as, “the capacity for a soil to recover its functional and structural integrity after a disturbance” usually relates to two aspects of the soil, i) its ‘performance’, which would relate to soil function and ii) its ‘state’ or structure which is related to the quantities of materials and their organization that constitute the soil. Performance (or soil function) is generally of more interest with regard to policy, given its more direct socio-economic impact (Eswaran, 1994). Resilience can be used to indicate the soil’s ability to recover from stress or degradation, or its ability to continue to function under a changed climate. This can be thought of as the soil’s buffer capacity with respect to climate change. Given the major predictions of climate change, soils will be more resilient if they maximise drought tolerance, maintain and enhance infiltration capacity to deal with wetter winters and more intense storm events. Therefore, management practices that improve soils in these contexts are of value for building resilience for climate change.

Defra has supported a scoping study focusing specifically on the projected impact of climate change on soil function (SP0538). The report splits reviewed literature into direct impacts (e.g. increased temperature on organic matter decomposition) and indirect impacts (changing inputs of leaf litter, how this impacts soil organic matter, with altered plant productivity). The report highlights the following areas of concern:

Direct
- Significant increases in SOM turnover.
- Increased losses of CO_2 from soils.
- Increased soil moisture deficit impacting arable production and soil food web dynamics.
- Enhanced survival of soil borne plant pathogens.
- Increase shrink swell of soils impacting infrastructure.
- Enhanced chemical attack of foundations.
- Unknown impacts on pesticide movement through the landscape.
- Leaching of N and DOC may be increased due to winter rainfall: and
- Increased rainfall may lead to increased soil erosion.

Indirect
- Increased crop yields due to longer growing season.
- Decreased yield in drought stressed areas.
- Enhanced tree growth: and
- Enhanced nutrient release and increased plant productivity may increase litter inputs offsetting C losses.

Another scoping study has addressed the issue of how climate change may impact nutrient pollution from agriculture (CC0378). It identified the lack of modelling capability specific to understanding climate change impacts. Site and catchment scale models were available for describing nutrient flux, but the climate model data to drive the models offered insufficient temporal resolution as daily time steps were required. Results of the modelling indicated the importance of rainfall from October to December in determining N and P losses; increased evapotranspiration (ET) in later, warmer, years partly offset increased rainfall. Soil flow and transport models tend not to contain information on biodiversity and soil biology, as such there is a lack of knowledge on how these will respond and the likely consequences. Given the need for obtaining soil property information for driving models, Defra has supported the development of a soil properties database for supporting climate change impact studies (CC0375). The role of the database is to characterise soil conditions under common management types as related to the UKCIP climate change scenarios; the effort focused on soil organic matter and soil wetness.

Following these scoping studies, Defra has commissioned research that is due to report in 2010 that evaluates the impact of climate change on soil threats (SP0571) in England and Wales. The work considers how each of the identified threats might be affected by climate change. A review of models for each threat was first identified, where it existed. Each model was driven by climate variables subject to expected change. The modelled effect of climate change on the soil threat could then be estimated by application of the appropriate model. The climate change drivers being used are the HadRM3 scenarios (the basis for UKCIP09) downscaled to 5km and a 1 day resolution. It was not considered that there was an adequate model to predict the effect of climate change on soil biodiversity or the incidence and magnitude of landslides. For the other threats, models were driven either directly by HadRM3 variables, or by outputs from the JULES model, itself driven by HadRM3 data. While this approach looks promising in providing a direct link through models from climate change drivers to soil threats, it highlights issues of uncertainty

Table 7.1 accepted soil indicators from the Defra website (Anon, 2010)

Function	Soil indicator
Food and fibre production	pH SOC Bulk density Olsen P Total N Aqua regia extractable (Cu, Cd, Zn, Ni) Extractable Mg and K
Environmental interaction	pH SOC Bulk density Olsen P Total N *Aqua regia* extractable (Cu, Cd, Zn, Ni)
Foundation	None
Soil biodiversity	*Yet to be determined*
Heritage and landscape	pH SOC
Raw material	None

associated both with the models themselves and with the data used to drive them.

In addition to the biogeochemical alteration threat posed by climate change, the major physical threats are temperature, drought and erosion. Whilst measures of soil biogeochemical health are well covered by soil indicators in Table 7.1 (Anon, 2010), physical properties are not. SOC can be a good indicator of soil physical behaviour and structure, but only in the context of soil textural class. Indicators suitable for understanding potential impacts of climate change on infiltration and erosion would be the soil water release curve (related to the pore size distribution), the aggregate stability, or drainage class; whilst for drought tolerance it might be soil moisture storage, with the median soil moisture from the probability density function providing a dynamic indicator, in addition to the soil water release curve. The 1995 report (IH report 126) on the hydrology of soil types (HOST) was an attempt to link soil type to hydrological behaviour across the UK, and might form a useful framework for determining areas of soils threatened by climate change from the physical perspective at the national and regional scale.

A review of current knowledge on the inter-relationship between soils and climate change was carried out in the EU project Clim-Soil (Schils, 2008). The report highlighted the complexity of ecosystem processes which contribute to changes in carbon fluxes and includes impacts on plant composition, phenology and production, and changes in carbon losses through impacts on decomposition, erosion and hydrological processes e.g. Davidson and Janssens (2006). It was concluded that the uncertainty in our current understanding contributes to the widely different results on changes in terrestrial CO_2 sequestration in models and currently prevents the further development of carbon-climate models. An important step to understand the implication of climate change on SOC will be the interlinkage between the thermal regime and moisture regime. For example, physical warming of the atmosphere will enhance soil temperature, but reducing soil moisture is a more direct threat to soil warming and increased fire risk (Hogg et al., 1992). The EU supports both experimental and modelling work on the effects of climate change and interaction with air pollution impacts in UK habitats and soils which builds on the EU Climate change experiment network (http://www.increase-infrastructure.eu/) and a range of research across ten research organisations (AQ0802).

Rewetting of UK peats is being tested as a means of peat restoration, with drain-blocking and vegetation removal being the most common techniques adopted across the UK (SP0556); in addition, this is likely to build the resilience of organic soils to climate change. Defra has just funded research to understand how drain blocking impacts greenhouse gas emissions (SP1202). Further work is required in this area in order to understand the processes of carbon capture in release, which forms the topic of discussion in the next section on soil organic matter decline. However, the four carbon catchments study spread across the UK aims to unravel some of the important processes and feedbacks (CEH, 2010)

References

Defra reports:

Anon, 2010 Defra website: (http://www.defra.gov.uk/environment/quality/land/soil/research/indicators/consortium/int-results.htm)

AQ0802 Terrestrial Umbrella: Effects of Acidification and Eutrophication on Terrestrial Ecosystems and their recovery.

CC0375 The development of soil properties database for England and Wales for climate change impact studies

CC0378 Scoping study of potential impacts of climate change on nutrient pollution (of water) from agriculture

PB13297 Safeguarding our soils a strategy for England

SP0538 The impacts of climate change on soil functions

SP0556 A compendium of UK peat restoration and management projects

SP0571 Use of ‘UKCIP08 scenarios’ to determine the potential impact of climate change on the pressures/threats to soils in England and Wales.

SP1202 Investigation of peatland restoration (grip blocking) techniques to achieve best outcomes for methane and greenhouse gas emissions / balance

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8) Evaluate research tackling threats that may degrade capital or reduce services

Safeguarding our Soils (PB13297) identified 3 main threats to soils:

- **Soil erosion by wind and rain.** Erosion affects both the productivity of soils but also water quality and aquatic ecosystems.

- **Compaction** of soil reduces agricultural productivity and water infiltration, and increases flood risk through higher levels of runoff.

- **Organic matter decline.** The loss of soil organic matter reduces soil quality, affecting the supply of nutrients and making it more difficult for plants to grow, and increases emissions to the atmosphere.

In addition, we also consider soil pollution as a fourth major threat for consideration:

- **Preventing soil pollution.** Soil pollution has long-term implications for degrading soil quality, and pollutants enter from many sources. Preventing contamination from the spreading of organic and inorganic materials on the land and from atmospheric deposition is required.

These threats to the soils of England and Wales degrade soil NC and ES. Soils are quickly destroyed or degraded, but take much longer to be restored, if they can be. The primary focus of this synthesis is to understand the state of knowledge with regard to the scientific evidence regarding these threats.

8.1 Soil erosion by wind and rain

Erosion is estimated to cost the UK economy ~£45 million per year through the annual estimated loss of 2.2 million tonnes of topsoil (PB13297). Wind and water are responsible for the erosion of soils, and in particular the loss of topsoil which contains the bulk of the soil nutrient stock. The consequences are lost production, reduction in water quality, as well as the silting up of drainage systems and water courses and reservoirs. Defra is committed to reducing the rates of soil loss to erosion in England and Wales.

Soil erosion is a complex process because it is affected by natural and human factors and by characteristics both intrinsic (soil properties, topography) and external (rainfall intensities and frequency) to the system. Therefore, due to this intermixing of factors it is often difficult to unravel cause and effect and to determine whether erosion rates are occurring at rates higher than would be occurring "naturally" at any location. As a result of the large number of underlying drivers, soil erosion rates vary temporally and spatially, which make the task of characterising national-scale erosion trends even more challenging. Erosion produces on-site and off-site effects, both of which can be serious and detrimental to the environment. On-site effects include reduction in soil stock through soil loss, reduction in fertility through nutrient removal and change in soil texture through preferential removal of fines. Off-site effects include soil and water pollution through transport of chemicals on sediment, sedimentation of rivers and reservoirs and the consequent impacts on ecosystem function. On the other hand we don't have a good understanding of how much of the soil lost by erosion is deposited elsewhere in the landscape, perhaps being of benefit, or conversely is lost to the ocean and completely lost from the soil system. The Environment Agency monitors sediment transport in rivers giving some indication of this flux.

Defra has funded ~10 projects directly on erosion since 1990 (SP0402; SP0406; SP0407; SP0404; SP0411; SP0413; SP08007; LE0101; LE0102), two thirds of which were on agricultural land and the remaining on upland erosion. Studies SP0402 and SP0406 (and partly SP0407) are related projects as are SP0411 and SP0413. Considering the related projects together, a total of 5 independent studies have been funded since 1990 on erosion under the Soil Protection Programme.

Key findings:

- Soil loss due to wind, tillage, crop harvest and farm machinery may be of similar order of magnitude as soil erosion by water, although their spatial distributions vary.

This finding is based on limited or 3rd party data (reports, websites, publications, theses etc.) in combination with GIS-based modelling. Currently there are very limited data on the various forms of soil loss at a spatial resolution, and temporal frequency, necessary for the above finding to be conclusive at a national scale for the UK.

- In uplands, there is now evidence of increasing biotically caused erosion (i.e. sheep and humans) compared to water-induced erosion which has not significantly changed over decadal timescales.

In the late 1990s, approximately 25,000 ha ($250km^2$) of upland England and Wales was found to be degraded due to erosion, the majority of which was attributed to water erosion. However, over time the largest changes in eroded area were found to be caused by human and animal trampling. Erosion initiation was attributed to the presence and action of water, whereas the continuation of erosion was attributed to the action of sheep and humans. Studies highlighted that discerning causes of erosion initiation and continuation is complex due to the interrelationships between biotic, abiotic and climatic factors. These studies have not been able to untangle the effects of these causes (SP0402).

- Long term estimates of gross erosion rates on arable land are in the order of ~3 – 16 $t\ ha^{-1}\ y^{-1}$ depending on the soil texture, slope gradient and landuse. Rainfall characteristics ultimately drive the erosion process depending on these variables.

These findings are based on Cs^{137}-derived erosion estimates which represent a time-averaged estimate of the mean annual soil redistribution rate over a period from the late 1950s to the present (SP0413).

- There is evidence to suggest that control measures in arable land can reduce runoff and erosion significantly.

Future Directions and Challenges

By its nature, erosion is neither constant in space nor time and it is affected by many different factors. This poses big challenges for the reliable estimation of erosion rates, especially at the national scale. The following points, stemming from the studies reviewed above, represent challenges that ought to be addressed in order to gain a fuller understanding of national-sale erosion rates:

- Measuring erosion over short timescales will only yield a limited understanding of the rates and severity of erosion processes across different land uses in the UK because erosion rates may vary dramatically between years and a long enough rainfall record is necessary to capture the range of erosion responses. Long-term monitoring is required at different spatial scales in order to capture small and extreme erosion events and in order to understand sediment redistribution within fields.
- The scale at which erosion is measured also exerts an influence on the outcome of the results. Using small-scale erosion plots offer many advantages, such as replicability, experimental control, ease and cost-effectiveness of experimentation and accurate measurement of runoff and soil fluxes. However, results must be interpreted with caution as plot-based erosion fluxes may not be representative of the whole field, the presence of the plot boundaries may lead to artificial flow conditions and short distances of soil transport within the plot may lead to an overestimation of erosion rates.
- Monitoring of suspended sediment in rivers is not an accurate indicator of erosion rates on fields because not all eroded sediment reaches the rivers. Estimates of sediment redistribution in fields are needed. Sediment tracers offer the possibility of estimating sediment redistribution patterns.

- Similarly, using aerial photography to estimate erosion can only be used where erosion features such as rills and gullies are visible. Lower but persistent sheet erosion processes may be overlooked because they are not noticed or because they have no visible features.
- The studies above highlight that there is still limited understanding of the interrelationship between different factors and their order of control on erosion. New insights are needed into the order of importance of different factors and the effects of the interactions.
- Erosion is a vector for nutrient and pollutant transport therefore determining the sediment sources and sinks (not just gross erosion) is important for addressing both on- and off-site effects of erosion.
- Understanding the potential effects of climate change on erosion should be addressed once a good understanding of the effects of land use has been gained.

Overall, it is suggested that future research directions on quantifying national scale erosion rates employ a long-term monitoring approach across land uses and spatial scales in combination with a variety of different measurement techniques, in order to determine erosion rates and sediment redistribution over a range of rainfall events.

8.2 Compaction

Soil compaction reduces soil porosity which reduces the infiltration capacity of water, enhancing runoff and the risk of soil erosion and flooding. In addition, reduced porosity and compaction increase soil strength, making it harder for plant roots to propagate in the soil, and often reducing oxygen levels required for plant growth. Defra is committed to developing practices and management that reduce compaction.

Key findings:

- Soil compaction, brought about by inappropriate management practices is a major threat to the soils of England and Wales and has an almost universally negative effect on a wide range of soil functions and ecosystem services.
- Compaction leads to an increase in surface runoff of rainfall and potential flooding, less capture of water and a reduction in yield.
- Subsoil compaction which is invisible may be on the increase.
- Grassland compaction is less well documented and studied.
- Twenty three square miles of countryside, much of which contains valuable soil resources, is lost to construction annually. Over-compaction of soils is considered an inevitable by product of the construction industry.
- There are a number of promising remote sensing geotechnical methods for mapping soil properties that potentially give an indication of compaction at field & catchment scales.

The EU Soil Thematic Strategy identified compaction as one of 8 major threats to soils. Safeguarding our Soils: A Strategy for England (PB13297) began by outlining three major threats to soils in England, one of which is identified as soil compaction.

Compaction results in an increase in soil bulk density, coarsening or loss of structural units, loss of pore volume (particularly larger pores). In such a condition the soil is also often ‘stronger’ which can be an undesirable attribute in agricultural soils resulting in impeded root growth. A dramatic reduction in water and air permeability occurs when soil is subjected to external loads which are greater than its shear strength. Soil strength is a dynamic characteristic which varies between different soils and throughout the year. In general terms soil is weakest when it is wet, or loose, or both and excessive stresses may arise artificially (agricultural or construction vehicles, the passage of implements) and from natural causes (animals, trees and rain). Compaction in the shallower surface layers is related to the stresses imposed by the tyre, track or hoof at the soil surface, whereas excessive stresses at depth are related to the total load of the vehicle: with increasing size of vehicles in recent decades, deep compaction has become a greater concern. Deeper subsoil compaction is a particular problem because it is more difficult to alleviate either by tillage or natural process such as wetting/drying or freeze/dry cycles; a particular issue is that it is not visible from the surface. Uncontrolled wheeling of arable land is said to cover up to 90% of the entire soil surface and repeated wheelings, treading by animals and cumulative rain (causing localised surface compaction or crusting) further exacerbate compaction effects. The loss of structure in unstable soils and shrinking of clay rich soils on drying can also result in increased bulk density.

In the last two decades there has been less Defra sponsored research specifically addressing the mechanisms that result in soil compaction (see ES0127 review). Prior to this date, and stimulated by the Strutt Report (Strutt, 1970), considerable effort was expended identifying the effects of field traffic on soil compaction on in particular arable soils and its effect on crop yields. During the period of this review, the study of compaction was the principal target of research for grassland (BD2304), short rotation coppice (OC9611) soil stripping and site restoration (LE202 & LE206) and construction sites (SP08005): while methods to alleviate compaction were reviewed in LE0208 (subsoiling) and SP0302 (rubber tracks). Because of the impact of soil compaction on the loss of soil structure and numerous associated soil functions, soil compaction has been addressed indirectly in numerous other Defra sponsored research projects. Also during the period covered by this review there was also an EU sponsored and Europe wide 'concerted action' entitled Subsoil Compaction (FAIR-CT97-3589)

Soil Compaction effects on Ecosystem Services

As well as leading to increased soil bulk density (a primary indicator of soil quality), compaction has been shown to impact significantly on the following soil functions and ecosystem services (see for example reviews in BD2304 and SP0305)

Soil quality	Reduction in total pore volume, size and continuity leads to reduced infiltration, greater runoff and associated risk of erosion and loss of P (both solute and particulate). Lower water storage leads to rapid water movement to streams and rivers following rain (greater risks of flash flooding). Compact soils remain wetter and weaker for longer reducing soil temperature, also resulting in lower structural stability and reduced water storage. As compact soil dries it becomes increasingly strong compared to an un-compacted soil (with negative impacts on root penetration).
Soil biology	Less soil fauna and flora and lower levels of biological activity and biodiversity.
	Increased denitrification, increased emissions of nitrous oxide (N_2O) and ammonia (NH_3), decreased uptake (oxidation) of methane (CH_4) and occasionally net emission of CH_4, decreased emission of NOX and reduced respiration and emission of CO_2. However, it should be noted that the processes responsible for trace gas exchange are often characterised by high spatial and temporal variability.
	Reduced plant and crop growth, in particular fewer and shallower roots resulting in less overall yield. Poorer crop establishment and greater levels of uncertainty.
Management	Wet and cold soils lead to less workable (or stocking) days, greater risk of further compaction and damage to soil structure. As compact soil dries it become increasingly strong, resulting in high tillage energy and greater fossil fuel use. In the absence of compaction less intensive and shallower tillage is required. Deep subsoil compaction may be impossible to alleviate by tillage. Difficulty in applying animal wastes to the land and a less efficient use of fertilisers. Difficulties in harvesting cereals, roots and energy crops all adding to the risk of increased compaction.

