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Opportunities for soil sustainability in Europe

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EASAC

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To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

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Foreword

Mahatma Gandhi once said that 'to forget how to tend the soils is to forget ourselves', reflecting our dependency on good quality soils for our food. At his time, most of the population still lived close to agriculture and the soils on which it depended; now, however, with the majority of the global population in urban environments, concrete and asphalt may be more familiar than soil, with little awareness of how much we rely for our well-being on the complex living ecosystems of soils which play such important roles in health, biodiversity, climate change, the water cycle and others.

Despite soils being so important for our daily life, in many regions of the world, unawareness, unsustainable industrialised agriculture, poverty and other socio-economic factors lead to destruction of good soils. Concerns over a general lack of awareness of the importance of soils, and global trends towards soil loss and degradation, led the United Nations 68th General Assembly to declare 2015 the International Year of Soils (IYS). IYS aimed to increase awareness and understanding of the profound importance of soil for human life, and to educate the public about the crucial role soil plays in food security, climate change adaptation and mitigation, essential ecosystem services, poverty alleviation and sustainable development. Since 2015, attention to soils globally has increased substantially and numerous programmes, also encouraged by the Sustainable Development Goals, have been initiated to promote sustainable soil management to protect the soil's ability to feed the growing global population, counteract biodiversity loss and slow down the rate of climate change.

Against this background, it may seem strange that only a year before IYS, the European Commission had withdrawn a proposed Soils Directive in the face of opposition from several Member States. Since then the debate on whether further steps in Europe are necessary to protect our soils has been in somewhat of a hiatus. Indeed, soils seldom make the headlines, and we rather take for granted that they will be there in future providing the same or improved productivity and other ecosystem services. Seldom do we think how long it took to create the soils that provide our crops or support our natural landscapes, or realise that, on a human timescale, they are essentially a non-renewable resource. When we do read about desertification we think of distant countries with little connection to our own well-being, whereas in fact it affects us as well both directly (in southern Member States) and indirectly (by driving poverty and migration pressures).

We therefore thought it was very timely when the Dutch Academy offered to lead an EASAC project on soils, based on the premise that a lot of science had emerged since the last time this was discussed in depth within the European Union, and that a review of the implications of such science to policy would be timely. EASAC's Environment Steering Panel supported this idea and EASAC Council agreed in May 2016. The project started in November 2016 with a scoping workshop comprising 20 experts nominated by EASAC academies. The expert group reviewed the science, and then worked with our Environment Programme Director to produce this report, which considers the implications for future EU policy.

The report focuses particularly on soil biodiversity and its contribution to above-ground diversity, soils and modern farming (including the European Union's Common Agricultural Policy), and linkages between soil, plant and human health. It also examines in detail the various interactions between soils and climate change (including the '4 per mille' initiative). There then follows a very detailed discussion about the possible policy implications.

We believe this report brings new perspectives to debate, which should revitalise discussions within the European Union on how we can work together to protect this essentially non-renewable resource in the absence of a Soils Directive. We point to several important synergies and possible ways forward to better manage soils nationally and to better coordinate activities between Member States. As the United Nations and its Food and Agriculture Organization prepare to conduct a global soil biodiversity assessment, this is the time for Europe to think again about what measures it should collectively take to protect the future of this valuable resource beneath our feet.

Thierry Courvoisier
President EASAC

Summary

Debate on how to achieve sustainable soil management across the European Union (EU) led to the adoption of the Soil Thematic Strategy in 2006, but insufficient support among Member States obliged the European Commission to withdraw proposals for a Soils Directive in 2014. Joint actions relating to soil sustainability remain within the 7th Environment Action Programme. Internationally, however, attention to soils has been growing, recognising the importance of soils as a non-renewable resource on which we depend for several key human needs as expressed within the Sustainable Development Goals. In view of the divergence of such trends within and outside the EU, the European Academies' Science Advisory Council (EASAC) decided to review recent scientific understanding on the role of soils and consider implications for EU policy. The study was assisted by an expert group led by the Royal Netherlands Academy of Arts and Sciences (Koninklijke Nederlandse Akademie van Wetenschappen) and is intended to contribute to debate and decisions within the European Commission, European Council and European Parliament, as well as national governments and other stakeholders.

The increased actions on soils in the international context include the formation of the Intergovernmental Technical Panel on Soils and the Food and Agriculture Organization's (FAO's) Global Soil Partnership. The United Nations' (UN's) Sustainable Development Goals on food security, human health and terrestrial environment make explicit reference to the need to preserve soil resources. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has also addressed issues on soil sustainability.

The crucial role of soils and the threats they face are described in this report, with a focus on understanding soils' ecosystem services, the role of soils in supporting above-ground biodiversity, maintaining sustainable soils in agriculture, linkages to healthy food and human health, and soils' contributions to mitigating climate change.

We conclude that there are several implications for policy, which include the following.

1. *Soil sustainability* has been defined by the Intergovernmental Technical Panel on Soils and these criteria should inform a review of EU-wide measurement and monitoring coordination between Member States and establish locally appropriate benchmarks to allow policy makers and land managers to determine whether they are moving towards sustainability. There are shortcomings to available data arising from different national monitoring systems which should be addressed; for example, through the European Soil Data Centre (section 7.2).
2. *Soil biodiversity* underpins the provision of key ecosystem services which support above-ground biodiversity and productivity. Biodiversity is protected under various directives and international agreements but without explicit mention of soil biodiversity. In the lack of a European Soils Directive, it is desirable to consider soil biodiversity protection within the Habitat Directive, Natura 2000 and other biodiversity-related initiatives (section 3).
3. There can be conflict between *short-term pressures* to maximise monetary returns through high input and high yields in agriculture, and long-term sustainability of the soil. The ability of soil to produce ecosystem services (food, feed, fibre, retaining carbon and nutrients in the soil, promoting structural stability, water infiltration and retention, climate regulation and below- and above-ground biodiversity) offer benefits to society as a whole (sections 4.2 and 7.7).
4. The *2013 Common Agricultural Policy revision*, placing the joint provision of private and public goods at the core of policy, recognises the need to balance the short-term private and longer-term societal interests, but initial evaluations suggest effects on sustainability have been limited. Options are available now to improve beneficial effects on soils (e.g. encouraging crop rotation within the crop diversification requirement and including wider areas of grassland in the permanent grassland protection requirement (sections 4.2 and 7.6)). When future measures are considered for the next Common Agricultural Policy, specific targets for improving soil should be included.
5. The increased demand for simultaneously delivering *multiple services* (to farmers and society) increases the need for expert advice. A strengthening of independent advisory and extension services is needed (sections 7.4 and 7.6).
6. A barrier to achieving sustainable use of soils is the *lack of awareness* of the extent and seriousness of land degradation, because food at the point of production and consumption is often very distant from the ecosystems that produced the source crop. The EU, national agencies and local authorities could provide a more supportive policy environment for a soil awareness and education strategy. Encouraging people to relate to food production and producers in their local soils could use labelling schemes, which show that farmers have managed their soil in a sustainable way (sections 7.6 and 7.7).
7. On *food quality*, high-yielding crops contain lower concentrations of *micronutrients*, and reduced

levels of *secondary metabolites*, which affects their contribution to a healthy diet. The roles of soil and crop breeding need to be better understood to prevent further micronutrient loss in higher-yielding crops (section 5).

8. The growing use *of human and animal antibiotics* and other medicines raises concerns about their effects on soil biodiversity and the development of new forms of antibiotic resistance in soil. Protecting soil biodiversity helps provide control of not only human, but also animal and plant pathogens. At the same time, soil microbes naturally produce numerous antibiotics that may offer a source of new antibiotics or other metabolites useful for humanity (section 5).
9. Soils play a key role in *climate regulation* and contain two to three times as much carbon as the atmosphere. Their importance is recognised in the '4 per mille' initiative, which offers many beneficial side effects (for soil biodiversity, soil structure, water holding capacity, increased nutrient cycling while preventing nutrient loss, and biological control) and should be supported. However, initial estimates of the potential to substantially offset the increase of atmospheric carbon dioxide are too optimistic. Increasing soil carbon depends on local soil characteristics, nutrient availability and land management, so location-specific advice is necessary (sections 6.3 and 7.4).
10. In the priority to increasing soil organic carbon, it is important not to overlook the potential for large losses of soil carbon through continued *unsustainable use of peat soils* or degrading wetlands. Protection and restoration of peatlands is critical to maintaining and increasing soil organic carbon in the EU. Options include encouraging European eco-label standards, rationalising grant schemes to incorporate the carbon stock value of peat, expanding funding options for peatland rewetting and paludiculture development, and providing incentives and rewards through land use, land-use change, and forestry accounting rules (sections 6.3 and 7.4).
11. *Climate change* has both direct and indirect consequences for soils, as it changes soil biodiversity and biogeochemical cycles, and causes shifts in natural range limits of plant and animal species to higher latitudes and altitudes. These drive changes in agricultural practices, local vegetation composition, conditions for local wildlife and may enhance the spread of invasive exotic plant species. All these changes have the potential to change local biodiversity, carbon stocks and nutrient cycles of soils, especially when agricultural and forestry practices are changing, ecosystems are colonised by species with novel traits or when diverse ecological communities become dominated by single species (section 6.1).
12. Loss of agricultural land through *soil sealing* increases the demand for agricultural imports which drives deforestation in countries exporting to the EU. Strategies for reducing demands on soil sealing (and other forms of land taking for mining, etc.) need to be applied; for instance, by integrating the full value of land taken (including the value of its ecosystem services) into the planning process for urban development and infrastructure, and by minimising demand for new surface mining by recycling minerals and construction materials. The EU analyses of community action required to reduce global deforestation should recognise soil sealing within the EU as a potential driver (section 7.3).
13. Many *business supply chains* depend on soils and their ecosystem services, so the current global trend of soil degradation across 12 million hectares each year threatens the capability to meet the growing global needs for food and resources as populations grow and diets change. This, combined with public interest in healthy food, protection from disease and cultural interest in parks, natural habitats and wildlife, broadens the stakeholders with an interest in soil and its sustainability (section 7.5).
14. Looking at the role of *international initiatives*, many processes of soil degradation are associated with food, forestry, textile, construction material and biofuel production, so pressures on soil are exacerbated by the demands of a rising global population. It is important that EU countries contribute to the range of international initiatives currently underway and incorporate the role of soils in achieving the Sustainable Development Goals (section 7.1).

1 Introduction

The fundamental importance of soils in supporting agriculture and forestry is widely recognised, with many examples of the drastic consequences of its loss[1]. However, in addition to the basic functions of supplying essential nutrients, water, oxygen and support for plants, we now better understand the many other essential services provided by soils in terrestrial ecosystems. Soils are a critical part of the hydrological cycle and can moderate flood risk and contribute to water purification. Moreover, soils contain massive quantities of carbon which, if released into the atmosphere, substantially accelerate the pace of global warming and the associated climate change. Fully functional soils support a biodiverse ecosystem which is essential for the stability of ecosystem functions and to suppress soil-borne diseases, while also providing a potential source of genetic resources. Moreover, although soils are the result of natural processes, these processes are exceedingly slow and from the perspective of human life times, soils need to be regarded as a non-renewable resource.