In general soil compaction has a wholly negative effect on ecosystem services. The impacts of soil compaction are also likely to include adverse affects on a number of the objectives of Defra's Environmental Stewardship (ES) Schemes: the maintenance of biodiversity; and protection of water and air environments.

Key findings from Defra Research on Soil Compaction

Stresses transmitted to the soil by a tyre or track tends to concentrate under its centre line (load axis) and the effect is greater with increased soil water content and reduced cohesion (as the soil becomes weaker). The region of maximum soil stress is not immediately at the tyre soil interface but some distance below. The actual depth at which this maximum stress occurs increases with soil moisture, but also with surface pressure and total wheel load. For example, a tyre with an inflation pressure of 200 kPa (30 psi) and a wheel load of 3 tonnes will cause more damage to the upper subsoil than a low pressure tire with an inflation pressure of 80 kPa (13 psi) and a wheel load of 5 tonnes. Therefore, guidelines in the form of axle or wheel load limits can lead to unnecessary and uneconomically low wheel loads.

One of the main requirements of tillage is the removal of soil compaction from the rooting zone. In the absence of wheeling the energy for ploughing was reduced by up to 45% (Watts & Dexter, 1994). In addition, under controlled traffic zero tillage becomes possible in a much wider range of soil types. The energy required for seedbed preparation under controlled traffic systems is substantially lower as their soil aggregates have both lower tensile strengths and greater friability.

Where sub-soil compaction is present and amelioration is needed, deep tillage has proved successful in re-establishing macro-pore continuity between the uncompacted rootable soil above and the impeding layer below, with minimal loss of bearing capacity. Subsequent biological and weathering activity assist in completing the remediation process.

Controlled traffic systems (CTS) maintain a zone more favourable for plant growth by restricting soil compaction to the traffic lanes thus providing a firmed, traffic lane and a loose rooting zone. CTS also offer the possibility for long-term management of traffic-induced soil compaction as it avoids machinery-induced soil compaction and allows optimization of soil conditions for both crops and tyres. In a review by Hanza & Anderson (2005) the authors stated that controlled traffic slows down the effect of recompaction on tilled soil significantly, increases soil water infiltration, decreases wheel slip, minimises losses of nitrogen by reducing the emission of N_2O, improves soil structure, increases soil moisture retention, reduces run-off, and makes field operations more timely and precise. Other studies have shown that controlled traffic with direct drilling provided marked improvements in timeliness of farm operations, allowing earlier planting opportunities in all types of season. Further, under controlled traffic, when surface seal is not a problem, tillage will not be necessary to obtain adequate infiltration rates except in the wheel paths. The wheel tracks in a controlled traffic system may occupy up to 20% of the land, but the losses in this area can be compensated by higher yield. Modern guidance systems allow high levels of precision (±2.5 cm) well suited for controlled traffic systems

Grassland: More than 30% of area of England and Wales is covered by managed grassland with the highest percentage in the wetter west and in Wales. Using readily available soil data (retained water capacity, depth to impermeable horizon and soil wetness class plus a further climate moistness factor), a map of grassland soils in England and Wales at risk of compaction identified that 1% were classified as severely degraded but up to 80% highly or moderately degraded.

Compaction by livestock can be either poaching (hooves penetrate the sward and plastically deform the soil) which occurs when the soil is wet, or treading (confined to the upper 10 cm) causing compaction in medium and dry soil conditions. The pressure under hooves can be substantially greater than under tractor wheels and doubles when the animal is moving. There is a strong positive relationship between stocking density and compaction. Rather surprisingly vehicle traffic intensity on grassland can be twice that under arable cropping.

Direct impacts of compaction on soil fauna under grassland vary with their relative size. Least affected are microfauna as even compacted soils have a vast array of small pores, although features such as a lack of O_2 and soil wetness influences population diversity and activity. Under anaerobic conditions this can lead to increased greenhouse gas emissions. Generally, compaction has a negative effect on earthworms, although the magnitude varies with species. The length of worm burrows in compact soils is less and they are more fragmented. This has implications for many other organisms (including plant roots) that occupy them as well as having important effects on soil hydrology, gaseous exchange and nutrient cycling.

The composition of grassland plant communities can respond markedly to soil compaction with certain varieties coping better than others and this often results in a measureable loss of plant diversity. Impacts of compaction include lack of available of water, nutrients and air to the roots and direct mechanical factors including increased soil strength. However, root action can help remediate compact soils by penetration, water extraction (shrinkage) and aggregate stabilisation (root exudates).

In general for a given soil type, water infiltration and storage in better structured grassland soils is greater than arable soils. However, most grassland in England & Wales is located in the wetter west and is frequently found on steeper land. In addition some grassland soils can become slightly hydrophobic when dry potentially restricting their infiltration rate. An example of runoff from heavily grazed areas was measured as 53% of total rainfall compared with 7% on ungrazed land. An assessment of the extent of soil compaction was carried out using a simple model of ‘vulnerability to compaction’ combined with known data on livestock numbers across England and Wales (Packman, 2004). Potential hydrological impacts of grassland soil to compaction using an adapted version of the empirical HOST model were identified. The model suggested for most catchments, compaction lead to a relatively small increase in standard percentage runoff (SPR) of less than 13% but there were a significant number of catchments where SPR values increased by up to 42%. Catchments with increased SPR also showed a decrease in base flow and aquifer recharge (max 8%).

Changes in soil properties caused by cattle treading on grassland soils can increase the susceptibility of soil to erosion processes, and thus transport of associated pollutants. Also, cattle movements break up soil aggregation and structure, and damage vegetation, so reducing effective soil cover and root density which would otherwise help reduce erosion rates. Erosion rates appear to be related to the degree of treading and associated compaction. Erosion models, effective at generating data on sediment load in runoff are not generally designed for compacted soils although in many bulk density is a changeable variable. The relative ease in which pollutants are absorbed onto sediment and are thus mobilised by sediment in compacted soils is less well understood.

Soil compaction in grasslands can result in changes in the exchange of trace gases between the soil and the atmosphere. In general, compaction results in decreased grass yield, increased denitrification, increased emissions of nitrous oxide (N_2O up to 7 fold increase) and ammonia (NH_3), decreased uptake (oxidation) of methane (CH_4) (and occasionally net emission of CH_4), decreased emission of NO_X and reduced respiration and emission of carbon dioxide (CO_2). However, it should be noted that the processes responsible for trace gas exchange are often characterised by high spatial and temporal variability (possibly related to localised compaction). To date, there appears to have been little or no attempt to estimate the implications of changes in compaction for gas exchanges at the landscape scale.

Many existing Environmental Stewardship options are synergistic with improving soil structure and therefore further enhancing biodiversity. There is however a lack of flexibility in some Environmental Stewardship schemes presenting conflicts for soil compaction. For example, windows of opportunities for farmers to correct soil problems may conflict with payment schemes. Fixed timing limits for grazing species-rich grasslands can also be a problem in years with extreme weather conditions. Also field margins are promoted for improving diversification but they are often very compacted from preferential trafficking with restrictions for subsoiling. Compacted buffer strips can also create a problem with increased run-off and associated nutrient loss. A blueprint for contractors and farmers relating to practices to reduce compaction should be produced. The information needed for this is largely available, but not in one place, and not necessarily easily accessible.

Short Rotation Coppice (SRC): Harvesting of SRC occurs after leaf-fall, between November and March and in the UK, this will inevitably mean operating when the ground is wet and soft. Since harvesters usually weigh more than 10 tonnes and are accompanied by tractors and trailers of a similar weight, there is concern that harvesting will result in serious soil compaction which could cause significant reductions in biomass production (Souch et al. 2004). The perennial nature of the crop and narrow row spacing tend to limit the use of wider low pressure tyres and ameliorative tillage. Wet, slippery conditions during harvesting increase the risk of soil structure damage and can cause wheel slippage and mechanical damage to stools which would also be expected to reduce yields.

On the limited SRC sites investigated moderate compaction (typical of current harvesting equipment) did not significantly reduce biomass yields. Heavy compaction (3 passes with 7 tonne vehicle) caused deep ruts, an increased soil strength, bulk density and reduced water availability down to 0.4 m and resulted in up to 12% yield depression (Souch et al., 2004). Soil loosening treatments designed to alleviate the compacted soil did not markedly improve the growth of willow. Most yield loss was thought to be due to wheel damage to the harvested stools.

Modelling of willow growth suggested that compaction was likely to cause a more significant biomass reduction where shallow soils prevent deeper rooting.

Soil stripping and site restoration: A survey (LE0206) showed the depth to which top soils had been stripped and stored prior to working of mineral sites was generally considered adequate. However, replacement depth was found to more variable. During restoration, planned profile depths were being achieved but valuable resources of topsoil were being wasted on some sites by deep placement, causing compact topsoil pans (LE0206). This provides a hostile environment for plant roots and risks a shortfall of topsoil in later phases of the restoration. Soil conservation strategies that necessitated separate stripping and replacement of up to three soil layers (top soils, sub soils etc) generally worked best in preserving agricultural quality.

Stockpiling soils significantly affected their structural condition. Only about half of the topsoils direct-moved from source land to restored land significantly deteriorated but the majority of those stockpiled lost some structure. Soil handling had the greatest impact on restoration quality. Scrapers usually gave rise to more compact conditions than other methods resulting in the creation of slowly permeable layers in soils that had previously been permeable, a reduction in rooting depth and a 70% chance of deterioration in agricultural quality. Avoiding trafficking of newly replaced subsoil and topsoils almost removed the risk of creating compact layers and only 25% of sites restored in this way had lost agricultural quality. However, some difficulties in subsequent use resulted due to the low bearing strength for agricultural equipment.

Compaction of soils during restoration is not necessarily a long-term problem if it can be alleviated by soil loosening techniques such as deep subsoiling. However, the results of research reported in LE0206 indicate that attempts to loosen compact soils have been less than successful on many sites.

Construction sites: The Campaign for the Protection of Rural England has estimated that 23 square miles of countryside, much of which contains valuable soil resources, is lost to construction annually. Although planning decisions should ‘take account’ of soil resources and soil is ‘mentioned’ in planning policy statements, the existing presumptions within planning decisions are insufficient to protect soil and future national food security

It is reported in SP08005 that over-compaction of soils is considered an inevitable by-product of the construction industry, particularly as build densities increase in line with central government policies. Landscape contractors accept that over-compaction of soils is a problem and generally try to alleviate it where it occurs but practical working arrangements on site usually make its alleviation difficult. Currently there is little incentive to improve working practices, legal claims related to over compacted soils are extremely rare and the financial loss associated with replacing plants that die due to over compacted soils is small. If compaction is so bad that plants die in localised areas, usual practice is to relieve compaction or poor drainage just within these small areas during the defects liability period when the contactor is liable for any defects. This approach is reactive rather than preventative.

Current policies to maximise sustainable drainage within developments is leading to greater awareness amongst designers and contractors regarding soil permeability, soil type, soil handling and soil condition, which bodes well for the future. However the incorporation of sustainable drainage (capable of dealing with a 100 year storm) in modern high density developments can be technically difficult and good practice guidance is still evolving.

Amenity grass and shrubs generally appear to survive but not prosper on over compacted sites. However, the effect of over-compacted soils on tree growth is probably far less sustainable, but compaction is only one of several plant growth issues that have to be tackled if the situation is to be improved. The provision of trees within urban areas is primarily a space planning/design issue rather than one of soil over-compaction and so probably cannot be resolved through soils policy alone.

The opportunities for reducing and avoiding compaction are greater than ever with new techniques and products, a more sophisticated attitude to urban design, and increasing client awareness of the importance of landscape, which in relation to the overall value of a development is now subject to far fewer cost constraints. To avoid and reduce over-compaction of soils within the amenity landscape current specifications such as the NBS (National Building Specification) should be reviewed in relation to subsoil and topsoil supply, handling and cultivation. There is scope for improved interaction between clients, designers, specifiers, main contractors, ground workers and landscape contractors to resolve compaction issues. This co-operation can be promoted through specification and guidance and with organisations such as Construction Industry Research and information Association (CIRIA).

Measurement of Compaction

Soil compaction generally results in an increase in bulk density caused as air-filled pores progressively collapse under applied stress. Bulk density can be measured directly by measuring the dry weight of a known volume of soil (known volumes are usually obtained using steel cores or occasionally by coating soil clods in wax or resin and measuring their volume by displacement). Indirect measures of compaction and bulk density include both the backscatter and transmission gamma radiation methods. These methods are no longer widely used because of cost and Health and Safety concerns. Other indirect ways of measuring bulk density include combined heat pulse and TDR techniques which measure gravimetric and volumetric water contents simultaneously and thus bulk density (Ren et al., 2005). There are a number of promising remote sensing geotechnical methods for mapping soil properties (geoelectric, seismic GPR/EMI and airborne hyperspectral) that aim to give an indication of soil bulk density and compaction, but these need further development before they become more widely adopted. None of these geotechnical methods have been used in the work reviewed here but it is an area of research.

Despite their shortcomings, soil penetrometers are widely used in compaction studies as a way of measuring the 'trafficability' of soils and comparing increases in strength as a result of field traffic or stocking. They are also useful in identifying soils where root penetration is likely to become restricted. Whalley et al., (2007) proposed a simple relationship linking penetrometer resistance to bulk density and soil water release characteristic. When incorporated into an agroecosystems model this allows the prediction of changes in soil strength throughout a growing season.

Water infiltration is a useful measure of compaction because it is sensitive and closely related to practical problems. Reduced infiltration rate leads to water saturation for longer periods during rain, with damaging effects on plant growth and the performance of machinery. Tension infiltrometers can give information on a range of pore sizes.

Predicting stresses in the soil: The best way to prevent subsoil compaction is to take care that soil stresses in the subsoil caused by wheel loads on the surface do not exceed the strength of the subsoil. Such an approach requires: (i) knowledge about the strength properties of soils, (ii) the distribution of stresses into the soil and (iii) models to calculate the stresses in the subsoil caused by the wheel load and to determine whether the soil stresses exceed the soil strength. Because soil strength strongly depends on soil moisture content, soil water and agroecosystem models can be used to determine the strength of the soil.

Quantifying the mechanical processes of compaction in agricultural soils can provide the necessary understanding to estimate and predict physical changes, allowing comparison with the maximum variations consistent with minimal damage to the productive potential of soil. Many attempts have been made to model soil compaction caused by farm machinery. Traditionally, stress–strain relationships that rely on empirical geo-technical engineering practices have been used to study compaction of agricultural soils. These methods can describe the changes in bulk volume; they cannot predict changes at pore-scale which is crucial for flow and transport processes. Improved models are needed to develop subsoil friendly wheel equipment or tracks and to evaluate compaction experiments and existing wheel equipment of agricultural and construction machinery.

Models to identify soils vulnerable to compaction: Different soils vary in their ability to support a given load without significant compaction. This ability is dependent on more stable soil properties such as soil type and structural packing arrangements as well as soil water content. Using this approach a small scale map of '*susceptibility*' to soil compaction in Europe has been produced (Jones, 2003) based on relatively stable soil properties (clay, bulk and packing density etc). Up to one third of European soils were found to be susceptible or highly susceptible to compaction. This '*susceptibility'* class can be converted into a '*vulnerability'* class by considering the likely soil moisture status at the time of critical loadings (see BD2304). Further refinements to this approach have been developed allowing other soil physical parameters, such as changes in air permeability to be estimated following compaction (Horn et al., 2005). These authors demonstrated that multi-regression equations can be used to calculate pre-compression (Pc) stresses i.e. the maximum principal stress the soil can withstand against any applied vertical load, from wheels or hooves. Pc values are modelled based on physical properties (texture, aggregation, and water retention), mechanical parameters (cohesion and angle of the internal friction). This technique has been demonstrated at various scales: from the

1:1,000,000 soil map for Europe up to the field or farm level (1:5000). This method also affords the possibility of geographically separating different levels of sensitivity to stress application and identifying their consequences for sustainable management.

Identifying the vulnerability of different soils to compaction damage is an increasingly important issue both in the planning and execution of farming operations and in planning environmental protection measures. It is potentially a useful tool towards achieving soil protection both in the UK and Europe.

Practical methods for avoiding or mitigating soil compaction

In a recent review (Hanza & Anderson, 2005) the following practical techniques were summarised on how to avoid, delay or prevent soil compaction:

(a) reduce pressure on soil either by decreasing axle load and/or increasing the contact area of wheels with the soil;
(b) work the soil and allow grazing at optimal soil moisture;
(c) reduce the number of passes by farm machinery and the intensity and frequency of grazing;
(d) confine traffic to certain areas of the field (controlled traffic);
(e) increase soil organic matter through retention of crop and pasture residues;
(f) remove soil compaction by subsoiling;
(g) crop rotations that include plants with deep, strong taproots and
(h) maximise root activity by maintaining nutrition levels to meet crop requirements to help the soil/crop system to resist harmful external stresses.

8.3 Decline of soil organic matter

Soil organic matter, the non-living organic material composed of carbon, hydrogen, oxygen, nitrogen, sulphur and phosphorus, is important for storing carbon, nitrogen, sulphur and phosphorus, and acting as the biomass energy store in soils. In addition to being a nutrient store, soil organic matter has many beneficial properties it imparts to soils including, increasing water retention and improving soil structure. The overall change in SOM as indicated by change in soil carbon[2] is determined by the balance between carbon inputs from photosynthesis and carbon losses through decomposition and hydrological processes, including erosion. Soil respiration, associated with decomposition and root activity, accounts for two thirds of carbon lost from terrestrial ecosystems. In peat-dominated systems dissolved organic carbon, may be exported hydrologically, and may represent an important pathway for carbon loss. Equally, in some heavily managed and degraded systems, the loss of particulate organic carbon, due to heavy erosion, may also be an important pathway for carbon loss. Preventing the decline of soil organic matter is critical for maintaining soil productivity, reducing greenhouse gas emissions, and preventing contamination of water sources. The Environment Agency estimates the cost of organic matter decline due to cultivation at ~£82 million per year. Given the cost and the need to reduce the rate of loss of stored soil carbon it is essential that soil management is optimized to retain carbon and SOM, for the benefit of the soil resource, its productivity, and for the wider issues of reducing carbon emissions.

Key findings:

- Major, widespread declines in soil carbon reported from the resurvey of the National Soils Inventory were not observed by the Countryside Survey. A long term woodland study suggests no overall change. There is agreement that there has been a decline in soil carbon in cropped land.
- Organic soils represent the UK's largest terrestrial carbon store and are vulnerable to carbon loss through inappropriate management; policy relating to organic soils should be targeted on preserving existing stocks.
- Available evidence suggests that intensive land-management remains the major cause of organic matter loss when it occurs at a local scale, perhaps augmented by rising pH due to large declines in atmospheric sulphur deposition on some soils.
- There is little evidence for climate driven changes in soil carbon to date. Some modelling work suggests increases in plant production in some habitats may currently compensate for predicted increases in decomposition rates and associated carbon loss.

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[2] As C is the major component of soil organic matter

Defra report SP0532 is the most recent work describing the potential threats to organic soils in England and Wales, which are estimated to cover 11 % of the land area, and are concentrated in the uplands. The report (SP0532) identifies the following 3 principal threats to organic soils:

(1) Agricultural and forestry practices, in particular those that lead to changes in soil hydrology, loss of carbon and soil erosion.
(2) Acid deposition, as a result of the sensitivity of organic soils to acidification and inputs of nitrogen, and their expected long recovery time.
(3) Climate change, as a result of the fact that organic soils are a major store of terrestrial carbon and that predicted changes in rainfall and temperature are likely to lead to an increase in organic matter decomposition and possible destabilisation of these soils.

In addition SP0532 identifies a range of pressures to SOC levels that include, climate change (increased temperatures and incidence of summer drought; increased winter rainfall and storms), landuse practices and management (afforestation/deforestation, peat extraction, drainage, burning of heather, grazing, fertiliser use, liming and mining) and pollution (deposition of sulphur and nitrogen, and heavy metals). Although these pressures can be articulated, it is clear that the interconnectedness of threats is not well understood, nor can the significance of each pressure be fully quantified apart from perhaps the extraction of peat.

The major trigger for concern regarding the stability of UK soil organic matter stocks, particularly decline, was the resurvey of a subset of sites in NSI, first surveyed between 1978 and 1983. Permanent grassland and arable/ley grassland sites were resurveyed in 1978-83 (SP0506), and ‘non-agricultural’ land (heathland, bog, woodland and unenclosed grassland) in 2003 (SP0521). Topsoils were resampled for a total of 2119 locations, with measurement of SOC content on a fixed depth 0-15 cm sample. The results, synthesised by Bellamy et al. (2005), suggested a mean rate of soil carbon loss of 0.6% yr^{-1}, with greater rates of loss from more organic-rich soils (over 2% yr^{-1} in soils with carbon contents greater than 100 g kg^{-1}). In the absence of any relationship between carbon losses and land-use, these decreases were attributed to climate change. Another source of evidence for changing carbon balances in upland organic soils comes from the Defra-funded UK Acid Waters Monitoring Network (Monteith and Evans 2005), which has shown a progressive increase in DOC concentrations in upland waters. This was identified as a potential soil carbon loss pathway by Bellamy et al. (2005). Conflicting results have come from the Defra co-funded Countryside Survey which resurveyed sites across a range of broad habitats in 1978, 1998 and 2007 (Emmett et al., 2010). Topsoils were sampled from 1099 locations across GB in 1978 and 1998 and 2614 in 2007 using a stratified random survey approach based on land classes. The sampling depth (0-15 cm fixed depth) was the same as the NSI, but area coverage was different as were period, chemical and statistical analytical methods. This assessment recorded an increase in topsoil carbon concentration from 1978-1998, a decrease from 1998-2003, and no overall change for the period 1978-2003 for GB as a whole or individual countries. Significant losses for arable and increases for woodland habitats were observed. These results do not therefore appear to confirm the trends from the NSI. The one exception was for intensively cropped land, where consistent decreases in carbon concentration suggest ongoing degradation linked to land-use.

Clearly there have been questions raised as to why there are these differences between the two soil monitoring programmes and the possible mechanisms for the large losses reported in the NSI study. Smith et al. (2007) noted that 0-15 cm fixed-depth sampling was not an appropriate method for measuring change in the carbon stock of deeper organic soils (in particular deep peats). This will also be a valid criticism of the CS data. In addition, they suggest the reported rates of carbon loss were inconsistent with the measured temperature sensitivity of soil organic matter decomposition. The original authors of the NSI paper have confirmed this finding using a modelling approach but suggest land use and management provide a realistic explanation for the trends observed. Evans et al. (2007) measured the radiocarbon content of DOC draining an upland system and found that most was derived from recently photosynthesised plant material, rather than old soil organic matter. They also noted that the NSI resurvey reported consistent increases in soil pH across land-cover classes (SP0506 and SP0521, recently reported in Kirk and Bellamy, 2010), linked to recovery from acidification, and suggested a possible mechanistic link with changes in upland carbon stocks. Recovery from acidification appears to have been the major driver of rising surface water DOC concentrations (Monteith et al., 2007), and soil carbon and pH changes were found to be correlated with spatial and temporal trends observed in the CS dataset (Smart et al., 2010). Work is ongoing in a Defra contract (SP1101) to explore possible reasons for these conflicting results focussing on re-analysis of NSI samples using a consistent analytical approach and repeat statistical analysis for CS to combine England and Wales results so they are directly compatible with the NSI findings.

At the local / catchment scale estimates of erosion suggest that in heavily eroding catchments 200 to 500 t peat km^{-2} yr^{-1} can be produced (SP0532), equating to 2-5 mm yr^{-1} of catchment surface down-wearing. Estimates of surface retreat from a number of highly eroding catchments across England and Wales ranged from 5 mm yr^{-1} to 74 mm yr^{-1}, with an average of 22 mm yr^{-1}. These figures represent the most extreme cases, it is estimated that 75% of deep peats are damaged or degrading in England (NE257).

It is important to draw a distinction between SOC stock estimated from the national soil surveys (NSI and Countryside Survey), and these values for catchment surface down-wearing. The national surveys determine SOC concentration in a given volume (0-15 cm) of top soil, they do not account for down-wearing. Therefore, the national surveys are likely to reflect more accurate estimates in soils with a rigid matrix (mineral soils), but may be inappropriate, or underestimate losses from organic soils where concentration may have remained relatively constant but the depth of material may have decreased. A useful contribution would be a comparison of the different approaches and estimated changes in SOC.

Overall, the evidence for a ubiquitous decline in soil organic matter stocks is inconclusive. On the other hand, it appears that intensively cultivated areas are losing carbon, and there are undoubted hotspots of severe and ongoing loss from some organic-rich soils, notably the extensive areas of peat in the English Fens that are under arable cultivation (discussed in SP0574) and areas of active upland peat erosion, notably in the Southern Pennines. Available evidence suggests that intensive land-management remains the major cause of organic matter loss, perhaps augmented by rising pH in some soils.

Peatlands

Peatlands have been the subject of intensive research and policy focus in recent years due to (i) their importance as major carbon stores, (ii) concern significant areas of deep peats may be in a degraded state, (iii) a perception of sensitivity to a changing climate and (iv) insufficient data to measure change in large-scale soil monitoring programmes e.g.NSI and CS. Defra's response was the formation of the Peat Partnership to help coordinate and focus activities (http://www.defra.gov.uk/environment/quality/land/soil/peat/partnership-project.htm).

Peatlands (and other organic-rich soils) represent the largest store of terrestrial carbon in the UK and form the focus of most effort with regard to protection of soil carbon stores. Peatlands cover an estimated 3% of Wales land area with a further 17.3% covered by organo-mineral soils (Ecosse, 2007). In England deep peats are estimated to cover 5.2% of the land area, whilst shallow peats, which are perhaps equivalent to organo-mineral soils for Wales cover a further 4% of the land area (NE257); much of this area has been impacted by land-management. Blanket bogs, which cover around 85% of the peatland area, have been affected by widespread drainage (gripping), management burning, afforestation and grazing. Raised bogs, particularly in the lowlands, are additionally affected by peat extraction for horticulture, while fens (6% of the total area) have been particularly heavily affected by intensive agriculture, notably in the English Fens. The extreme cases of extraction or prolonged intensive agriculture can lead to complete loss of the peatland carbon stock, whilst other forms of management (particularly those that lead to a lowering of the water table) can lead to a reduction of the carbon sink function of the peatland, or a transition from carbon sink to carbon source. The components of the carbon balance that need to be considered in determining a peatland soils carbon sink function are identified in SP0574 as:

(a) NEE (net ecosystem exchange) – the net exchange of carbon dioxide between the peatland surface and the overlying atmosphere. The usual convention is that a negative NEE represents uptake of carbon by the peatland (although not all authors conform to this convention).
(b) Net methane losses from the peatland surface to the atmosphere.
(c) Inputs of dissolved organic carbon in rainfall.
(d) Water-borne losses of carbon dioxide.

(e) Water-borne losses of methane.
(f) Water-borne losses of dissolved inorganic carbon.
(g) Water-borne losses of dissolved organic carbon.
(h) Water-borne losses of particulate organic carbon.

SP0574 found that there was, “wide variability in the aims and approaches used in studies of carbon-balance processes in peatlands, which makes it very difficult to bring data together into a common format” preventing meta-analysis.

The carbon budget of peatlands, and effects of management, were the subject of a recent detailed review (focusing on the role of CH_4 emissions) for Defra, project SP0574. This review has led to the current Defra project SP1202 to investigate the impacts of grip-blocking on the peatland GHG balance, for which the SP0574 review is being updated. In addition, research led by JNCC (with a range of funding partners including Defra) is reviewing the current knowledge, and designing a national-scale research programme to address the effects of peatland management on C and GHG balances. In addition, the NERC QUEST programme was commissioned by the EA to fund research on the implications of climate change for upland carbon-rich soils in the UK, (including peatlands), and the effects on ecosystem services such as carbon storage, flooding and water quality. The report is not yet available but some of the questions the project has focused on scientifically or will address in policy briefings have included (LWEC, 2011):

- What are the climate and hydrogeographic conditions where peat exists in the UK now and where it will exist in the future?
- How will climate change affect the distribution of peat globally?
- Will peat still form in UK uplands in 2100 and what changes in distribution can be expected?
- How does the ‘climate pressure’ compare with other pressures on UK upland soils?
- What are the implications for provision of ecosystem services such as carbon storage, flood protection (run-off) and water quality (DOC)?
- What are the implications for managing upland soils? e.g. when and where and how is it worth restoring/protection?

In light of these ongoing activities, we have not attempted to repeat these assessments here, and therefore focus on relevant synthesis of findings and research needs.

Synthesis of findings and research needs for peatlands:

- There are very few UK peatland sites where full, reliable C or budgets can be constructed. Those that are available suggest that UK peatlands continue to act as modest C sinks unless subjected to high management or climatic pressure (Billett et al., 2010).
- The number of reliable field experiments of the effects of peatland management on C/GHG balances is also limited; many peat restoration studies lack either full C flux measurements, or a robust experimental design (i.e. replicated and controlled measurements pre- and post-restoration)
- CH_4 emissions represent a small component of the peatland Carbon budget, but are significant in GHG terms due to the high global warming potential of CH_4 compared to CO_2. This reduces the beneficial climate regulation role of peatlands, but is unlikely to negate it in most systems.
- CH_4 emissions are highest where water tables are high, and lowest in drained systems. This partially counterbalances changes in CO_2 balance observed during peatland drainage and re-wetting.
- Fluvial fluxes represent a significant part of the peatland C budget, with DOC typically the dominant form of fluvial loss in all but the most heavily eroding systems. The fate of both DOC and POC is incompletely known, adding uncertainty to measured GHG budgets.
- The major increases in UK surface water DOC concentrations over the last 20 years suggest rising rates of peatland DOC loss. However, this is thought to be mainly due to increased organic matter solubility as soils recover from acidification, rather than peat degradation.
- Nevertheless, rates of peat DOC loss may also be affected by management (including drainage and burning) and by vegetation type. Drain-blocking appears to lead to some reduction in DOC losses.

- POC losses are strongly affected by peat management and condition, and can be dramatically reduced by re-vegetating bare peat and blocking erosion gullies and ditches.
- Peatland restoration will not necessarily convert a system from a GHG source to a GHG sink. In most cases, however, it appears to have a net beneficial impact.
- The most rapid rates of peatland C loss occur in drained fens used for intensive agriculture, particularly in the arable areas of the English fens. Despite this, only a small fraction of current UK peatland carbon research is focused on fen peats.
- Organo-mineral soils, which cover a large area of the UK uplands, represent an important additional carbon store, much of which is used to support upland agriculture. While the potential for these soils to gain or lose carbon may be smaller than for deep peats, their role in the overall UK soil C balance remains under-researched.

Research priorities:

- Improved quantification and monitoring of the UK peat carbon stock based on a well-designed survey covering the full depth of peat, and measuring C content and bulk density as well as depth.
- Comprehensive flux studies of the current C and GHG balance of peatlands, including different peatland type, management and condition.
- Risk assessment of UK peatlands to climate change – being addressed by QUEST project
- Effects of water table and vegetation type on the overall peatland GHG balance (including CH_4 and fluvial fluxes) – being addressed by SP1202.
- Information on the long-term fate (in GHG terms) of DOM and POM exported from peatlands in rivers – being addressed in SP1205
- Quantification of the overall net GHG effects of peatland afforestation and deforestation, taking into account the long-term fate of extracted timber as well as the peatland GHG balance
- Studies of the GHG balance of fenland systems, in particular areas under current intensive agriculture, and restored ex-agricultural fens (taking into account N_2O as well as CH_4 fluxes)

Management Practices to Protect and Enhance Soil Carbon Storage

Increasing the soil carbon content can only occur either by increasing carbon input, decreasing carbon output or by a combination of the two through improved management. Agricultural management systems and forestry operations can strongly influence soil processes such as carbon sequestration and erosion. Examples include drainage of and cultivation of waterlogged organic soils, leading to aeration, increased microbial decay and an associated increase in CO_2 emissions. There are two main approaches to increase C-pool in terrestrial ecosystem. Land-use changes e.g. returning marginal agricultural land back to forest or restoring grasslands on degraded lands, which will cause a step change in C-storage for a given land area, whereas 'best management practice' proposals e.g. sustainable forestry, reduction of intensity of tillage on croplands, prevention of drainage on peatlands optimises the land-use and C-storage potential already present (Dixon et al., 1994; Janzen, 2004). Land management to increase C-sequestration may be only a limited, relatively short-term response to the reduction of CO_2 in the atmosphere (Scholes and Noble, 2001). However, a well managed, conserved soil, irrespective of land-use sometimes has other benefits, e.g. an agricultural soil that is sequestering C is more fertile and stable and a forest is more ecologically diverse, thus the relative ability of the soil to accumulate C can be used as an indicator of ecological and ecosystem performance (Janzen, 2004).

Table 8.1 gives an indication of the estimated gain/losses of soil C for a range of land-use changes and land management practices (SP08010). There is a high degree of uncertainty in this data due to lack of relevant studies e.g. forest to grassland pasture or variations caused by contrasting management regimes on the same land-use type, particularly arable and grasslands (Soussana et al., 2004) and the broad geographic nature of the studies cited in the peer review literature cited.

An evidence base for the effects of land use and management practices on soil carbon in the UK specifically was collated to develop the Land Use, Land Use Change and Forestry inventory (SP0567, IF0154, CEOSA 0805, now Department of Energy and Climate Change and AC0114).This inventory uses an evidence base from the literature plus modelling approaches to estimate the impact of land management changes on soil and vegetation carbon stores. Over time there has been a range of associated research within the LULUCF inventory contracts to meet identified research gaps in the knowledge base. Overall, there is poor evidence about the linkage between many land management activities and changes in soil carbon.

Defra has also commissioned a range of work focused on developing best management practices to protect and enhance soil carbon storage. Most of the recent work commissioned has been in the form of reviews between 1990 and 2008 (SP0561, SP08010, ES0127), actual research commissioned by Defra has focused on filling important knowledge gaps including (SP0130, SP0501, SP0518).We divide the research findings into four major land management types: arable, grasslands, forestry and peatlands and wetlands. Practices that have been the subject of research are synthesized in Table 8.1 a-d, showing the management practice, the estimated change in carbon, and the source; all sources are reported from both Defra reports and the wider literature.

Other research to develop the evidence for UK soils has been the Ecosse project (Ecosse 2007) which focussed on organic soils. This included as review of carbon stocks in organic soils, development of a development a dynamic models for C cycling in organic soils and synthesis of best management practices to protect and enhance carbon all in organic soils. Whilst a synthesis of UK studies, adaptation of literature data for UK soil types, timelines for benefits to be realised, and land available were recently combined to identify best options for maintaining soils carbon stores in Wales. Both studies highlight the importance of the understanding soil type in determining the direction and magnitude of change in soil carbon in response to management change.