Such considerations led the European Commission (EC) to include soil in the Sixth Environment Action Programme in 2002 and introduce a Soil Thematic Strategy (EC, 2006). As part of the support for this strategy, the European Union's (EU's) Joint Research Centre (JRC) conducted a comprehensive review of the state of soils in Europe (JRC, 2012) which identified numerous threats to soil sustainability and the challenges to achieving sustainable soil uses in the future. Since then, attention to soils has been increasing further at the global level; for example, the Global Soil Partnership was established in 2012, leading to the 2015 UN International Year of Soils.

Concerns over the sustainability of soils in the above analyses included the continued losses through 'soil sealing' (covering living soil by housing, infrastructure, construction, etc.), compaction and reductions in soil quality and soil organic carbon (SOC) content through intensive agriculture and forestry, erosion by both water and wind, salinisation, and contamination by toxic materials. Estimates of the costs of some of these threats were up to €38 billion annually for 25 EU countries (EC, 2012a) but this figure did not include costs from biodiversity decline, sealing or compaction. More comprehensive estimates in England and Wales put costs at approximately £1.2 billion per year from erosion, compaction, decline in organic matter content, loss of soil biota, diffuse contamination and surface sealing (Defra, 2011).[2]

As pointed out by the European Commission (EC, 2012a), '*Soil degradation has a direct impact on water and air quality, biodiversity and climate change. It can also impair the health of European citizens and threaten food and feed safety*'. More recently, the role of soil in storing or releasing carbon (and therefore a direct link with climate change) has been recognised with the launch of the '4 per mille' initiative (to which 17 EU countries have committed) to increase carbon levels in soil by 0.4% per year as part of climate change mitigation strategies. In addition, more knowledge has been gathered on the interaction between soils and diseases (plant, animal and human), adding another dimension to the debate on protecting soils' useful functions.

In view of this increasing emphasis on the multi-functionality of soils, EASAC's council decided to examine the implications of recent scientific research for integrated policy solutions towards ensuring the sustainability of Europe's soils. This project has been guided by an expert group comprising leading scientists of many different disciplines from 20 of EASAC's academies, led by the Royal Netherlands Academy of Arts and Sciences (Koninklijke Nederlandse Akademie van Wetenschappen, KNAW). Expert group members and their fields of study are shown in Annex 1. EASAC thanks the expert group for their invaluable contribution in identifying the key scientific issues and their potential implications for policy, and thanks the other experts nominated by EASAC academies who contributed during the peer review process.

This report is intended to contribute to discussions and decisions on policy in the European Commission, European Council, European Parliament, as well as national governments, international non-governmental organisations and other stakeholders. After describing the current status and challenges of soils in Europe, the report identifies areas where science interacts with policy within the main themes of biodiversity and soil ecosystem services, the role of soils in above-ground biodiversity conservation, the interactions with agriculture and food quality, soils' links with human, animal and plant health, and interactions with climate change. We conclude with a detailed discussion of a range of policy issues that emerge from the initial scientific analysis[3].

[1] The massive soil erosion during the 1930s US dustbowl led Franklin D Roosevelt to comment that 'the nation that destroys its soil destroys itself'.
[2] England and Wales comprise less than 3% of the area of the EU.
[3] Some soil-related issues not covered in this report have been analysed elsewhere (for example, for more information on land contamination and remediation, and on salinisation, see JRC (2015), and for soils and forestry, see EASAC (2017a)).

2 The role and importance of soils from recent science

As recognised in the EU and in the global initiatives already mentioned, soils are fundamental to human well-being (Box 1). Soils supply the complete range of ecosystem services shown in Table 2.1, and should be seen as part of natural capital, its processes and related functions (see, for example, Dominati *et al*., 2010; Kabindra and Hartemink, 2016). The ecosystem services contribute to human well-being by supplying essential nutrients and water, provide anchoring support for plants and food supply, playing a critical role in the global carbon balance and the hydrological cycle, and providing genetic resources as well as cultural and historical services. The biodiversity in soils, ranging from microorganisms to soil macrofauna (e.g. bacteria, archaea, fungi, protists, nematodes, microarthropods and earthworms), underlies many of these ecosystem services, can suppress soil-borne diseases of plants, animals and humans, as well as providing genetic resources for antibiotics and other microbial products. The many functions and ecosystem services provided by soil and the organisms living within it are interrelated and addressing the sustainability of soils requires full recognition of this multi-functionality.

Soils and the organisms living within them play a critical role in the entire landscape; their roles in agriculture are illustrated in Figure 2.1. The multi-functionality of soils and their associated ecosystem services will vary with the ways in which they are managed, ranging from their natural state, through intensive agriculture, to degraded and abandoned. As illustrated in Figure 2.2, when soil is in its natural state, a full range of ecosystem

Box 1 Soil functions and ecosystem services

Soils perform a large variety of functions and services, many of which are directly or indirectly related to the soil biota and its biodiversity (Bardgett and van der Putten, 2014). These are most widely referred to as 'ecosystem services', although the term 'nature's contributions to people' is also used (see, for example, IPBES, 2018a). For example, the decomposition of organic matter involves microbes and small invertebrates, which turn plant litter and organic material from roots back into nutrients that can be taken up for plant growth. During this process, part of the carbon stays in the soil as part of plant roots, soil organisms or material not yet decomposed, reducing levels of atmospheric carbon dioxide. The functioning of soil also depends on soil structure, which facilitates soil aeration and the flux of water and gases through the soil and the colonisation of soil by growing plant roots. Well-aerated soils may enhance the removal of certain greenhouse gases (GHGs) (Ball, 2013). Nutrients are retained and/or recycled, which reduces their leaching to surface or ground waters, reducing the dangers of eutrophication, and water treatment costs.