The numbers reported in Table 8.1 a-d represent the evaluation of the gains and losses in carbon stocks in the different ecosystems to date by evaluating past changes and practices but there are some key issues which need to be highlighted. (* denotes Defra report where references found)

Table 8.1. Net increment rate of carbon in soils according with land use change and land management practices. Positive numbers indicate carbon sequestration, negative numbers carbon losses.

a) Arable	**Net C rate and *uncertainty* (x 10^3 kg C ha^{-1} yr^{-1})**	**DEFRA projects or reference**
Land use change		
		SP08010*
Arable to Ley:Arable Rotation	1.6	Smith P. *et al*., 1997
Arable to Grassland (50 yr)	0.3 - 0.8	IPCC, 2000
Arable to Grassland (35 yr)	0.63	Jenkinson *et al*., 1987
Arable to Grassland (15-25 yr)	0.3 - 1.9 ± 0.6, *110 %*	Vleeshouwers and Verhagen, 2002; Guo and Gifford, 2002; Murty *et al*., 2002
Arable to Grassland with short leys (20 yr)	0.35	Soussana *et al*., 2004
Arable to Permanent pasture	0.27	Post and Kwon, 2000
Arable to Forestry (115 yr)	0.52 + 1.53(C in veg)	Hooker and Compton, 2003
Arable to Forestry	0.62 + 2.8(C in veg.)	Smith P. *et al*., 2000a; Falloon *et al*., 2004
Arable to Forestry (25 yr)	0.3 - 0.6, >*50 %*	Guo and Gifford, 2002; Murty *et al*., 2002
Arable to Forestry	0.5 - 1.4, >*50 %*	Cannell *et al*., 1999; Maljanen *et al*., 2001a
Permanent crops to Arable	-0.6 and 1.0 -1.7, > *50 %*	Smith P. *et al*., 1996; Guo and Gifford, 2002; Murty *et al*., 2002
Revegetation on wetlands from arable	2.2 - 4.6, > *50 %*	Kamp *et al*., 2001
Land management		
Organic farming	>0 - 0.5	SP08010*
(crop residues, cover crops, compost, sludge)	0.3 - 0.8	
Cereal straw and crop residue incorporation	0.69 (0.1 - 0.7)	
Compost	0.4 (0.2 -1.5)	
Solid animal manure incorporation	0.37 (0.2 -1.5)	
Slurry application	0.4 (0.2 - 1.5)	
Sewage sludge application	0.26 (0.1 - 0.3)	
N-fertilization	0.2 (0.1 - 0.3)	
Permanent revegetation of arable set-aside	0.5 - 1.9	
Permanent shallow water table in farmed peatland	1.4 - 4.1	
Permanent crops and perennial grasses	0.62 (0 - 0.62)	
Ley-arable rotation (extensification)	0.54 (0 - 0.54)	
Deep rooting crops	0.62 (0 - 0.62)	
Bioenergy crop production	0.62 (0 - 0.62)	
Conservation tillage	>0 - 0.8	
Reduced tillage	0.2 (0 -0.2)	
No till farming	0.39 (0 - 0.4)	Smith P. *et al*., 2000, 2005a; 2008; Falloon *et al.*, 2004 Freibauer *et al*., 2004
Set aside	0.2 (0 - 0.2)	
Cropland, temperate climate range, no tillage (P)		
With changes in climate and CO_2	0.45 - 0.69	
Without changes in climate and CO_2	0.40 - 0.68	Jain *et al*., 2005
Cropland, corn and winter rye (M)		
Till and no N-fertilizer	-0.30	
Till and N-fertilizer (low, medium, high)	0.07, 0.08, 0.30	
No till and no N-fertilizer	0.03	
No till and N-fertilizer(low, medium, high)	0.17, 0.20, 0.57	West and Marland, 2003

b) **Grassland**	**Net C rate and *uncertainty* ($\times 10^3$ kg C ha^{-1} yr^{-1})**	**Defra projects or reference**
Land use change		
		SP08010*
Grassland - Arable (20 yr)	-0.95 ± 0.3, *95 % CI*	Sousssana *et al*., 2004
Grassland - Arable	-1.0 to -1.7, *> 50 %*	Smith P. *et al*., 1996; Guo and Gifford, 2002; Murty *et al*., 2002
Grassland - Afforestation (general, 90 yr)	0.1 ± 0.02, *95 % CI*	Sousssana *et al*., 2004
Native vegetation - Grassland	0.35	Conant *et al*., 2001
Land management		
Fertilizer input	0.3	SP08010*
Conversion to grass-legume mixtures	0.3 - 0.75	
Intensification of permanent grassland	0.2	
Intensification of nutrient-poor grassland	-0.9 to 1.1	
Permanent grassland to medium duration leys	-0.2	
Short duration leys to grassland	0.3 - 0.4	
Increased duration of leys	0.2 - 0.5	
Improved grazing management	0.35	
Improved grass species	3.04	
Introduction of earthworms	2.35	Conant *et al*., 2001; Soussana *et al*., 2004
Grazing (5-10 sheep)	0.05	Thornley and Cannell, 1997

c) **Forestry**	**Net C rate and *uncertainty* ($\times 10^3$ kg C ha^{-1} yr^{-1})**	**Defra projects or reference**
Land use change		
		SP08010*
Forestry - Arable	-0.6	Guo and Gifford, 2002; Murty *et al*., 2002
Forestry - Grassland	-0.1 ± 0.1, *95 % CI*	Sousssana *et al*., 2004
Land management	(units = 10^{15}g C yr^{-1})	
Increasing timber growth on timber land	0.138 - 0.190	
Growing short-rotation woody crops for energy	0.091 - 0.180	
Increasing tree no./canopy cover in urban areas	0.011 - 0.034	Metting *et al*., 2001

d) **Wetlands and peatlands**	**Net C rate and *uncertainty* ($\times 10^3$ kg C ha^{-1} yr^{-1})**	**Defra project or reference**
Land use change		
		SP08010*
Moorland - Grassland	-0.9 to -1.1	Sousssana *et al*., 2004
Peatland - cultivation	-2.2 to -5.4	Freibauer *et al*., 2004
Wetland - Arable (temperate and boreal)	-1.0 to -19	Watson *et al*., 2000
Wetland restoration	0.1 - 1.0	Watson *et al*., 2000
Revegetation on wetlands from grassland	0.8 - 3.9, *> 50 %*	Kamp *et al*., 2001
Land management		
UK peatlands - natural accumulation	0.7	Cannell, 1999

Synthesis of findings and research needs for management practices:

- There is a great deal of uncertainty and few UK studies for most management options to protect and enhance soil carbon stores. The literature reviews often cited are a synthesis of the global evidence base which are unlikely to be appropriate to apply to UK soils and vegetation types. The range of values in net C benefits and large uncertainty range illustrate this issue. There have been a number of attempts at expanding and applying the current knowledge base to UK systems.
- All options have a variable timeline for benefits to be realised in addition to a new equilibrium - so called ‘saturation’.

- It is important that options to enhance carbon storage are “permanent” if the full benefits are to be achieved, so that carbon stored is not subsequently released back into the atmosphere.
- There is the possibility of displacement where benefits achieved in one area are offset elsewhere (e.g. manure being concentrated in one field to enhance soil carbon stock thus creating hotspots of soil carbon rather than increasing soil carbon overall).

Land-use change over the next century in Europe is projected to decrease in cropland and grassland areas. In cases where the area of cropland or grassland decreases, soil organic C-stocks in these land-use types are also predicted to decline by 2080 by 20-44 % (Smith J. *et al*., 2005a). Conversely, the European forests are projected to accumulate net gains in soil C (0.1-4.6 x 10^{15} g, Smith P. *et al*., 2005b). Other drivers such as climate change; change in fertiliser use due to cost, technology advances, and N deposition will also result in changes in soil carbon which may enhance or reduce the benefits achieved through direct actions to protect and enhance soil carbon stores.

8.4 Contamination

The build up of pollutants in soils can cause damage to ecosystems through acidification and eutrophication, or pose a more direct threat to human health, e.g. heavy metal contamination; more commonly metals in high concentrations will kill or inhibit soil biota degrading soil development and function. Defra has committed to preventing soil pollution and dealing with our legacy of contaminated land; and wishes to see reduced levels of pollutants entering the soil from the atmosphere and from materials spread to land. In addition, Defra has demonstrated that it is important to improve our understanding of the risks to human health and the environment from soil pollution; ensure advice on the use of materials spread to land reflects the latest scientific understanding; improve understanding of the impacts of contaminated land and sustainable remediation techniques; ensure contaminated sites that pose a significant risk to human health and the environment are identified and steady progress is made towards their remediation.

Key findings and future needs:

Acidification and Eutrophication

- Continuation of soil monitoring networks and surveys to track acidification recovery especially in organic-rich soils and areas receiving large amounts of atmospheric nitrogen deposition.
- Continued research into the effects of sustained atmospheric nitrogen deposition on soil and terrestrial ecosystem eutrophication and acidification recovery with links to research on freshwaters.
- Continued development of biogeochemical models to simulate soil and ecosystem nitrogen dynamics encompassing interactions with acidification and the carbon cycle and linking to models of soil and above-ground biodiversity change.

Metals and other contaminants

- Metals are input to soils from a variety of sources. The importance of atmospheric deposition as a source to agricultural land has declined in general in the past 40 years, and for some metals land application of materials is the largest single source.
- Continued inputs of metals to soil may cause potential deleterious effects in the long term (> 50 years) but this is strongly dependent upon input rates and in most studied situations effects are not predicted to occur for at least 100 and up to 1000 years.
- Controls on the emission of organic compounds such as dioxins to the atmosphere, introduced in the 1980s and 1990s, have resulted in significant declines in soil inputs.
- Accumulation of persistent pesticides in soils is an issue of decreasing concern as modern pesticide formulations are more degradable in the environment.
- Sheep dip chemicals are a source of potential concern for soil function since land treatment is the major disposal mechanism and sheep dip compounds have been shown to be acutely toxic to some soil organisms.
- Application of metal-enriched sludge to land has demonstrated significant, if inconsistent, effects on the soil microbial community, crop yields and crop metal concentrations. Soil invertebrate abundance, diversity and function have been shown to be potentially sensitive to copper and zinc.

- Evidence suggests that there are no significant environmental consequences from PAHs, PCBs or PCDD/Fs when sludge is applied to agricultural land.
- Pesticides have been noted to affect soil microbial and rhizobial functions and in the long term to reduce numbers of soil organisms and depress soil enzyme activities.
- While enteric pathogens do not affect soil function, there are potential concerns regarding transfers of plant pathogens via return of soils residues to land of *E. coli* transfers from manure to surface waters.
- Current research on veterinary medicines suggests that effects on biota are unlikely although a wider range of compounds may need to be assessed than has previously been the case.
- Contaminated land remediation has focused on sites contaminated by metals, metalloids and organic compounds and subsequently used for housing. Remediation predominantly comprised excavation and off-site disposal of soil.
- No significant development in the understanding of the human health implications of contaminated land has taken place since the 1990s. The potential for health effects due to contaminated land could not be dismissed, but no evidence was found for widespread effects. Uncertainties in current risk assessment procedures are sufficient to preclude quantitative estimation of the overall impacts of land contamination on human health.

Reduce levels of contaminants entering the soil

- Continue to monitor emissions and deposition to UK soils of key contaminants (e.g. metals and organics).
- Periodically update the metals inventory to reflect the latest knowledge on inputs.
- Periodically review potential new sources of contamination (e.g. changes in usage and emissions of metals, use of new veterinary medicines and pesticides, increasing use of nanomaterials) for possible risks to soil ecosystems and human health.

Advice on the use of materials spread to land

- Consider periodic spatial monitoring of metal contents in materials such as manures and sewage sludge.
- Consider a more spatially explicit inventory of metal inputs to agricultural soils to pinpoint potential ‘hotspots’ of risk, using the latest available knowledge on the variability sensitivity of different soil types to metals such as copper and zinc.

Impacts of contaminated land

- Progress in understanding the human health risks due to contaminated land is slow. It is suggested that regular reviewing the state of the art is done so that policy may be informed by the most up to date findings.

Contaminated land remediation

- Continue to monitor land management and the use of remediation methods.
- In-situ remediation of contaminated land appears to be little used currently in terms of the overall number of sites that have been managed to remove contamination. A cost-benefit analysis of available in-situ techniques in comparison to off-site disposal could inform policy advice to local authorities on techniques for in-situ remediation.

8.4.1 Acidification and eutrophication

Policy background: Two major expert reviews have been commissioned by Defra in the last decade to provide a scientific analysis of the available evidence on emissions, concentrations, deposition and effects of transboundary air pollutants (sulphur, nitrogen, ground-level ozone, volatile organic compounds and heavy metals) in the UK (NEGTAP 2001; RoTAP 2010). The reports consider impacts on terrestrial and freshwater ecosystems and have included an assessment of impacts on soils. The main policy context for these reviews and related Defra funded research is the UNECE (United Nations Economic Commission for Europe) Convention on Long-Range Transport Air Pollution (CLRTAP) which supports international monitoring and modelling of air pollutants and provides the framework for a number of international and domestic emission control measures including the Environmental Protection Act (1990), the EC Directive on Integrated Pollution Prevention and Control (IPPC) (Directive 96/61/EC), the Gothenburg Protocol (UN/ECE Executive Body Decision 30/11/1999), the Large Combustion Plant Directive (National Emission Reduction Plan Regulations, SI2007, No 2325) the MARPOL Protocol Annex VI: Regulations for the Prevention of Air Pollution from Ships, the European Standards for emissions from road vehicles and the National Emissions Ceilings Directive (NECD Directive 2001/81/EC). An important philosophy underlying the CLRTAP is that emission control measures should be based on an assessment of the effects of the pollutants on the environment rather than simply relying on arbitrary percentage emission reductions or on what can be achieved through best available technology. The soil acidification and eutrophication monitoring, research and modelling funded by Defra is therefore targeted at understanding and evaluating effects on soils in relation to atmospheric deposition and predicting responses to future emission reduction scenarios.

Summary of Defra funded activity: The assessment of soil acidification and eutrophication within RoTAP has drawn extensively, but not exclusively, on data and outputs from Defra funded monitoring networks (ECN, CS, NSI and the ICP Level II Intensive Forest Monitoring network; see section on Soil monitoring and measurement), experimental and gradient studies (UKREATE umbrella project AQ0802; AQ0802) and modelling and mapping activities (Critical Loads and Dynamic Modelling Umbrella project AQ0801; AQ0801). Outputs from the latter, including critical loads maps and scenario assessments are submitted to Defra and the Working Group on Effects under the CLRTAP to support development and evaluation of emission control policies at UK and European levels.

Current state of knowledge: Data from the national surveys and monitoring networks provide consistent evidence of an increase in soil and soil water pH (reduction in acidity) and a reduction in soil water sulphate concentrations (RoTAP 2010). Statistical analysis has clearly linked the increase in soil pH to the decline in sulphur emissions (Kirk et al., 2010) demonstrating a major benefit of the emission control policies over the last 30 years. Recovery may be slower than expected in organic soil as a result of buffering by organic acids (Emmett et al., 2010b).

The situation for nitrogen is more complex. Despite a 50% reduction in NOx emissions since 1970 and a small reduction in ammonia emissions (20% since 1990), there was little change in total nitrogen deposition between 1987 and 2006 (RoTAP 2010), raising the question as to what effect these continuing nitrogen inputs might have on soils. Experimental and gradient studies (AQ0802) show that sustained atmospheric nitrogen inputs can increase soil nitrogen storage and accelerate the nitrogen cycle releasing inorganic nitrogen from the soil store. Where this leads to increased nitrate leaching, soil acidification will occur, offsetting the potential benefits from reduced sulphur deposition. The risk of soil acidification from continuing levels of nitrogen deposition increases with time as the soil becomes further nitrogen enriched. In carbon-poor, N limited systems, increased inorganic nitrogen availability may stimulate plant growth causing an increase in production of carbon-rich plant material which is subsequently incorporated into the soil. This carbon effectively ‘dilutes’ the nitrogen signal and slows the N cycle. These processes may explain the observations from CS2007, where small but significant decreases in total nitrogen concentration were observed between 1998 and 2007 in the top 15 cm of soils in semi-natural and woodland broad habitats accompanied by a trend towards an increase in C/N ratio (Emmett et al., 2010).

Soil nitrogen enrichment (nitrogen eutrophication) can lead to vegetation composition change and there is strong evidence that nitrogen deposition has significantly reduced the diversity of plant species in a range of habitats of conservation value over large areas of the UK (Haines-Young et al., 2000; NEGTAP 2001). Results from the most recent CS have demonstrated a continuing link between nitrogen deposition and plant species composition in the UK but with no further declines in plant diversity over the last decade in areas of high nitrogen deposition (Carey et al., 2008). Sustained nitrogen deposition is likely to threaten achievement of favourable conservation status in sensitive habitats as required by the Habitats Directive.

Critical loads: Within the CLRTAP, critical loads provide an effects-based risk assessment tool for the development of pollutant abatement strategies. A critical load is defined as “the quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge”. Critical loads may be derived empirically or by using models which calculate the critical load so that a specified “critical chemical limit” is not violated. Critical load exceedance is the amount by which pollutant deposition exceeds the critical load. Exceedance of steady-state critical loads represents the potential for harmful effects from pollutant deposition to systems in steady-state conditions; thus current exceedance of a critical load does not necessarily equate with current damage. Similarly, achievement of non-exceedance of a critical load does not necessarily mean that the affected system has recovered. The Critical Load Function for acid deposition quantifies the combined acidification potential from both sulphur and nitrogen deposition.

The area of UK broad habitats where acid deposition exceeds the acidity critical load has declined from 71% (1996-98 deposition data) to 54% using data for 2006-08 and is predicted to drop to 40% by 2020 (RoTAP 2010). However, nitrogen is now a far greater contributor to exceedance of the critical load of acidity than sulphur. The critical load for nitrogen eutrophication is exceeded by current (2006-08) nitrogen deposition for 58% of the area of sensitive terrestrial UK habitats. This value has hardly changed since the mid-1980s but is expected to decrease to 48% by 2020 (RoTAP 2010).

Monitoring of acidifcation and eutrophication: Monitoring of soil acidifcation and eutrophication can take the form of monitoring the inputs of acidity and nitrogen from the atmosphere or an assessment of change in soil acidity and nitrogen status, the latter associated with changes in C:N ratio, plant available nitrogen and plant species cover.

The UK Acid Deposition Monitoring Network was established in 1986 to monitor the deposition of acidity, sulphur and inorganic nitrogen compounds from the atmosphere throughout the UK (AQ0620; AQ0619; AQ0616). The network currently consists of 38 bulk precipitation monitoring sites sampled every two weeks supplemented by variable numbers of sites measuring gas, aerosol and particulates for sulphur and nitrogen compounds (http://www.airquality.co.uk/monitoring_networks.php?n=acid) The data provides national scale information for the modelling of acid and nitrogen deposition at the 5 x 5 km scale for the calculation of critical load exceedance and dynamic simulation modelling using models such as MAGIC and VSD (AQ0802).

The Countryside Survey, the NSI and the RSSS have all provided synoptic spatially extensive assessments of soil acidity as measured by soil pH. Recent data from Countryside Survey showed a significant increase soil pH between 1978 and 1998 in all Broad habitats apart from Coniferous Woodland. However there was no significant pH change in more acidic, organic-rich soils between 1998 and 2007, although soil pH did increase significantly in Broadleaved Woodland, Arable, Improved grassland and neutral grassland Broad Habitats (Emmett et al., 2010). Coniferous Woodland broad habitat has shown no significant change in soil pH since 1978, and this requires further research to understand why there has been no response despite the reductions in acid deposition over this period.

More limited spatial coverage but higher temporal resolution data are provided by the ECN from two weekly measurements of soil solution chemistry alongside periodic (five and ten yearly) assessments of soil pH. The ECN soil solution chemistry provides data on 15 chemical variables and has demonstrated significant declines in soil solution sulphate concentrations at three sites, with significant increases in soil solution pH at almost all sites over the last 15 years (1993 – 2007; Morecroft et al.,2009).