Soils provide plants with micronutrients and trace elements that are essential in small amounts to provide humans with healthy food (see, for example, Singh *et al*., 2017). Soil functions may also affect how soils control parasites and diseases of humans, animals and plants (Wall *et al*., 2016) since soil biota play an important role in controlling soil-borne plant diseases through complex ecological processes (Raaijmakers and Mazzola, 2016). Soils may also provide a 'disservice' by harbouring human pathogens, such as Q-fever, tetanus and anthrax, which have caused casualties in Europe (Jeffery and van der Putten, 2011). Not only may animals act as vectors for soil-borne diseases, but there are also specific animal (as well as plant and human) pathogens that can survive passage through the soil ecosystem (Wall *et al*., 2016).

These ecosystem services may be compromised in degraded soils; for instance, loss of water-holding capacity in degraded soils increases risks during extreme weather events anticipated in a warmer climate (Allan and Soden, 2008; EASAC, 2013, 2018), whether because of increased susceptibility to extreme droughts or run-off during heavy rain events leading to flooding. Maintaining and restoring soils for producing these ecosystem services[4] will also achieve an uptake of more carbon to the soils (Morriën *et al*., 2017). Both climate adaptation and mitigation can be assisted by soil conservation which also helps improve soil fertility, thereby reducing the costs for nutrient inputs in agricultural lands.

Soils also contain relicts from previous climate conditions and from previous civilisations which can help us understand how ecosystems survived under natural climate variations, and how former societies were organised and interacted with either self-induced or natural global environmental changes. A perhaps less well-known role of soil is that soil characteristics are increasing being used by forensic scientists to help catch and convict criminals (Wald, 2015).

Protecting soils should recognise the effects of different practices. For example, land use intensification can reduce soil biodiversity by physical disturbance, which also hampers soil structure, and disintegrates soil organic matter (SOM). This in turn can lead to physical soil degradation and to an increase in soil erosion rates. Growing crop and tree monocultures and the use of heavy machinery can cause soil compaction, while soil pollution by chemical pesticides and high levels of nutrients further stress the soil. Such threats together will result in a reduction of water-holding capacity and aeration of the soil, which increases emissions, the need of larger machinery for cultivating the soil, which further exacerbates soil compaction and erosion. There is a strong feedback between many of these threats to fully functional soils and a holistic collaborative approach to soil management is thus crucial.

[4] Along with ecosystem services, other terms also often used include 'soil quality', which is defined as 'an account of the soil's ability to provide ecosystem and social services through its capacities to perform its functions under changing conditions' (Tóth *et al*., 2007). The term 'soil functions' refers to the capabilities of soils that are important for various agricultural, environmental, nature protection, landscape and urban uses; these are analogous to ecosystem services.

Table 2.1 Ecosystem services from soils (adapted from ITPS, 2015).

Ecosystem service	Soil functions
Supporting services	
Soil formation	Weathering of primary minerals and release of nutrients Transformation and accumulation of organic matter Creation of structures for gas and water flow and root growth Creation of charged surfaces for ion retention and exchange
Primary production	Medium for seed germination and root growth Supply of nutrients and water for plants
Nutrient cycling	Transformation of organic materials by soil organisms Retention and release of nutrients on charged surfaces
Regulating services	
Water quality regulation	Filtering and buffering of substances in soil water Transformation of soil contaminants
Water supply regulation	Regulation of water infiltration and flow within the soil Drainage of excess water from the soil and into ground and surface water
Climate regulation	Regulation of GHG emissions
Erosion regulation	Retention of soil on the land surface
Disease regulation	Control of plant, animal, and human diseases
Provisioning services	
Food supply	Providing water, nutrients, and physical support for growth of plants for human and animal consumption
Water supply	Retention and purification of water
Fibre and fuel supply	Providing water, nutrients, and physical support for plant growth for bioenergy and fibre
Raw earth material supply	Provision of topsoil, aggregates, peat, etc.
Surface stability	Supporting human habitations and related infrastructure
Refuges	Providing habitat for soil animals, birds, etc.
Genetic resources	Source of unique biological materials
Cultural services	
Aesthetic and spiritual	Preservation of natural and cultural landscape diversity Source of pigments and dyes Place for burial (ashes to ashes, dust to dust)
Heritage	Preservation of archaeological record

services is provided. When intensively used for primary (crop) production only, the ecosystem provides primarily biomass yield at the expense of climate regulation, biodiversity conservation, water retention and fibre production, whereas land abandoned as a result of degradation has lost its capacity to provide services.

Given the importance of soils to fundamental human needs and well-being, there is an extensive history of international discussion and policy on soils, as summarised in Box 2.

In addition to the overview of the threats and risks to soils provided by the Intergovernmental Technical Panel on Soils (ITPS) globally (Box 2) in 2015, key threats in Europe (EC, 2012a; JRC, 2015) are shown in Figure 2.4 and summarised in Box 3.

Recent science also offers a range of novel technologies and approaches that contribute to our understanding of the complex interactions between soils' physical, chemical and biological properties and the multiple ecosystem services provided. Examples are described in Box 4.

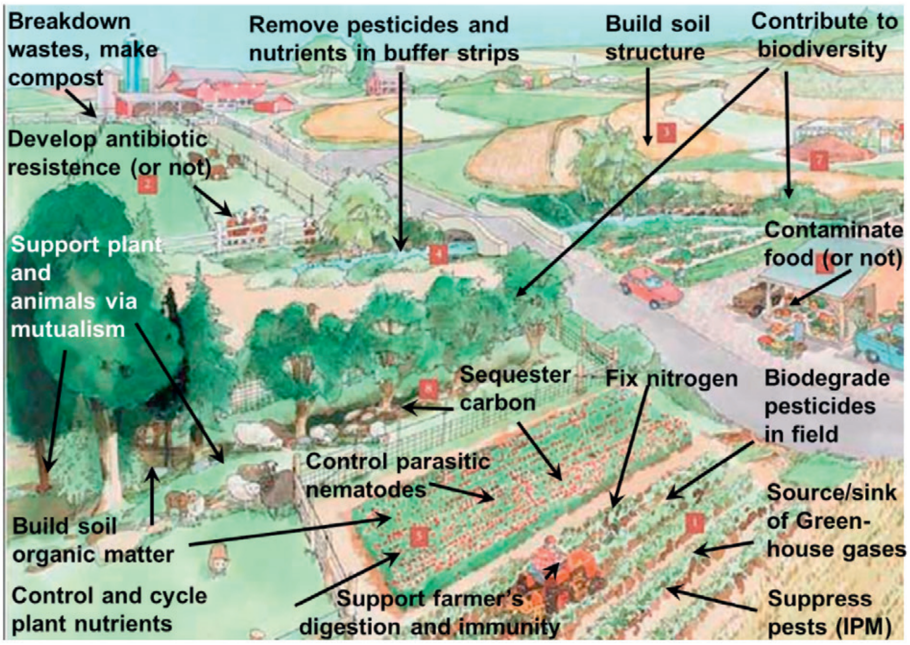

Figure 2.1 Soil organisms contribute to a wide variety of soil ecosystem services (Kate Scow, University of California, Davis).

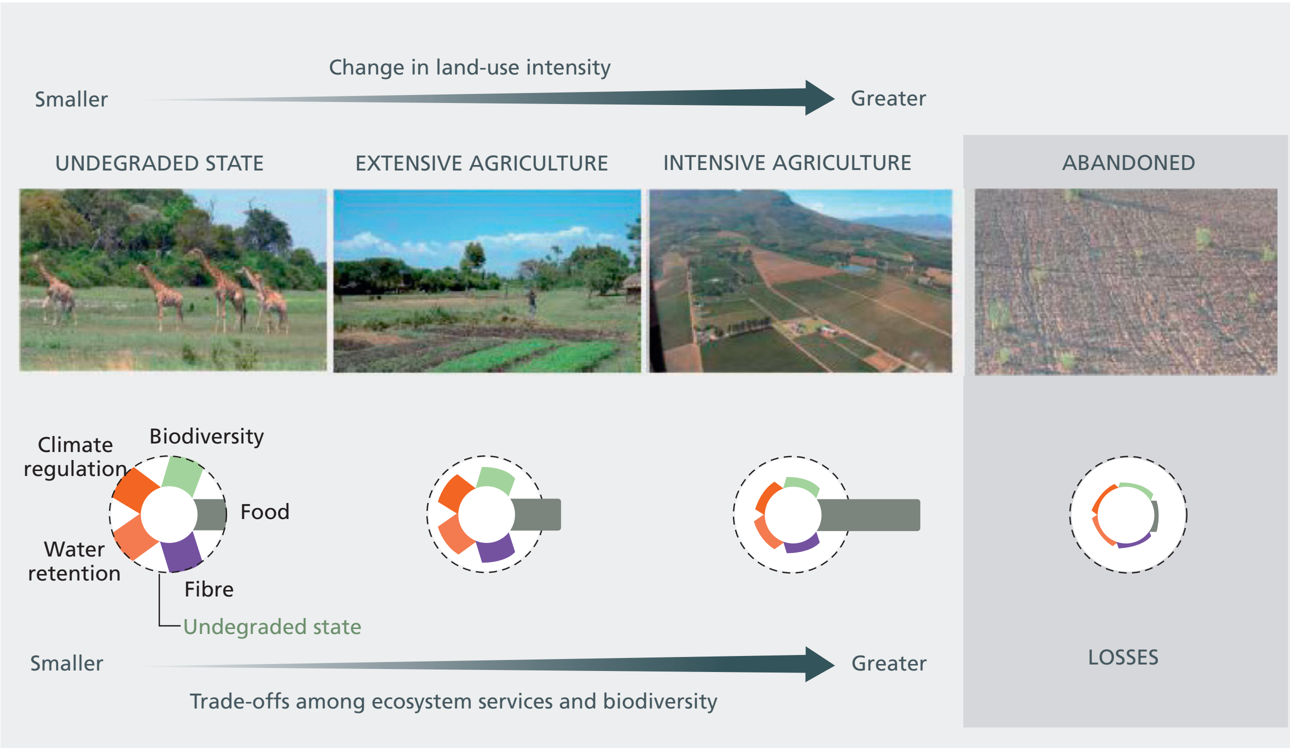

Figure 2.2 Change in the supply of ecosystem services (nature's contributions to people) as land use intensity increases (from IPBES, 2018a; see also Foley et al., 2005).

Box 2 International policy framework

In the past 6 years, international developments have included the following.