Soil nitrogen content to 15 cm has only been measured by the most recent Countryside Survey so no spatially extensive time series data are available for the UK. There were no significant trends in shallow soil solution nitrate or deep soil ammonium concentrations between 1993 and 2007 at the ECN sites (Morecroft et al., 2009). Trends for nitrate in deep soils and ammonium in shallow soils were not consistent with significant changes at some sites and no change at others.

Key findings and future needs

- The area of UK broad habitats where the critical load for acidity is exceeded has declined by roughly 20% between 1997 and 2007 although 54% of the area is still exceeded.
- There is growing evidence of a recovery from acidification in soil pH across the majority of Broad Habitats in England and Wales and in soil water chemistry at many sites across the UK. There is a continuing need to monitor soil acidity response in relation to the future deposition climate as critical load exceedance mapping still that the critical load for acidity is exceeded across more than half the total area of broad habitats.
- Further work is required to explain the lack of surface soil pH response seen in Coniferous Woodland Broad Habitat in relation to forest soil processes and management.
- Atmospheric deposition of inorganic nitrogen compounds remains an issue for concern and nitrogen is now the main contributor to acid deposition rather than sulphur.

- The critical load for nitrogen eutrophication is exceeded by current nitrogen deposition for 58% of the area of sensitive terrestrial UK habitats and this value has hardly changed since the mid-1980s. A small decrease to 48% is expected by 2020.
- The scientific challenges to understand the environmental effects of sustained, high levels of nitrogen deposition need to be met in order to inform policy options for emission control. This would include a combination of:
  - long-term monitoring of soil and soil water nitrogen status, coupled to assessment of vegetation status and change;
  - continued experimental work to understand soil nitrogen processes and interactions with other environmental drivers (e.g. climate and land use change); and
  - continued development of biogeochemical models to simulate soil and ecosystem nitrogen dynamics encompassing interactions with acidification and the carbon cycle and linking to models of soil and above-ground biodiversity change.

8.4.2 Metals, organic pollutants and biological contaminants

The presence of chemical and biological contaminants in soils can both pose a direct risk to human health and adversely impact on soil ecosystem services by impairment of function, e.g.

- accumulation of contaminants in crops to levels potentially harmful to humans and farm animals (impact on the provision of food and fibre); and
- presence of contaminants in soils to levels causing significant impairment of ecosystem function (impacts on the provision of food and fibre and support of biodiversity).

Current state of knowledge: Sources of metals to UK soils vary according to land use. Atmospheric deposition dominates in natural and semi-natural systems (including forested soils), but has fallen significantly (up to tenfold depending on location and metal) since the early 1970s, in line with decreases in emissions from sources such as fossil fuels and leaded petrol (for lead) (Baker, 1999). More recent monitoring (Fowler et al.,2006; AQ0716) has confirmed these declines. Deposition remains the single largest source of some metals to agricultural land as a whole (Table 8.2), but some metals for which deposition was previously the largest single source (e.g. copper), land application of materials is now more significant. In improved grassland and arable systems, inputs are largely due to the application of materials such as sewage and paper sludges, animal manures, fertilisers and composts, which contain metals. Defra has funded research (Alloway et al., 1998, SP0547) to assess inputs of metals to UK soils by the inventory approach, which allows amounts of metals entering UK soils to be periodically assessed according to source. Since many metals persist in soils for long periods of time this approach allows for proactive assessment of the need to reduce inputs. Based on the most recently available figures, the relative importance of sources to metal inputs to UK agricultural land may be estimated (Table 8.2).

Quantifying sources at a national scale is useful for the ‘bigger picture’ but does not capture spatial variability in inputs, which may be important for considering potential effects. Thus, atmospheric deposition represents a large scale diffuse input across a wide area, while sewage sludge applications are confined to <1% of agricultural land (SP0547) and thus inputs to those soils are far higher than the national average. Similarly, inputs of metals due to manure applications will vary spatially according to the intensity and nature of livestock production.

Table 8.2. Relative importance of the five largest inputs of metals to UK agricultural land. Data from SP0547 with the exception of deposition data for all metals except Hg, from AQ0716. SS = sewage sludge; IW = industrial wastes.

Zn	Cu	Ni	Pb	Cd	Cr	As	Hg
Deposition	Manures	Dredgings	Lead shot	Fertilisers	Fertilisers	Deposition	Deposition
Manures	SS	Deposition	Deposition	Deposition	SS	Dredgings	SS
Dredgings	Deposition	Manures	Dredgings	Manures	Manures	Manures	Dredgings
SS	Dredgings	Fertilisers	SS	SS	Deposition	Fertilisers	compost
Footbaths	Fertilisers	SS	Manures	Dredgings	Composts/ IW	SS	N fertilisers

Removal mechanisms for metals include leaching and offtake in crops (and volatilisation in the case of mercury) but in most cases losses are small compared with the total present, thus metals may persist in soils for very long periods. Application of materials to land has benefits including increasing organic matter and nutrient contents, reducing fertiliser needs and diverting materials from landfill, however the resulting build-up of metals in soils has the potential to impair soil fertility and function in the long term. The time taken to reach concentrations where effects may be potentially observed varies according to land use (e.g. manuring and cropping practices) and on soil type. Monteiro et al. (2010) simulated the effects of copper and zinc inputs from animal manures on concentrations in European soils including four UK soils. Depending upon the level of input it was expected to take between fifty and over one thousand years to reach potentially harmful metal concentrations in the UK soils; the highest input levels were expected to occur due to application of piglet manure (for copper) and veal, lamb or broiler manure (for zinc) at rates equivalent to 350 kg N/ha/a.

Organic pollutants may enter the soil by a number of pathways including atmospheric deposition and the land application of sludges etc., as well as specific pathways such as leaks from electrical capacitors in the case of polychlorinated biphenyls (PCBs). Inputs will thus vary spatially with land use. Periodic source inventories of specific organic pollutants (e.g. Dyke et al., 1997; CPEC51; ED43184) provide national scale estimates of releases to land, although uncertainties can be high, not least because there may be a large number of source types. The most recent inventory (ED43184) showed that the greatest single of dioxins was waste burning (not including incineration) and accidental fires, accounting for 34% of total releases to land. The next four largest sources, namely the non-ferrous metal industry, incineration, landfill and the power industry, contributed 56% of the total. Transformers and capacitors were the dominant source of PCBs (81%) while waste water activities contributed a further 15%. Pesticide manufacture and use contributed all releases of hexachlorobenzene (HCB). Controls on the emission of organic compounds to the atmosphere, introduced in the 1980s and 1990s, have resulted in significant declines in soil inputs.

Organic pollutant fate in soils depends strongly upon the tendency of compounds to be volatilised back to the atmosphere or degraded. Studies of archived soils (Wang et al., 1995; Alcock et al., 1995; Jones et al., 1995) indicate that historic inputs of chlorobenzenes (CBs), PCBs, polychlorinated dibenzodizoins and dibenzofurans (PCDD/Fs) and low molecular weight hydrocarbons have been largely lost by volatilsiation, while nonvolatile compounds such as polyaromatic hydrocarbons (PAHs) tend to persist. Biodegradable compounds also exhibit lower soil residence times than those resistant to degradation (SP0547). Pharmaceuticals and their metabolites are likely to be largely input via sludge application, although there is uncertainty regarding biodegradability and removal efficiency in wastewater treatment, and hence about concentrations in sludges (SP0547). Transfer of oestrogenic compounds in wastewater to sludge is small and inputs to soil from livestock manures are considered likely to be more significant. Veterinary medicines are used extensively in livestock areas, particularly areas of pig production. Sheep dip chemicals are a source of potential concern for soil function since land treatment is the major disposal mechanism and sheep dip compounds have been shown to be acutely toxic to some soil organisms (SP0547). Radionuclides may enter soils from natural or anthropogenic sources. Atmospheric deposition is the major source; concentrations in land applied materials appear negligible (SP0547). Biological contaminants may enter soils and the food chain via application of livestock manures and irrigation water. Manure application is the most important source of enteric pathogens (SP0547). Pesticides may enter soils by direct application or through fall during crop application, by irrigation or flooding of land with contaminated water, or deposition of contaminated precipitation (SP0547). Since around 1990 application practice has emphasised more frequent lower level application of fungicides, insecticides and herbicides to larger areas than was previously the cases, while application of growth regulators, molluscicides, nematicides and seed treatments has increased. Seed treatments have the greatest potential impact on soils due to their method of application. Newer pesticide formulations are more biodegradable within the environment and wastewater treatment systems; thus the direct input of persistent pesticides (such as organochlorines) via sewage sludge application is currently less of a concern than in the past. Pesticide fate in soil is highly variable, depending upon mobility within porewater and the tendency to degrade.

Defra research on the potential risks of metals to natural and semi-natural soils has centred on the development of critical loads approaches for metals (EPG 1/3/144; AQ04503; AQ0812/CPEA24). Effects-based steady state critical loads for nickel, copper, zinc, cadmium and lead have been calculated for the UK. The most recent calculated critical loads (AQ0812/CPEA24) showed no areas of exceedance of the critical load for nickel and almost none for cadmium. There was very little exceedance of copper, lead and zinc critical loads for the bog and heathland habitats, and areas exceeded were also relatively small for grassland and managed coniferous woodland However, over 50% of the areas of managed broadleaved woodland and unmanaged (coniferous and broadleaved) woodland were exceeded for copper, lead and zinc. The most widespread exceedance of critical loads was across central, eastern and southern England, where critical loads are generally lower and rates of deposition are generally higher. Dynamic modelling of in natural and semi-natural systems showed that accumulation and losses of metals are slow (timescales of decades to centuries) and indicating that the steady state approach used to calculate critical loads could be usefully supplemented by dynamic modelling to assess time trends in metal accumulation.

Work in AQ04503 developed toxic threshold concentrations (critical limits) for Ni, Cu, Zn, Cd and Pb in soils that account for soil chemistry effects on metal toxicity (Lofts et al., 2004). The critical limit concentrations relate to risks to the soil ecosystem. Accounting for soil chemistry allows spatial variability to be taken into account in calculating critical loads and assessing toxic effects.

Defra research on the potential risks of metals to agricultural soils has focused on metals in sewage sludge. Application of metal-enriched sludge to land at nine experimental sites (SP0117; SP0128; SP0130) has to date demonstrated significant effects on the soil microbial community, crop yields and crop metal concentrations; however, not all effects were inverse and neither were effects consistent across all sites. Creamer et al. (2008) studied the effects of elevated copper, zinc and cadmium concentrations on soil invertebrate abundance and diversity at a single experimental sludge site and concluded that earthworm, nematode and enchytraeid abundances, and litter decomposition rates, were sensitive to copper and zinc. Defra project SP0534 (Scoping biological indicators of soil quality - phase II) will soon report on the response of PLFAs, nematodes and micro-arthropods at a greater number of the experimental sludge sites and will provide further data linking metal concentrations and effects on soil ecosystem communities and function.

Evidence suggests that there are no significant environmental consequences from PAHs, PCBs or PCDD/Fs when sludge is applied to agricultural land (SP0547). Persistent organic compounds may be transferred through food chains which could present risks to higher organisms (SP0547). Veterinary medicines such as antibiotics are a source of potential concern since they may potentially affect the microbial community, particularly through the development of resistant strains of pathogens that may enter the human food chain (SP0547). Targeted monitoring of the concentrations of seven priority veterinary medicines in the environment (Boxall et al., 2006) suggested that average concentrations in soils were unlikely to impact biota, although further monitoring and assessment of a wider range of compounds was proposed as an option. Impacts of radionuclides present in soils depend on exposure pathways, organism, bioavailability, and dose (SP0547). This report suggested further research on the effects on biota of the low dose rates and chronic exposures typically encountered in waste management situations.

Generalisation regarding the impacts of pesticides in soils is hampered by the wide range of pesticide types. Multiple pesticide applications may have an enhancing or deleterious effect on soil biological processes. Effects noted on soil microbial function have included depression and subsequent stimulation of respiration, due to increased activity of a few resistant microorganisms. Some studies on insecticide effects have detected inhibition of rhizobia while others have found no effects. Long term effects seen have included reductions in numbers of soil organisms and depression of soil enzyme activities. Pesticide effects on soil invertebrates in arable crop systems were studied under the project SCARAB (Tarrant et al., 1997; Frampton, 1997). Two pesticide regimes representing farm practice at the time (1990-1994) and reduced inputs (by 50%, with no insecticides) were inconclusive for earthworms, since variability in populations across the two sites studied was greater than variability due to the different treatment regimes. Epigeic Collembola abundances were affected by repeated application of organophosphorus insecticides.

Enteric pathogens tend not to survive well in the external environment, so soil functions are not affected. There are concerns regarding the transmission of plant pathogens through the recycling of organic materials and return of soils residues to land following vegetable/root washing (SP0547), and other research has indicated that *E. coli* transfers from deposited or applied livestock manures may be a source of concern for surface water quality (e.g. Kay et al. 2008) although the role of the soil in this process (e.g. Oliver et al., 2007) is not well researched at present.

Defra research on contaminated land assessment and remediation is focused at strategic and policy level (e.g. Wood et al., 2002). Development of guidelines and models for risk assessment of contaminated land is partly done by the Environment Agency, while remediation research is funded by a variety of stakeholders including the Department for Business Innovation and Skills, and industry. Guidance and modelling tools (e.g. the Contaminated Land Exposure Assessment Model, CLEA) are available to assist the risk assessment process. Defra has funded development of the version of CLEA for application to radioactively contaminated sites (RS01022). Health Criteria Values (HCVs) (Environment Agency, 2009a) are derived by assessment of toxicological data on risks to human health from contaminant exposure and may be used in CLEA to derive threshold soil contaminant concentrations (Soil Guideline Values) above which further site investigation and/or remediation is required.

The Environment Agency is legally required to periodically report on the state of contaminated land in England and Wales and the related activities of local authorities; the most recent report (Environment Agency, 2009b) found that an estimated 10% of contaminated sites are dealt with by regulation (through the provisions of Part 2A of the Environmental Protection Act 1990), with the remainder dealt with through the planning system. Local authorities had identified over 700 sites as contaminated although the actual number of contaminated locations was estimated to be lower at 100-150. About 150 sites had been remediated by March 2007. Metals/metalloids and organic compounds were the most frequent sources of contamination. Current land use on identified sites was predominantly (>90%) housing and humans were overwhelmingly identified as the receptor of potential concern. Remediation methods largely comprised excavation and off-site disposal of contaminated soil.

Project SP1002 reviewed the current state of knowledge on the potential human health effects of contaminated land. The review indicated no significant shift in understanding since earlier reviews in the 1990s and 2000s. Overall, no evidence was found for widespread impacts of contaminated land on human health although the potential for health impacts could not be dismissed. The report identified several current sources of uncertainty in the assessment of risks, the most important of which were: incomplete characterisation of the contaminant concentration, use of conservative estimates of exposure, use of modelling to predict exposure, extrapolation of toxic effects from animals to humans, and the lack of consideration of mixtures of contaminants. The report concluded that 'The current state of knowledge is insufficient to quantitatively estimate overall impacts, if any, of contaminated land on human health'.

Monitoring of soil contamination: Monitoring of chemical contamination in soils can take two forms: monitoring of inputs and of resulting concentrations. Current and past monitoring includes:

- Countryside Survey: monitoring of total metals (Cd, Cu, Ni, V, Pb, Zn) and PAHs, PCBs and organochlorine pesticides in topsoils (0-15cm) in 2000, and metals (Cd, Cr, Cu, Ni, Pb, V, Zn and Li, Be, Al, Ti, Mn, Fe, Co, As, Rb, Se, Sr, Mo, Sb, Sn, Cs, Ba, W, Hg, U) in topsoils (2007) at 256 rural locations in England, Scotland and Wales (Black et al., 2002; Emmett et al., 2010b).
- The UK Soil and Herbage Survey (Environment Agency, 2007): monitoring of total metal (As, Cd, Cr, Cu, Pb, Mn, Hg, Ni, Pt, Sn, Ti, V, Zn), PAHs, PCBs and dioxins at 122 rural, 28 urban and 50 industrial locations across the UK.
- The Heavy Metals Monitoring Network (AQ04504): heavy metals in precipitation at 15 sites across the UK and national mapping of deposition to soils. This network remains in operation, funded under project AQ0716.
- National Soil Resources Institute datasets on metal (Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, Pb, Se, V, Zn) concentrations (total and extractable) in topsoils of England and Wales at 6,127 locations (1 location per 5km x 5km grid) from 1983, and a partial resampling from 1995 (http://www.landis.org.uk/data/nsitopsoil.cfm#nsitopsoil83)
- The British Geological Survey G-BASE survey, comprising total metal (Mg, K, Ca, Ti, Mn, Fe, V, Cr, Co, Ba, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Y, Zr, Nb, Mo, Pb, Bi, Th, U, Ag, Cd, Sn, Sb, Cs, La, Ce, Ge, Sc, Hf, Ta, W, Tl, Te) concentrations in topsoil (5-20cm) in the Humber-Trent and East Anglia regions (one site per 2 square km) and in 20 urban areas (4 samples per square km) (http://www.bgs.ac.uk/gbase/home.html).
- Targeted monitoring of priority veterinary medicines in agricultural soils, as part of an Environment Agency-funded project (Boxall et al., 2006).

From an ecosystem services perspective, associated monitoring of potential effect indicators for humans and ecosystem is important. The Countryside Survey also comprises sampling of soil faunal diversity (2000 and 2007) and microbial diversity (2000) while the Soil and Herbage Survey includes measurements of metals and organics in vegetation.

The use of inventories to quantify contaminant inputs to soil can be considered a proactive form of monitoring. The best developed input inventory approach is that for metals (SP0547) although its resolution is currently not sufficient to identify spatial variability in inputs, which may be important in determining risk at regional and local scales.