- A Global Soil Partnership was established in 2012 as a voluntary partnership including all governments, non-governmental organisations and other stakeholders aiming towards achieving sustainable soil management at global and national scale.
- A high-level scientific advisory panel, the ITPS was formed in 2013 (Montanarella, 2015).
- 2015 was declared the International Year of Soils by the United Nations (UN), which has stimulated interest in soils and their sustainable management.
- The 'Status of World's Soil Resources' report (ITPS, 2015) emphasised that urgent action is needed to reverse negative trends.
- Soils play an important role in achieving half of the UN Sustainable Development Goals (SDGs); specifically SDGs 2, 3, 6, 7 and 12–15, which relate to food security, human health, land management including land restoration, water security and climate change and biodiversity preservation (Figure 2.3 and discussed further in sections 3–6).

Non-legally-binding agreements and guidelines promote the development of national legislation for the protection of soils, such as the FAO's Global Soil Partnership, the revised World Soil Charter of the FAO (FAO, 2015) and the related 'Voluntary Guidelines for Sustainable Soil Management' (FAO, 2017a). The last of these provide guidance on minimising soil erosion, enhancing SOM content, fostering soil nutrient balance and cycles, preventing, minimising and mitigating soil salinisation and alkalinisation, preventing and minimising soil contamination and acidification, preserving and enhancing soil biodiversity, minimising soil sealing, preventing and mitigating soil compaction, and improving soil water management. These and other agreements and guidelines provide a useful framework for national governments to act towards sustainable soil management. A recently established European Soil Partnership, a regional soil partnership within the Global Soil Partnership, invites governments to join a 'coalition of the willing' towards European soil protection.

A comprehensive review of the state of the world's soils (ITPS, 2015) observed that most of the world's soil resources are in only fair, poor or very poor condition with 33% of land '*moderately to highly degraded*' because of erosion, salinisation, compaction, acidification and chemical pollution. Further loss of productive soils should be avoided by applying sustainable soil management, using scientific and local knowledge and evidence-based, proven approaches and technologies. Four initial priorities of the ITPS are as follows:

- sustainably managing soils to increase supply of healthy food for the most food insecure (preventing further degradation and restoring productivity of soils already degraded);
- stabilising or increasing SOC, with all countries aiming to achieve a stable or positive net SOC balance;
- stabilising or reducing global nitrogen or phosphorus fertiliser use while simultaneously increasing fertiliser use in regions of nutrient deficiency;
- because of lack of or out-of-date data, observation systems are needed to improve knowledge about the current state and trends in the condition of soil.

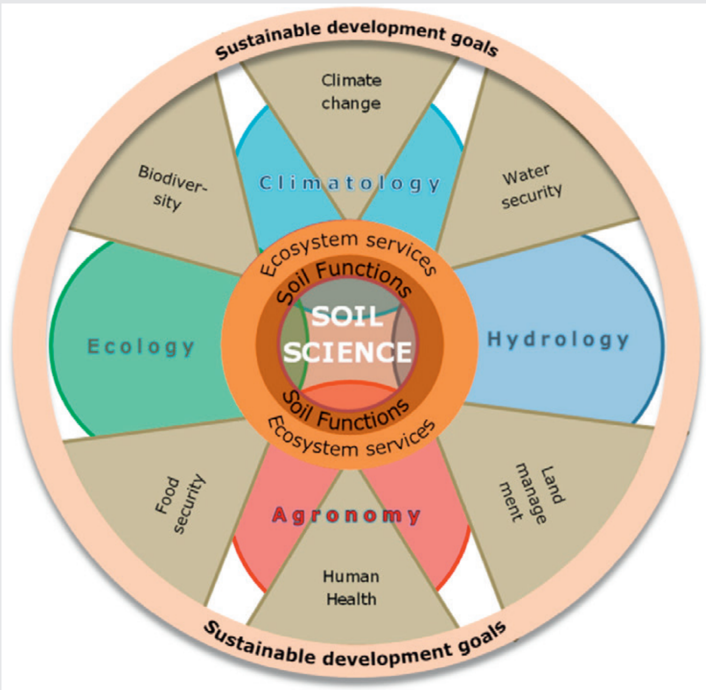

Figure 2.3 Significance of soils and scientific fields towards the realisation of the UN SDGs (a simplification of Keesstra et al., 2016). The grey triangles indicate the SDGs that are critically influenced by soils; the coloured circles are the various fields of soil science contributing to the SDGs.

The most recent scientific assessment of the global status of soils can be found in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) land degradation and restoration assessment (IPBES, 2018a). This contains the key messages stating that

- currently, degradation of the Earth's land surface through human activities is negatively impacting the well-being of at least 3.2 billion people, pushing the planet towards a sixth mass species extinction and costing more than 10% of the annual global gross product in losses of biodiversity and ecosystem services. It is also a major contributor to mass human migration and increased conflicts;
- investing in avoiding land degradation and the restoration of degraded land makes sound economic sense; the benefits generally far exceed the costs;
- timely action to avoid, reduce and reverse land degradation can increase food and water security, can contribute substantially to the adaptation to and mitigation of climate change and could contribute to the avoidance of conflict and migration;
- avoiding, reducing and reversing land degradation is essential for meeting the SDGs and would deliver co-benefits for nearly all of them.

Within the EU, the 'Thematic Strategy for Soil Protection' adopted by the EC in 2006 was followed by the JRC review already mentioned and a policy report on the implementation of the Strategy and ongoing activities in 2012 (EC, 2012a). Despite the withdrawal in 2014 of proposals for a Soils Directive, the EC '*remains committed to the objective of the protection of soil and will examine options on how to best achieve this*'. The Seventh Environment Action Programme, which entered into force on 17 January 2014, recognised that soil degradation is a serious threat to food, water and climate security and aims that land will be managed sustainably in the Union by 2020 so that soil will be adequately protected, that the remediation of contaminated sites will be well underway, and that the EU and its Member States will give increasing efforts to reduce soil erosion and increase SOM.