Options for further work

Improve understanding of the risks to human health and the environment

- The sludge trials represent a potentially invaluable source of knowledge on the long term effects of copper, zinc and cadmium in agricultural soils and future monitoring of soil ecosystems and functions at the sites would enable evaluation of longer term effects. It is suggested that the findings be evaluated in the context of maintaining soil biodiversity as well as fertility and crop viability.
- The bioavailability of contaminants is recognised as an important control on the exposure of ecosystems and bioavailability is now being considered in the setting of threshold soil concentrations of some metals, including copper and zinc, with respect to ecological risks. A re-evaluation of the sludge trial results in the context of metal bioavailability could improve the consistency and interpretation of the effects seen at the different sites and allow the re-appraisal of current limits on metals.
- Increasingly, international research into the risks of contaminants in soils is focusing on the sensitivity and resilience of soil organisms, ecosystems and functions to multiple stressors (e.g. climate and chemicals), including mixtures of contaminants (e.g. EU NoMiracle project). Field knowledge of the possible effects of multiple stressors is however small. If feasible, the proposed National Soil Monitoring Network could be extended to include measures of non-contaminant stress (e.g. soil temperature and moisture), providing an integrated monitoring database for field research into the effects of multiple stressors on soil functions and services.

Reduce levels of contaminants entering the soil

- Continue to monitor emissions and deposition to UK soils of key contaminants (e.g. metals and organics).
- Periodically update the metals inventory to reflect the latest knowledge on inputs.
- Periodically review potential new sources of contamination (e.g. changes in usage and emissions of metals, use of new veterinary medicines and pesticides, increasing use of nanomaterials) for possible risks to soil ecosystems and human health.

Advice on the use of materials spread to land

- Consider periodic spatial monitoring of metal contents in materials such as manures and sewage sludge.
- Consider a more spatially explicit inventory of metal inputs to agricultural soils to pinpoint potential ‘hotspots’ of risk, using the latest available knowledge on the variability sensitivity of different soil types to metals such as copper and zinc.

Impacts of contaminated land

- Progress in understanding the human health risks due to contaminated land is slow. Regular review of the state of knowledge will ensure that policy is informed by the most up to date findings.

Contaminated land remediation

- In-situ remediation of contaminated land appears to be little used currently in terms of the overall number of sites that have been managed to remove contamination. A cost-benefit analysis of available in-situ techniques in comparison to off-site disposal could inform policy advice to local authorities on recommended techniques for in-situ remediation.

- Continue to monitor the progress of contaminated land management and use of remediation methods.
- Consider targeted research to address uncertainties in the risk assessment procedures for contaminated land.

References

Defra reports:

AC0114 Agricultural GHG inventory research platform
AQ0616 UK Eutrophying and acidifying atmospheric pollutants (UKEAP)
AQ0619 Ammonia monitoring in the UK 2003-2008
AQ0620 Management and operation of the UK acid deposition monitoring network – new contract 2006-2008.
AQ0716 Heavy metal deposition mapping - new contract
AQ0801 Critical loads and dynamic modelling umbrella.
AQ0802 Terrestrial umbrella: effects of eutrophication and acidification on terrestrial ecosystems.
AQ0812/CPEA24 Development of an effects-based approach for toxic metals – Phase II.
AQ04503 Further development of an effects based approach for cadmium, copper, lead and zinc.
AQ04504 UK heavy metal monitoring network.
BD2304 Scoping study to assess soil compaction affecting upland and lowland grassland in England and Wales
CPEC51 A Review of the current source inventories for dioxin and dioxin-like PCBs for air, soil, & water with view to updating emission factors/estimates and inclusion of new sources.
ED43184 Review and update of the UK source inventories of dioxins, dioxin-like polychlorinated biphenyls and hexachlorobenzene for emissions to air, water and land.
EPG 1/3/144 Development of a critical load methodology for toxic metals in soils and surface waters: Stage II.
ES0127Defra research in agriculture and environmental protection between 1990 and 2005: summary and analysis.
IF0154 A preliminary assessment of the greenhouse gases associated with growing media materials
LE0101 To provide guidelines to reduce the risk of water erosion on susceptible soils used for arable cropping
LE0102 To map soil erosion risk areas in England and Wales
LE0206 Evaluation of mineral sites restored to agriculture
OC9611 The effects of soil compaction on biomass production in short rotation coppice of willow
PB13297 Safeguarding our soils a strategy for England
RS01022 Radioactively contaminated land: Development of RCLEA model.
SP0117 Effect of heavy metals from sewage sludge on the growth and yield of legumes.
SP0128 Effects of historic sewage sludge additions on soil heavy metal availability and biological processes.
SP0130 Effects of sewage sludge applications to agricultural soils on soil microbial activity and the implications for agricultural productivity and long-term soil fertility: Phase III.
SP0302 To reduce damage to soil structure through fundamental advances in tractive elements such as rubber tracks
SP0305 A national soil vulnerability-based framework for provision of farm-specific guidance on the management of soil structure
SP0402 Research on the quantification and causes of upland erosion
SP0406 Upland soil erosion data analysis
SP0407 Arable and upland NSI erosion resurvey
SP0404 Soil erosion control in maize
SP0411 Documenting soil erosion rates on agricultural land in England and Wales
SP0413 Documenting soil erosion rates on agricultural land in England and Wales - Part 2
SP0501 Effect of farm manure additions on soil quality and fertility.
SP0506 Comparison of original and re-sampled National Soil Inventory data
SP0518 The interaction of minimal cultivation regime and N fertiliser rate on soil C and N cycling: Ropsley.
SP0521 Changes in organic carbon content of non-agricultural soils.
SP0532 Vulnerability of Organic Soils in England and Wales.
SP0534 Scoping biological indicators of soil quality - phase II
SP0547 Sources and impacts of past, current and future contamination of soil.

SP0561 The effects of reduced tillage practices and organic material additions on the carbon content of arable soils
SP0567 Assembling UK-wide data on soil carbon (and greenhouse gas fluxes) in the context of land management.
SP0574 A literature review of evidence on emissions of methane in peatlands.
SP1101 Comparison of soil carbon changes across England and Wales estimated in the Countryside Survey and the National Soil Inventory
SP1202 Investigation of peatland restoration (grip blocking) techniques to achieve best outcomes for methane and greenhouse gas emissions / balance.
SP08005 The impact of subsoil compaction on soil functionality and landscape
SP08007 Scoping study of lowland soil loss through wind erosion, tillage erosion and soil co-extracted with root vegetables
SP08010 Review of carbon loss from soil and its fate in the environment.
SP1002 Potential health effects of contaminants in soil.
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9) Review attempts to value services provided by the soil resource

It has been noted that it is important to "*invest in improving our understanding of how degradation affects soil functions and how best to tackle it*." (PB13297) Economic analysis of soil ecosystem services is critical to choosing the best policies for tackling degradation. However, to be useful, analyses must provide estimates of benefits at the margin, net of costs, and which are interpretable in respect of specific policy instruments. This report evaluates the work carried out to date towards this goal, and identifies key areas for future work. Since economic valuation is a cross-cutting theme, we reviewed relevant projects and publications from across Defra.

Key findings:

- **Overview:** Economic analysis is a cross-cutting theme and relevant research spans Defra. It includes: guidance on methods, inventories of data, scoping studies, broad scale valuations and economic analyses of specific policy instruments.
- **Methods and data:** there is considerable information on how to undertake valuations of soil functions, though in most cases the evidence base is patchy. Benefits transfer, cost-based estimates and stated preference methods have some potential to overcome this but considerable care is required in their interpretation.
- **Valuations:** research to date has focussed on total rather than marginal valuations or on gross rather than net benefits of ecosystems, which limits its policy relevance.
- **Policy evaluations:** Where these have been made they tend to be partial, focussing on *either* the costs of environmental protection *or* the benefits.
- **Guidance for future work:** is needed to combine estimates of costs and benefits of soil protection in policy-relevant analyses conducted at the margin. Future valuations will always be limited by gaps in knowledge and this suggests more rigorous approaches to benefits transfer and changes to primary data collection.

Overview of Defra economics relating to soil

Defra work on economic valuation with relevance to soil has been undertaken across the department, not simply within the Soil Protection Program[3]. It is summarised briefly in this section and reviewed in more detail later on.

Guidance, scoping studies and data inventories: Defra has developed guidelines for the valuation of ecosystem services which are applicable to all areas (NR0103; Vaze et al 2006; PB12852). This work is ongoing (NE0104) and forms part of the broader effort to develop an ecosystem approach (NR0118). Inventories of relevant data include (NR0106) for social and economic data in general and topic-specific scoping studies for the valuation of peat ecosystem services (SP0572) and landscape (ER04001). SP08004 collated much of the available evidence on the value of soil ecosystem services.

Valuations: Defra commissioned a total valuation of all terrestrial ecosystem services in England (NR0108), also NR0125, while (SP08004) carried out a partial valuation of soil services and SP1601 aimed to "review the overall costs and benefits of soil erosion measures and to identify cost-effective mitigation measures".

Cost-effectiveness studies / partial analyses of soil related policies: Finally, a number of projects have used economic analysis to assess some aspect of soil-related policy instruments including cross compliance (DO101); integrated diffuse pollution mitigation measures (ES0203, ES0121); nitrate mitigation options (NT2511); phosphorus mitigation options (PE0203); and Environmental Stewardship (ER04003, MA01047).

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[3] A systematic study was made of the Defra publications database of all projects and publications listed under "soil protection" or "economic research". Reports and projects cited were followed up and a careful search was made of other relevant areas of the Defra website, combined with the author's own knowledge of the field.

Other work: It is also important to note the Inter-Departmental Group on Costs and Benefits (in which Defra is involved but which to date covers only air quality and noise) and the review of the economics of sustainable development. Defra has contributed to work on carbon valuation (Defra 2007) while guidance on social discount rates is provided by HM Treasury (2003).

Method development

Approaches to the valuation of ecosystem services and to the economic assessment of environmental policies are quite well established, at least for the case where sufficient data is available, and are generally well summarised in general Defra guidance (PB12852) and guidance specific to soils (SP08004). Unfortunately, in many cases data is not sufficient, and three methods are advocated by these reports to fill gaps: benefits transfer, stated preference techniques, and cost-based estimates. All three have their place, but the following should be noted.

Benefits transfer is the inductive use of values derived from one study in another context. It is necessary in order to allow economic valuations to be carried out at reasonable cost, but of course has its limitations. NR0108 provides extremely cogent options on how to value government research, whether economic or biophysical, these should be borne in mind by Defra when commissioning new research.

Stated preference techniques are strongly advocated by SP08004 in several cases where information on the benefits of soil functions is lacking. However, it is doubtful as to whether stated preference techniques can provide useful information on the welfare effects of soil protection/degradation in cases where the underlying causal links to human welfare are poorly understood (e.g. water quality), since stated preference techniques rely on fully informed preferences. As Dixon (2008) notes "the good point about CVM is the same as the bad point—you always get an answer!"

Cost-based estimates are heavily used by SP08004 where estimates of the benefits of soil are lacking, but the costs of measures to protect soil function are known. These values are presented as lower-bound estimates of the benefits of soil protection. However, it should be noted that this is only true if it is assumed that soil protection policy is rational, efficient and based on perfect information about the welfare effects of soil protection. It is thus circular to use such values in policy-relevant assessments of soil value.

Valuations

The main valuation of ecosystem services completed to date by Defra is NR0108. However, this analysis was constrained to focus on the *total* benefits of ecosystem services, rather than the *marginal* benefits. Such an approach has considerable problems which are well recognised in the literature (e.g. Toman 1998, Turner 2003) and in Defra guidance, which clearly advocates marginal analyses (SP08004, PB12852) and indeed by NR0108, who stated that:

"*a total valuation exercise is not useful in considering policy implications and its usefulness for advocacy could also be questioned given the limitations encountered in this study*

Within the soil program, SP08004 did estimate *marginal* benefits of soil functions. However, they were severely constrained by data limitations in doing so, especially where benefits are highly context specific. More importantly, they did not in general provide evidence on the costs of soil protection (except where these are used to estimate benefits). Their estimates therefore give little indication of the *net* benefits of specific soil management policies and very often the link between policy action and soil function was shown to be weakly understood.

Economic analyses of policy

Several projects have addressed economic aspects of specific policy instruments, though it must be said that most relevant policy instruments appear to lack such evaluations. In each case they have focussed on only one side of the instrument – either the costs of environmental protection (e.g. NT2511, PE0203, ES0121) or the benefits (e.g. ER04003) and true cost-benefit analyses are therefore lacking. One-sided analyses such as these are useful, allowing for example the costs of a particular regulation to be minimised, but they do not ensure efficiency (e.g. they do not tell us whether a regulation is necessary or not).

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Defra (2007) The Social Cost Of Carbon And The Shadow Price Of Carbon: What They Are, And How To Use Them In Economic Appraisal In The UK. Defra, London.
DO101 Evaluation of Cross Compliance
ER04003 Estimating the Non-Market Benefits of Environmental Stewardship
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ES0203 The cost-effectiveness of integrated diffuse pollution mitigation measures
MA01047 Estimating the incidental socio-economic impacts of Environmental Stewardship
NE0104 Development of Guidelines for Use of Benefits Transfer in Policy and Project Appraisal
NR0103 Valuing our natural environment
NR0106 Inventory Study on Natural Environment Data II
NR0108 Valuing England’s terrestrial ecosystem services
NR0118 Scoping the potential benefits of undertaking an ecosystem assessment for England
NR0125 Valuing ecosystem services in the East of England
NT2511 Cost curve of nitrate mitigation options
PB12852 An Introductory Guide To Valuing Ecosystem Services
PB13297 Safeguarding our soils a strategy for England
PE0203 Cost curve assessment of phosphorus mitigation options relevant to UK agriculture
SP0572 Ecosystem Services of Peat - Phase 1
SP08004 Economic Valuation of Soil Functions Phase 1: Literature Review and Method Development
SP1601 Soil Functions, Quality and Degradation – Studies in Support of Implementation of Soil Policy
SP1606 The total costs of soil degradation in England and Wales
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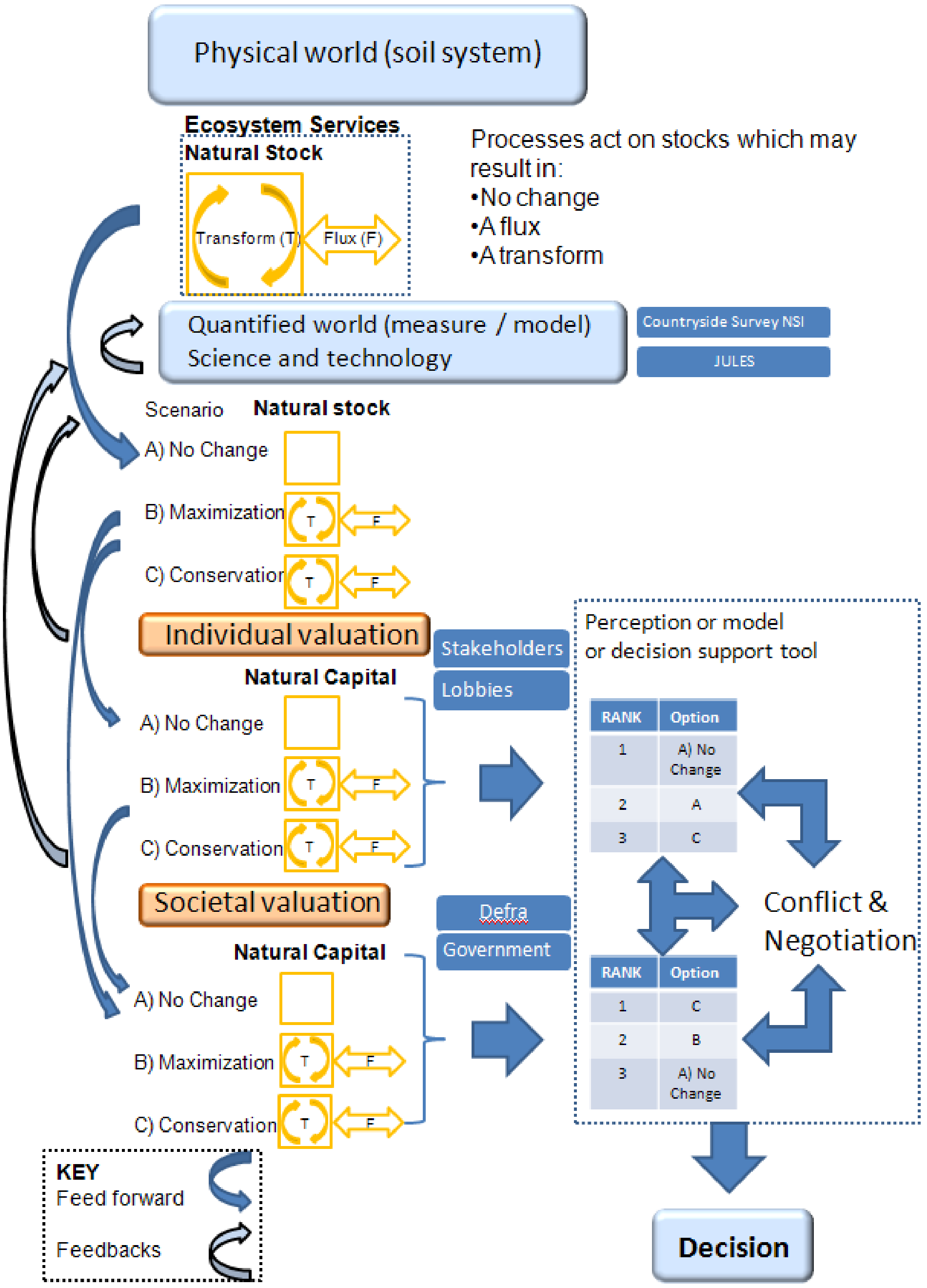
10) Vision for future soil protection in England and Wales

Based on Defra's aim of moving to an ecosystem based approach for environmental management (PB12853) this section examines concepts identified in this report and places soil protection, in the context of the natural capital / ecosystems approach. It is hoped that this section will serve as a continued synthesis, and as the basis of a road map for indicating the options with regard to applying the ecosystems approach.

This report began by using the Natural Capital / Ecosystem Services concept for soils presented by Robinson et al., (2009); where we defined the soil stocks as NC and the ES as the fluxes and transforms, this report suggests this division is not appropriate, and that NC is an integral part of ES as discussed below. Given the progression of ideas developing from this synthesis it has become clear that there is still confusion that results from the terminology, especially in terms of what can be measured and what is opinion or a perceived benefit in the context of ES. As a result a new conceptual framework is proposed which aims to provide more clarity (Figure 10.1).

Figure 10.1 The decision making process based on the physical world, our measurement or model of this, and how it's valued by individuals and society. Ecosystem services defined as the natural stocks, fluxes and transforms. Stocks become capital following valuation.



This framework recognises soil natural stocks that become soil natural capital when they acquire a value; the natural stocks are the fundamental resource; processes act on the stocks resulting in, no change, a flux, or a transformation. The *status quo* results in no-change in the stock, as can a transformation (depending on how it is measured), whereas a flux will result in an increase or decrease of the stock. The ES and disservices based on this division result from all of the stock, its transforms and fluxes; all of these can be measured or modelled using physical units. In the next step a biophysical model or measurement/monitoring program is used to assess, or describe, the stock and its flows and transforms. These will be monitoring programs like the National Soil Survey and Countryside Survey or models like JULES. Although measurement and modelling are largely objective when fundamental units are used, e.g. mass, energy, length, they do start to become subjective once we begin to group things; for instance, soil types, peat and mineral soils etc.

Given a description of the stocks, valuation can be added which may be monetary or some other valuation system. The valuation is divided into two components, individual valuation, which may be individuals or stakeholder groups; and societal valuation which is an aggregate of stakeholder values and may include a value put on things like earth system function. There are different ways a system can be valued, e.g. monetised or assigned a relative value, and these values have an objective and subjective component. Where the objective component might be considered the utility of the item which is a constant, e.g. the number of kcal obtained from a kg of wheat, and can be determined by the labour that went in to the production of the item, whilst the subjective component would be how much someone is prepared to pay. The values assigned to a system by stakeholders and societal bodies then feed into the decision making process. This is where decision support tools would be used to try and reconcile the different perceived values of a system, often through a process of negotiation and conflict, ultimately leading to a decision.

This whole process also contains feedbacks that inform the process. For instance, advances in science and technology inform the process of measurement and modelling by determining what is known, what can be measured and modelled. In the same way stakeholders view different aspects of a system as important and create bias toward measuring certain parameters that they feel are important; this may be at the expense of other parameters. This also occurs through societal valuation and priorities, recent examples include the increased monitoring of carbon, which 30 yrs ago was perceived as being of much lower importance. Ultimately the decision leads to a change in the system, from which we learn something; this again ultimately feeds back into out quantification of the physical world. Given this modified framework the classical concept of ecosystems services being the flows of goods and services is redefined as:

"*The goods and services derived from the natural soil stocks, fluxes emanating from them, or transformations of stock, which benefit society*".

This allows recognition that stocks themselves can be an important ecosystem service, for instance the carbon stock in soils which buffers the atmosphere, or the soil moisture stock which provides an available pool of water for all terrestrial life. Assessment of ecosystem services would then need to clearly determine if the stock is the basis for the assessment, or flux or transformation. Currently, some communities argue for measurement of fluxes, whilst others stocks. What is needed is to determine which is more appropriate, or perhaps determine both the stock and flux, and use one to refine the other, but avoid double counting.

This emerging concept sets forth the need for a measurement / modelling framework for soil natural stock assessment, and for soil protection and management within the ecosystems approach. In order to become operational, this framework will need the development of appropriate measurement/monitoring methods and biophysical models as well as trade-off models and decision support tools. In the case of soils, biophysical process models that incorporate impacts of vegetation type on soils would likely be an eventual goal. Many of the threats lead to changes that could be, as a fist approximation, considered 1-dimensional. A biophysical model that considers fluxes of mass and energy through the soil profile, such as hydrus (Simunek et al., 2005), or JULES (Blyth et al., 2010) for national scales, may be a good starting point. However, there is a serious need to link the physics, chemistry and biology in an integrated way in order to understand the full impact of soil threats. There also needs to be serious thought given to trade-off approaches and how to develop this in an effective way, tools like inVEST (Nelson et al., 2009) perhaps indicate the way forward for developing tradeoffs and decision support approaches. In the following sections the different aspects are explored in more detail.

Monitoring

Developing the biophysical modelling approach requires both data for modelling input and data to act as ground truth for prediction; this prediction data should feedback in an iterative way to help improve and update models, and possibly help optimize sampling. This process is not a foreign concept to environmental scientists working to understand the environment. Many concepts have been developed, however, data resources may not be in the correct format as required by models, or offer adequate temporal and spatial resolution to provide needed inputs. The National Soil Inventory contains important soil stocks that would be used in modelling, but lacks others, perhaps the more dynamic soil state variables like moisture and temperature. Monitoring frameworks such as Countryside Survey (Emmett et al., 2010) address the issue of monitoring change in soil stocks such as SOM, soil biota, pH and heavy metals and repeat surveys every ~8 years but don't capture data to depth or more dynamic variables. An issue emerging in the literature is the need to measure both bulk density and soil depth for monitoring purposes to obtain realistic stock and change assessment; difficulties with fixed length measurements for change determination are discussed in Lee et al. (2009) and subsequent literature. A comprehensive monitoring programme tailored to the needs of soil protection biophysical modelling would best be developed given a modelling framework. This would require identifying a modelling approach, determining the required inputs, and using the model to help design an optimal monitoring scheme to reduce uncertainty.

Monitoring programmes specifically address the issue of how land-use and climate change are impacting certain stocks and provide an important temporal snapshot for national scales. Data from the National Soil Inventory may provide other inputs. However, low cost, sensor technology should offer the opportunity to augment this with a soil monitoring network capable of capturing changes in the more 'dynamic' soil stocks, such as soil moisture, temperature, and some gases, (currently O_2 and CO_2 sensors are available) on a daily basis. In the USA, the soil climate analysis network (SCAN stations) has been deployed across America by NRCS to obtain spatio-temporal data to provide evidence of climate change at the land atmosphere boundary (http://www.wcc.nrcs.usda.gov/scan/). It provides a valuable way of determining actual soil response to a changing climate that can help interpret and improve model prediction. The ECN sites in the UK are the closest equivalent but only 12 exist and data on soils is limited to temperature, some moisture and some chemistry. Expanding this to incorporate more stand alone sensor technology for soil moisture and gas, and to collect measurements for biology could provide an important data set that supports modelling applications like JULES. In addition, current measurements tend to be limited to sensor measurements at the soil profile scale ($<1m^3$ of soil), or to estimates from remote sensing that has footprints of km's. There is an intermediate scale gap, and a need to develop a multi-scale observational network that crosses scales, which hopefully emerging technologies will address.

Modelling

Advances in low-cost computational power have dramatically improved our ability to model complex environmental processes at a range of scales. Biophysical soil/ecosystem models to address local, regional, and national scales are in need of development. These models must focus on integration of processes and the understanding of emergent behaviour through complex interaction. The models must integrate across physical, chemical and biological processes, in order to help us understand changes in NC and ES that occur through complex drivers; they should also incorporate drivers such as vegetation type which are important predictors of soil behaviour.

Modelling in the context of management generally includes two components: a description of the processes of concern (biophysical model); and management optimisation (trade-off algorithm) based on some quantification of the utility of outcomes. In conceptual terms, a management driver is routed through a biophysical model to provide a simulated outcome. Both the management option and the outcome have a utility, and a full modelling approach seeks to optimise that utility. This is a control optimisation problem which in principle can be tackled using well-established techniques. The appropriate integration of process modelling with control optimisation in practice should be a key area for model development. While full industrial-style process control is likely to be inappropriate in soil management, there is scope for a technology transfer of some of the principles and practices. One of the key recognised difficulties lies in assigning quantified preferences to a range of outcomes, and to a large extent this is outside the realms of science, relying on input from stakeholders.

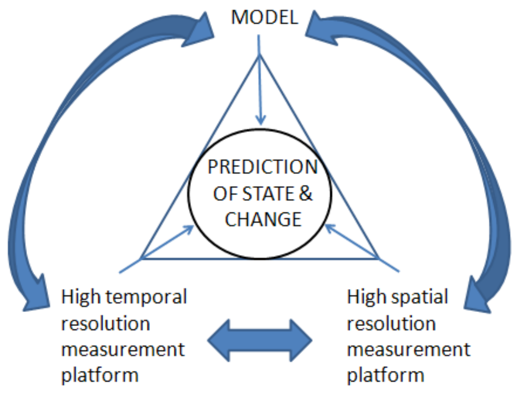
Optimisation with respect to management options is a function of the sensitivity of processes to these options, with respect to desired outcomes. This sensitivity is unlikely to be obvious for complex processes and their models. Automated, fully computerised, optimisation searches out this sensitivity and uses it to select good management options. This generally requires very large numbers of model runs (~10^3-10^4), which may not be practicable for large models. A simple rough-and-ready alternative is to use "scenario" management options to drive individual model runs, which is the approach taken with InVest, (Nelson et al., 2009). This may fail to give a full optimum where different management options have correlated effects, but is likely to give a good general indication of the best management options and the extent to which they are applied.

For the national scale a key process model under development as a community model in the UK is JULES; though there are other models in other countries, researchers in the UK are focused on the development of JULES. It operates in one dimension vertically through the land surface including the vegetation cover and the soil. The model simulates the energy, water, carbon and nitrogen budgets. As a 1-d model it is defined at a point on the land surface, but typically, in application, the point is taken to be a grid square, and large areas are modelled as comprising contiguous grid squares. The key drivers for JULES are atmospheric, and the model includes a soil parameterisation, based for England and Wales applications, on the NSRI LandIS database, with vegetation cover derived from the CEH Land Cover Map 2000 (BD1905) (to be succeeded by land cover map 2007). Management options can be identified with particular changes in the vegetation or soil parameterisation. Changes in the atmospheric drivers may be due to climate change, or, for example in the case of irrigation, by management options. JULES is under continual development to improve parameterisation, and the most appropriate parameterisation may depend on the use to which the model is put. The needs of soil protection are likely to stimulate improvements to the soil process component of the model, and to improved representation within the model of particular management options. One option would be to link ECN style platforms with comprehensive soil measurement to feed into JULES and provide data, against which modellers could test and improve prediction. It is important to remember that the models tend to handle changes in dynamic, environment driven processes, but do not account easily for manmade change such as point source pollution.

Within JULES climate change influences model drivers, the key variables are temperature, precipitation and radiation. Projected values of these, derived from downscaled general circulation model simulations, were used at a 1km grid scale to drive a range of soil threat models at a mixture of time steps in SP0571. Some of these models were unable to respond directly to atmospheric drivers, but could respond to outputs from JULES, which provided, for example, soil moisture estimates for use in a compaction model ("Workable Days"; WD). As an example of the use of JULES to assess management options, WD could also be used with JULES run with adjusted soil hydraulic parameters, representing a range of tillage options. Compaction responses could be scored, and tillage options modified so that the projections of the combined application of JULES and WD optimised the compaction scores, taking account also of any other costs associated with the tillage options.

The projected influence of a change on recognised soil threats within England and Wales has already been addressed through modelling (SP0571). Which examined, soil erosion, salinity through inundation, contamination via acidification, carbon, and sealing through workable days. At present there is no model for biodiversity as our understanding at the national scale is weak. Using the same basic approaches some of the soil stocks, and changes in them, could be estimated. For instance, changes in soil moisture stock could be estimated and temperature used, as could changes in nitrogen stock. Comparison with long-term monitoring could be used as a check of model predictive capability and ultimately a combined

Figure 10.2 The three pronged approach to measure the state and change of UK soils to help protect them from soil threats.



measurement and modelling national assessment tool could be developed. This approach would be best to incorporate both measurement and modelling platforms into an integrated approach to determine soil state and change (Figure 10.2). In a similar way to weather forecasting, predicting soil change in response to drivers could be developed as a long term vision, where models are continually updated by new measurements, understanding and discovery. A soil monitoring approach could combine high temporal resolution measurements from sensor networks, with data obtained from sporadic surveys, that are required to tell us how land use change is impacting the soil system.

Valuation and Policy Linkage

Economic valuations require approaches which are appropriate for the specific context – a recipe approach is neither desirable nor possible. Nevertheless, the required techniques are well understood, and between them, NR0108 and SP08004 provide a clear vision of future research needs in this area. NR0108 suggest that "*in future the focus should be on marginal assessments*" and they provide important specific options on how Defra funded research of all forms can best contribute to such analyses. It would be desirable for these options to be communicated to those responsible for commissioning science (whether social or biophysical) within Defra. SP08004 states: "*In order to be relevant for policy-making, monetary estimates should be presented in terms of the marginal value of the soil function i.e. the value yielded by an additional unit of the service provided… The proposal should set out explicitly how the values could be applied in a cost-benefit analysi*s" and they make clear that the costs (including transaction and opportunity costs) of soil protection must be evaluated alongside its benefits.

In addition to these options, valuations must be interpretable in terms of the costs and benefits of a particular policy action of interest. Gross annual estimates of the costs of soil degradation at the national scale are not likely to be, by themselves, very useful for policy-making as opposed to advocacy. However, since valuations are expensive, it may not be feasible for the number of valuations to approach the number of policies. One option is to move from commissioning one-off valuations, towards developing a decision-support framework akin to that developed for transport policy (e.g. WebTAG, (Dept for Transport, 2010). The advantages of such a framework are that it would allow analysis of policy options to be conducted quickly, without the need to commission new research at least for preliminary evaluations during the early stage of policy development. It maximises the value of new and old research, facilitating its use for as-yet-unplanned policies. It would be capable of being used at multiple scales (national, regional, local) and individual components of the framework would be updateable as new information emerged. It could build on the ecosystem services approach, and as such there will be economies of scale in developing the framework across multiple areas (soil, water, biodiversity) and multiple countries within the UK. The main disadvantage is that it would require some initial investment of effort to develop the framework (including any portal required) and perhaps in new empirical research into key knowledge gaps.

In addition, few economic valuations provide real estimates of error or uncertainty, nor do they provide detailed sensitivity analyses. This prevents the identification of those key information gaps which account for the greatest degree of uncertainty. Requiring greater attention to the propagation of uncertainty throughout the analysis, from the underlying science through to the valuations, would greatly help in both policy-making and the prioritisation of future research. It would also be methodologically innovative. Economic valuations have not yet made use of systematic review methods, which are well-developed in health sciences, and are increasingly applied to policy-relevant science questions in the environment (Pullin et al 2009). Since economic valuation requires the review of, and selection amongst, multiple data sources, applying systematic review methods would make it far more rigorous, repeatable, and hopefully more accurate. It is important to note that Defra does have its own value transfer guidelines.

Synthesising across scales

The focus of this report has been to consider Defra soil protection research in the context of soil stocks and services. In the introduction to this chapter we redefined ecosystem services, indicating that they are a result of the soil stocks, fluxes and transforms. As a result the identification or assessment of a service could be conducted by measuring the stock, the flux, a transformation, or a surrogate driver of the change in stock. There are different philosophies on how best to monitor changes in stocks. Some prefer to measure fluxes to determine change but this over looks knowing how much stock there is might be important. Many assessment systems use the DSPIR (Driver, Pressure, State, Impact, Response) method for evaluation. Given our efforts to identify stocks, in Table 10.1 we attempt to describe the determination of the soil 'state' for this framework. We consider our soil stocks in the left column. The different colours attempt to give an indication of how dynamically the stocks change with reference to anthropogenic time scales. The dynamic variables are those that alter on a daily basis, where as the semi-dynamic are those more likely to alter over years to decades, whilst the static are unlikely to change over decades to centuries, which helps to incorporate the concept of soil change with a temporal scale. State, is then divided into stocks and fluxes, and these are subdivided into direct measurement or modelling, or proxy measurement and modelling to assess the soil resource; National and Local scales are considered. Each category / colour under this represents whether we currently '*Have something*' in terms of historical or current data or modelling; '*Could have something*' in terms of data that could be synthesized or collected by minimal expansion of current monitoring; '*Requires extensive expansion of current, or new monitoring or modelling platforms*' (MM); or that the data are '*Not easy to obtain*' given current data or methods. Some data sets are identified which fill gaps, for instance CS (Countryside Survey); NSI (National Soil Inventory); ECN (Environmental change network); JULES (land surface model); Ecosse (Carbon model) etc. The summary table (10.1) should be viewed as a working tool and open to modification, but is perhaps helpful in assessing our current progress in determining soil stocks to be protected.

Table 10.1 Synthesis of approaches used to determine soil state.

	STATE							
Parameter to be determined	**STOCK**				**FLUXES**			
	Direct measure	Direct measure	Proxy measure	Proxy measure	Direct measure	Direct measure	Proxy measure	Proxy measure
Scale	National	Local	National	Local	National	Local	National	Local
1) MASS								
Solid: Mineral stock	NSI	NSI			Soil depth	Soil depth	Weathering rate	Weathering rate
Nutrient stock (old) (new)	NSI/CS	NSI					Nutrient budget	Nutrient budget
OM/Carbon stock (old) (new)	NSI/CS	NSI					Carbon balance ECOSSE	Carbon balance ECOSSE
Organisms	CS	ECN MM						
Gas: O_2	ECN MM	ECN MM						
Liquid: soil water content	ECN MM	ECN MM			Met station	Met station	Water balance JULES	Water balance Hydrus
2) ENERGY								
Thermal Energy	ECN MM	ECN MM	Surface temp	Surface temp	Met station	Met station	Thermal balance JULES	Thermal balance Hydrus
Biomass Energy	NSI/CS	NSI				Flux towers	Carbon balance ECOSSE	Carbon balance ECOSSE
3) ORGANIZATION / ENTROPY								
Physico-chemical Structure	MM	MM	Workable days	Workable days				
Biotic Structure	🟥	🟥						
Spatio-temporal Structure	NSI/CS	NSI						

Information status

Have something (Historical or current data)

Could have (Could be synthesized or collected from current information with some extra data collection)

Requires extended or new monitoring platform or modelling (MM)

Not easy to obtain (Difficult to obtain with current data or methods)

Stock, time scale for change

Static

Semi Dynamic

Highly dynamic

*blue and yellow indicates there is a fast turnover pool and a short turnover pool; white indicates no available information.

References

Defra reports:

BD1905 Land cover map 2000

NR0108 Valuing England’s terrestrial ecosystem services

PB12853 Securing a healthy natural environment: An action plan for embedding an ecosystems approach

SP0571 Modelling the impact of climate change on soils using UK climate projections

SP08004 Economic valuation of soil functions phase 1: Literature review and method development

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Conclusions

This report draws together a synthesis of Defra funded research on soils and their protection from 1990-2008. The report describes Defra research on soil protection in the context of the ecosystems approach, which identifies 3 scales of importance, which we adopt for the review of soils information; these are:

- national, regional and local

There is no clearly accepted definition of what the ecosystem goods and services provided by soil are. As a result this report reviews the research in the context of the 'Mass-Energy-Organization' soil natural capital framework, identifying soil stocks. The soil natural capital framework offers a classification system for soil components that can be measured and assessed. In addition, by adopting this approach the report finds that much of the Defra funded work between 1990 and 2008 can be fitted into a soil stocks / natural capital framework. Given the soil natural capital framework, soils data collected during the synthesis timeframe tends to emphasize more static soil variables such as soil texture or carbon content. There is less emphasis on the more dynamic soil variables such as moisture content and temperature, and their impact on functions such as nutrient cycling, and runoff and infiltration. Knowing how these parameters change will be important for determining the impact of climate and land-use change on soil behaviour.