Within the UN Framework Convention on Climate Change (UNFCCC), the '4 per mille' initiative aims at increasing soil carbon levels by 0.4% per year, aiming to sequestrate 2–3 gigatonnes[5] of carbon per year (Lal, 2016; Minasny *et al*., 2017). Cross-border issues also relate to the spread of infectious diseases through increased global mobility, which includes the transport of soils (Balcan *et al*., 2009). The role of soils in supporting above-ground biodiversity also makes soil protection relevant to other EU-directives, such as the Habitat Directive and Natura 2000, and to the EU's commitments to the Convention on Biological Diversity.

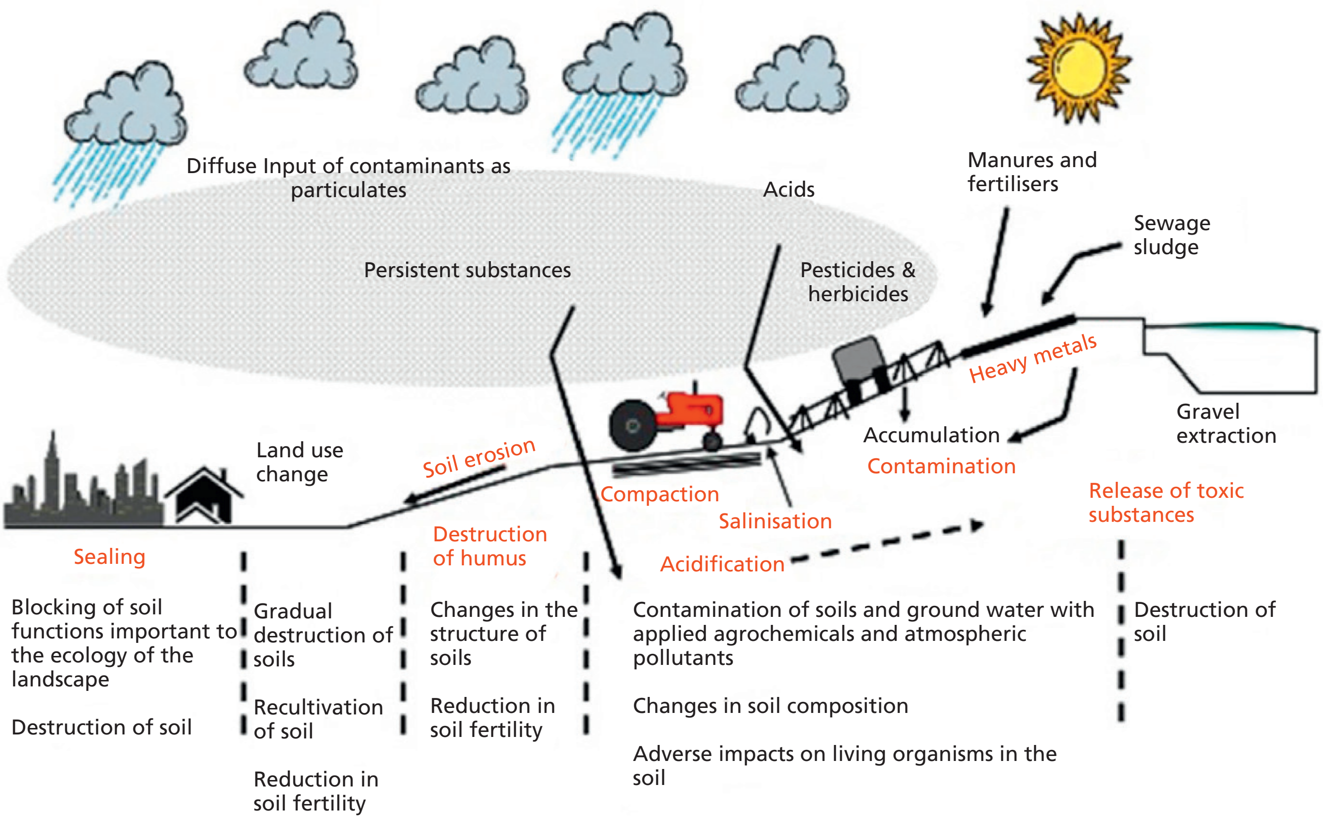

Figure 2.4 Threats affecting European soils (Montanarella, 2010).

[5] 1 gigatonne = 1,000,000,000 tonnes.

Box 3 Threats to European soils

Loss of SOM and SOC. Recent trends in land use and climate change have resulted in SOC loss globally at a rate equivalent to 10–20% of total global fossil fuel emissions (Olivier *et al*., 2015). Almost half of European agricultural soils have low organic matter content (Rusco *et al*., 2001) and SOC contents are still decreasing in many areas. Similar trends may be seen as a result of intensive forestry with the removal of tree residues (EASAC, 2017a). Areas where arable farming is combined with manure supplies from animal farms might be less sensitive to organic matter decline (Reijneveld *et al*., 2009), but these face other risks such as nutrient leaching to ground water. Peatland ecosystems (see section 6.2) are particularly sensitive to increasing temperatures and lowering water tables that increase biodegradation and release carbon dioxide to the atmosphere. The EU27 have about 229,000 square kilometres of peat soils containing an estimated 18.7 gigatonnes of carbon (Montanarella *et al*., 2006).