This synthesis identifies important soil stocks, the next step would be to link these with the broader ecosystem services work that is currently being conducted, e.g. the National Ecosystem Assessment and Countryside Survey, to create a full ecosystems approach incorporating soils. As a step in this direction this report defines soil ecosystem goods and services as:

"*The goods and services derived from the natural soil stocks, fluxes emanating from them, or transformations of stock, which benefit society*".

This definition offers an operationalizable way forward through the measurement of soil stock-and-change, which can be used to assess changes in soil ecosystem services. However, an accepted classification/typology of soil ecosystem services is still required and is an important step to developing an agreed way forward for soils.

Notes

Note 1: A short summary of the main options and knowledge gaps from the individual UKSIC indicator reports:

- **Food and fibre (SP0548)**

This project considered 16 potential soil quality indicators from SP0512 which were related to food and fibre production. The majority of these indicators are from the "higher-level" category (e.g. crop yields, area under agricultural land use, etc) with only three soil-specific indicators (respiration quotient from CO_2, microbial biomass quotient and potential nitrogen mineralization). The project concluded that although there was plenty of data available for the higher-level indicators, their robustness was considered inadequate. However, all 13 higher-level indicators were recommended for monitoring with suggestion for improving data quality. The indicators associated with soil microbial biomass and activity were recommended for further development with field trialling. The project also recommended the inclusion of clay content, pH, labile carbon, cation exchange capacity, soil microbial biomass, mineralizable N and Olsen P, with reference to SP0512.

- **Environmental interactions (SC030265)**

This project considered the sifted set of indicators from Stage 1 and further reduced this to eleven potential indicators on the basis of published information and expert opinion (see Table 4.3 in chapter 4 of this report). It is important to remember that the selection and testing processes were focussed on identifying and developing indicators that would have specific resonance with broad-scale (national) soil monitoring (Tier 1). In this instance a minimum dataset (MDS) of indicators would be used to collect information across the UK to identify headline trends and areas at risk. At this level, it is envisaged that existing data on soil properties can be used to broaden the dataset and enable early trend analysis to be undertaken. The project also proposed that Tier 2 would be more specific monitoring for sites identified through the use of triggers or through a risk-based approach and Tier 3 would be focussed on localised issues. The project collated and evaluated data and information regarding the setting of trigger values for indicators to flag potential 'headline' issues of concern with soils. A key recommendation was the need to develop these further with field-based approaches. A subsequent ("road-testing") project piloted an approach to develop "prompt" values using heavy metals as a case-study (SC050054SR1). This project highlighted that, although there are limits for metals with respect to food production and environmental protection, very few limit values for metals have been validated environmental and ecosystem protection. Key findings of the project were that the existing limit values in the Sludge (Use in Agriculture) Regulations and the Code of Practice for Agricultural Use of Sewage Sludge may not be sufficiently protective of soil quality and under-protective of wheat grain cadmium concentrations. The project concluded that there was a balance to be struck between environmental protection / regulation and the application of organic materials to land. The project proposed that 'prompt values' should be considered against changes in soil metal concentrations over time to provide an early warning approach by which mitigation or remediation activities can be addressed before harm to soil functions occurs.

- **Foundation for the built environment (SP0554)**

This project assessed indicators for monitoring soil as a foundation for the built environment. These had been suggested in an earlier project 'Identification and development of a set of national indicators for soil quality' (SP0512). The indicators were investigated for a trial area covering Bedfordshire, Hertfordshire and Cambridgeshire and changes determined over 10 years. This project evaluated four potential indicators from SP0512. Three are higher-level indicators (area of greenfield land lost to development, area of land / number of sites protected from development and area of land lost to mineral workings) while the pollutant loadings is an integrative indicator. The project concluded that none of these indicators are currently sufficiently robust or sufficiently related to monitoring the platform function of soil. It was proposed that pollutant loads could be developed to determine where exceedance of critical levels for soils could constrain development. The project also proposed the extent of soil sealing as a new potential indicator, to monitor changes in the area of soil used as a platform.

- **Soil organic matter as an indicator of soil health (SP0546, with SP0310, SP0303, SP0521, SP0533, SP0545, SP0519, SP0306)**

This project analysed and reviewed existing data on soil organic matter (SOM) and soil carbon to derive a robust indicator of SOM which could be used to monitor for a halt in the decline of soil organic matter caused by agricultural practices in vulnerable soils. Two groups of vulnerable soils with respect to SOM were identified (1) already at or below a lower threshold and (2) above the threshold but which are showing a greater than average rate of loss (c.f. Bellamy et al., 2005). The project proposed the low SOM soils could be addressed through practical measures such as Good Agricultural and Environmental Condition whereas soils with higher rates of loss may be driven by climate change and land management in upland areas and would need alternative strategies. The results from this project were used to inform the establishment of the first Headline Indicator of soil quality. Soil organic matter has now been set as a headline indicator for the Sustainable Food and Farming Strategy (SFFS) for Outcome 5 on the better use of natural resources. The project also highlighted the potential of different soil carbon fractions to provide useful information on soil functions.

- **Biological indicators of soil quality (SP0529)**

The SQID project was established to prioritise biological indicators of soil quality for broad-scale monitoring. The feasibility of using biological indicators in broad-scale monitoring had been established earlier through inclusion of soil microbial and invertebrate measures in Countryside Survey 2000 (Black et al., 2003). In parallel, the NERC Soil Biodiversity Programme and other international initiatives had developed and trialled novel and much needed methods for characterising and measuring soil biodiversity (see Usher et al., 2006). Phase 1 of the SQID project reviewed and evaluated >180 potential biological indicators of soil quality for relevance to soil functions and application to broad-scale monitoring. The indicators were identified from literature reviews and consultations with experts. A semi-objective approach (“logical sieve”) was developed to synthesis the available information and to compare the suitability of a wide-ranging and large number of potential indicators. The approach provides an audit trail of the selection process and provides a mechanism for re-evaluating indicators as and when new information becomes available or alternative decision-making is required. The sieve was used to rank the potential indicators. A final list of 13 indicators (see Table 4.3 in chapter 4 of this report) was obtained from peer-review of the top-ranking indicators (Ritz et al., 2009). At an expert workshop, one biological indicator - microbial community structure using PLFA analyses - was given over-whelming support for application in monitoring. The report also acknowledges that there are key “missing” indicators in the final list. Two principally omissions are; rhizobium and earthworms. The later was constrained by the practical requirements of field sampling. The omission of rhizobium reflected practical methodological issues and the specificity of rhizobium to food/ fibre production. The 13 biological indicators have been field trialled extensively using long-term experimental sites and by linking to the 2007 Countryside Survey.

- **Use of remote sensing (Wood et al., 2004)**

Remote sensing has long been used for terrestrial monitoring, including of soil, and may offer a means to obtain good quality information, cost-efficiently. This report reviewed the suitability of various methods and proposed a suite of 9 potential indicators, which are:

- Indicator 1. Trends in the natural area of soil, as affected by marine erosion and accretion. Various methods are suitable with some already being used to monitor coastal retreat predictions (e.g. Shoreline Management Plans).
- Indicator 2. Proportion of sealed soils. A range of methods are considered suitable for assessing urban expansion, or in-filling, and for distinction between vegetated and non-vegetated surfaces.
- Indicator 3. Above-ground biomass production, as an indicator of continuing biomass productivity of soil. There are various methods being developed to monitor above-ground biomass, with further research required to establish their effectiveness in the UK environment and whether they indicate a change in soil functional capacity.
- Indicator 4. Proportion of brownfield soil area under woodland. Good baseline and subsequent change on extent of both brownfield soil and woodlands exist from aerial photography and other records. It is proposed that straightforward GIS interrogation of these datasets would provide some indication of correspondence. Development of remote sensing would be required to identify the soil types associated with these areas since current national soil data for England and Wales is too coarse, at 1:250,000 scale, to assess the soil *types* under woodland.
- Indicator 5. Area of agricultural soil converted to woodland. Delineation and area estimation of current and past agricultural land is probably best done using land records held by Government.

However, optical remote sensing could be used to obtain a less precise output. This output could then be interrogated alongside woodland inventory data.

- Indicator 6. Current area of specific soil-related habitats (bog, moorland, etc.). Digitised aerial photography, and high-resolution multispectral sensors (e.g. IKONOS, Quickbird) that warrant investigation for improving on current techniques.
- Indicator 7. Eutrophication events, as an indicator of nutrient breakthrough from soil systems. It would appear that a tiered approach to monitoring could be implemented. From spatially-distributed nutrient delivery models, high risk areas could be flagged. This screening process would allow the acquisition of medium resolution data (airborne or satellite) to be targeted. Remote sensing images might then be able to flag eutrophication based on simple vegetation index measures.
- Indicator 8. Area of 127 greenfield soil area taken in to the built environment. The requirements here are similar to those for sealed soil monitoring (indicator 2). However, the context is different, since it is only the urban fringes that are expanding into 127 greenfield sites. Any optical image resolution of less than 2m is considered suitable.
- Indicator 9. Change in the area of soil ploughed, as an indicator of potential damage to archaeological heritage. Optical images could be used to identify ploughed land, either visually, photo-interpretation, or by automatic image classification/change-detection routines. Some success has also been achieved in distinguishing ploughed *vs.* un-ploughed (low/minimum tillage) arable land. The use of all sensor types would benefit from *a priori* knowledge of recent land use and cover types; a benchmark against which change could be compared.

❖ Indicators of resilience (LQ06, SNIFFER, 2006)

Soil resistance was defined as “the capacity of a soil to continue to function with change throughout a disturbance” and soil resilience as “the capacity for a soil to recover its functional and structural integrity after a disturbance”. Both resistance and resilience are highly specific to soil types, with some types considered more resilience and resistant than others e.g. brown earths > mineral gley > peaty gley > peat. From a comprehensive review and expert workshops, various headline indicators were proposed where existing data would support rapid development in one or more soil types; 4 physical, 3 chemical and 3 biological (see Table 4.3 in chapter 4 of this report). Secondary indicators were identified for their potential but down-graded based on cost and / or unsuitability for a wide range of soil types. It was proposed that resistance and resilience should be selected depending on the type of perturbation or stress that soil will be subjected to since certain indicators will be more suitable for certain stresses. Thresholds were also reviewed and, where available, presented with respect to individual soil functions. However, it was stressed that considerable research will be required to establish thresholds for soil recovery or resilience with a degree of confidence. There is little information on the soils ability to recover to a “normal situation” through management or natural processes, partly because there is no information on what would be acceptable / the “normal situation” for different soils. Barriers to the adoption of indicators of soil resilience / resistance were considered with priorities given to the need for improved accessibility of data (whether better / free access to current digital data or the need to digitise historical / potentially baseline data) and a limitation of suitable (practical / field-based) soils skills as a barrier to the implementation of an effective soil protection policy. The recommendations included:

- the need for rapid, cost-effective chemical and biological methods
- reference values for poor / good quality soils, and resistance/resilience of different soil types under different land uses.
- Develop and quantify the capability of each soil type for a particular function and purpose under varying climatic conditions, in a similar vein to the land capability for agricultural approaches, land classification systems and soil suitability for land spreading of wastes.

❖ An assessment of potential soil indicators for the preservation of Cultural Heritage (Donaldson and Wilson, 2006)

This project recommended a sub-set of potential indicators to monitor the function of soils in preserving archaeological and cultural heritage resources and landscapes and identified gaps in the current knowledge of the threats to the resource and its response to changes in identified indicators, the availability of base-line data, and suitable monitoring methodologies and instrumentation. The indicators are intended for monitoring national level future changes in soil quality which have a detrimental impact on the archaeological and cultural landscape resource. They are not designed to provide an assessment of the current state of the resource or to monitor directly the consequences of soil change on that resource, nor are headline indicators designed for use in regional or local-scale monitoring although their potential application at smaller scales is discussed. Coastal erosion and sea-level change are not in the remit for this study. A series of potential indicators were assessed for Sensitivity, Practicability, Efficiency and Cost, and Integration. Soil pH, soil organic carbon context and superficial deposits lost annually to mineral extraction and peat cutting (area, volume and depth) were identified as both relevant and currently practicable potential headline indicators of cultural heritage (see Table 4.3 in chapter 4 of this report). In each instance, it was suggested that only a small investment would be required to establish the most appropriate methodologies for analysis and interpretation, and to compile the necessary background data. It was proposed that the analytical methodology for soil pH and soil organic carbon should be chosen in accordance with those used in the development of existing data sets (e.g. the National Soil Inventory) to ensure comparability. A number of highly relevant indicators were found to be impractical based on current technologies, knowledge of the resources response and / or the availability of suitable baseline data. These include: erosion and sediment redistribution, water-table depth and fluctuations, and / or soil redox potential, plough depth and area of new cultivation. Because of their potential importance to the preservation of cultural heritage it is recommended that these areas should be a high priority for further research with the aim of developing indicators in the near future. Key knowledge gaps with respect to SQIs for cultural heritage were identified as:

- Landscape level responses to changes in soil fertility, drainage, chemical and biological properties:
- Effects of fertilisers and pesticides on buried artefacts:,
- Threats to archaeological monuments in areas of land-use other than arable:
- Responses of archaeological artefacts to change over time and the importance of pedogenic thresholds:
- The establishment of soil / artefact equilibria and the effects of perturbations of different scale: and
- The effect of microbial activity on the decomposition of organic deposits and artefacts, and the response and consequences of changing soil conditions, particularly within buried deposits.

References

Defra Reports:

SP0303 To quantify the effects of cultivation on soil stability and on organic matter
SP0306 Critical levels of soil organic matter
SP0310 To develop a robust indicator of soil organic matter status
SP0512
SP0519 Critical levels of soil organic carbon in surface soils in relation to soil stability, function and infiltration
SP0521 Changes in organic carbon content of non-agricultural soils
SP0529 SQID: Soil quality indicators - developing biological indicators
SP0533 Initial assessment of projected trends of SOC in English arable soils
SP0545 Spatial analysis of change in organic carbon and ph using re-sampled National Soil Inventory data across the whole of England and Wales
SP0546 Soil Organic matter as a headline indicator of soil health
SP0548 Soil indicator robustness testing: Food and fibre
SP0554 Soil indicator robustness testing: Foundation for the built environment
Wood et al., 2004 The use of remote sensing to deliver soil monitoring (http://www.defra.gov.uk/environment/quality/land/soil/research/indicators/documents/soil-remotesensing.pdf).

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Donaldson, D.A. and C.A. Wilson. 2006. An assessment of potential soil indicators for the preservation of Cultural Heritage.

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Note 2: Principal measurements taken in datasets of soil properties of England and Wales

(i) NATMAP Survey

Natmap is the National inventory of soil properties collected by NSRI. These properties were measured at the time of collection and therefore the dataset has not been updated since collection. The inventory serves as a basis to many National soil property estimates as it contains the National Soil Map and relevant properties such as bulk density values. Properties included are as follows

Properties	Parameters Included
Soil series	Soil series name, subgroup, definition
Hydrology	Depth (cm) to rock, Hydrological rock type, Depth to gleying, Depth to slowly permeable layer, Integrated air capacity, HOST, Bypass flow, Baseflow Index, Standard percentage runoff
Agronomy	Available water profiles for different crops, Available water to 1m for a specific soil type, water available between suctions of 50 and 1500 kpa, Depth to rock, Peaty topsoil, Calcareous topsoil
Pesticides	Groundwater protection Policy category, pesticide leaching potential class, Pesticide surface water runoff class
Horizon fundamentals	Layer Designation, upper and lower depth, texture, carbon, pH
Horizon Hydraulics	Upper and lower depth, Bulk density, total porosity, volumetric water content at 5, 10, 40, 200, 1500 kpa, Ksat, calculated water content at quasi-saturation, Van Genuchten's parameters

(ii) NSI Topsoil Survey

The national soil inventory is a spatial, point dataset with 6127 points located on a 5 km grid across England and Wales. It was collected by 1984. A re-sampling (SP0115) occurred in the mid 90's for arable and rotational grassland sites (1994-5; 853 of the original 2578 sites) and for managed permanent grassland sites (SP0118) (1995-6; 771 of the original 1570 sites) and in 2003 (SP0521) for non-agricultural sites such as bogs, scrub, rough grazing, woodland (555 of the original 1505 sites). The sub-sampling was based on sufficient samples to determine changes ion organic C at 95% confidence.

Properties	Parameters
Soil Series	Grid references, Upper and lower depths, Texture (estimated in field), Von-Post scale for assessing degree of decomposition of peat, Matrix colour, mottling presence + size + colour + abundance, Structure (shape, size & degree of development of the aggregation, peds, clods), stone abundance & size & type, carbonate, coating, nodules, porosity, boundary.
Chemistry	pH, Metals (aqua regia, EDTA), Olsen P, Extractable Cations
Texture	Clay, silt, sand

(iii) Countryside Survey

Countryside Survey provides scientifically reliable evidence about the state or 'health' of the UK's countryside today. It was undertaken in 2007, 1998, 1990, 1984 and 1978. It is used to identify change (and the relative rate of change) in the countryside.

Soil Properties	Parameters Examined.
Physical	Bulk, density, hand texture
Chemistry	Soil organic matter and Carbon content, Soil pH, Phosphorus, Mineralisable and total N, Metals, POP's
Biological	Invertebrates, Microbial diversity,

(iv) Representative Soil Sampling Survey

The RSSS monitors the pH and nutrient status of agricultural soils in England and Wales. It has been going since 1969 and yearly sampling is amalgamated into 5 year periods.

Soil Properties	Parameters Examined.
Physical	
Chemistry	Soil pH, Soil P (extractable), Soil K (extractable), Soil Mg (Extractable)
Biological	

(v) Environmental Change Network

Sampling undertaken at 12 terrestrial sites on a

Soil Properties	Parameters Examined.
Physical	Soil Survey (initial, 5 yearly, 20 yearly).
Chemistry	Soil solution (major anions and cations) – Fortnightly.
Biological	

References

Defra reports:

SP0115 Resampling of selected soils from the National Soil Inventory sites
SP0118 Resampling of permanent grassland sites from the National Soil Inventory
SP0121 Scoping study for the mathematical analysis of national soil inventory data