Soil biodiversity decline. Intensive agriculture (and forestry) reduce soil biodiversity through several mechanisms (e.g. physical disturbance, compaction, lethal and sub-lethal impacts of pesticides and herbicides on the soil biota, and inorganic fertilisers), making soils less efficient, more sensitive to weather events such as extreme drought and rainfall, and reducing organic matter (Tsiafouli *et al*., 2015; de Vries *et al*., 2012, 2013). Restoring soil biodiversity requires a variety of management changes, and this process may take years to decades (Morriën *et al*., 2017).

Erosion and landslides. According to the European Environmental Agency (EEA), 16% of Europe's land is vulnerable to erosion by rain and wind, which threatens to remove soil needed for farming. More recently, IPBES (2018b) estimated that erosion has affected 25% of agricultural land in the EU and has increased by some 20% between 2000 and 2010 (combined with a decline in SOM, IPBES noted that this might compromise food production). A changing climate is projected to increase this risk, as heavy and extreme precipitation events over various parts of Europe are expected to increase throughout the 21st century (Rajczak *et al*., 2013). Increased rainfall intensity will accelerate the rates of soil erosion by water (Panagos *et al*., 2015). Likewise, predicted increased wind velocities (Tobin *et al*., 2015, 2016) will enhance wind erosion during those periods when soils are left bare, or between sowing and emergence of crops. Topsoil transported by runoff causes significant soil quality losses on site, but also leads to off-site consequences such as muddy floods, surface water pollution, reservoir sedimentation and damage to infrastructure and private property (Boardman and Poesen, 2006). Shifts to arable cropping and adoption of new crops (e.g. maize, or future crops replacing maize) under a warming climate may increase future rates of erosion and exacerbate the effects of climate change (Nearing *et al*., 2005; Mullan, 2013). Soil tillage, root and tuber crop harvesting, land levelling, soil quarrying and soil removal at construction sites also increase soil erosion (Poesen, 2018). Restoring soils at eroded sites, such as following landslides, may take decades to centuries (Błońska *et al*., 2016).

Soil compaction. Quantifying the soil properties to determine sub-soil compaction is laborious and thus there are limited data on soil compaction across Europe. Studies from some individual countries are available. For example, in England and Wales 10–16% of the grasslands had problems with compaction and were in poor condition (Newell-Price *et al*., 2013). In 1994, soil compaction was responsible for the degradation of some 33 million hectares in Europe (Soane and Van Ouwerkerk, 1994). The JRC (2015) has also compiled a map showing the vulnerability of European soils to compaction. Current drivers of soil compaction include the increased wheel pressure of heavier agricultural machinery. Soils are especially vulnerable to compaction when waterlogged, or otherwise in poor condition, and this can increase soil erosion, due to reduced infiltration and increased runoff from overland flow.

Soil sealing. In Europe, almost a tenth of the land surface is sealed with impermeable material, and around 500 square kilometres of land are sealed annually. The amount of sealed soils is a key environmental indicator for the magnitude of hydrological and ecological implications of urbanisation to ecosystem service provision and flood sensitivity (Arnold and Gibbons, 1996). Urban sprawl and the associated destruction of the soil loses SOC, biodiversity and most ecosystem services and is essentially irreversible. Loss of good agricultural soil in Europe increases demand for imports which may come from poorer soils elsewhere in the world (e.g. rain forest and semi-arid dryland soils) and intensify pressure for further clearance for agricultural purposes. Given the increasing pressures to provide food for an increasing global population (as well as dietary changes), the area of arable soil land per capita in the world has already decreased by half between the 1960s and the 2010s (i.e. from 0.46 hectares in the 1960s to 0.21 hectares in the 2010s; OECD–FAO, 2018), and the most productive soils have already been put to agricultural use. Demand has been driving conversion of forests and drylands to agriculture, where many soils are of poorer agricultural status, requiring high artificial inputs of fertilisers or irrigation. Protecting existing agricultural land of high productivity has become even more important (Hermele, 2012).

Contamination. Many European cities contain 'brownfield sites': soils contaminated as a result of past industrial activity and mining. Also, widespread use of pesticides has resulted in accumulation of pesticide residues in soils (Silva *et al*., 2017). Soil contamination can affect human health through the food chain (via the soil–crop–human or soil–crop–animal–human chains).

Salinisation. Salinisation severely threatens plant growth in drylands with excessive evaporation such as the Mediterranean, and coastal areas with salt water intrusion such as coastal polders (Libutti and Monteleone, 2017).

Box 4 Novel science and technology applied to soils

There is substantial research activity leading to novel developments, insights and technologies that may enhance sustainable use of soils. Here, an overview of key findings is presented, while acknowledging that this is not exhaustive. The challenge will be to put such novel technologies and insights into actions (Montanarella, 2010).

New science and technology offer farmers more accurate and precise means of optimising crop management according to soil types (see, for example, Bouma and Wösten, 2016). Many *in situ* sensors have been introduced that can continually characterise ground and surface water conditions; proximal and remote sensors can determine the actual state of soils, crops or natural vegetation, and air quality can be continuously monitored. Global positioning system-based land management with live measurement of soil chemical properties allows farmers to adjust fertiliser supply to the local soil fertility conditions, recognise disease and disease-free spots, and weed presence on crop fields (see, for example, Stoorvogel, Kooistra and Bouma, 2015). Soil–water–plant–atmosphere models are now widely available and well tested, and there is scope for artificial intelligence when assembling data and performance indicators for given soil types, accessible in various databases.

Agro-ecologists are learning how nature can reduce crop exposure to natural enemies by using landscape complexity, flower strips (Tschumi *et al*., 2015), and inclusion of green manures and cover crops in rotation that may promote mutualists (pollinators and mycorrhizal fungi), while reducing the spread of pests and pathogens, and controlling their outbreaks by promoting natural enemies. This offers a soil management approach, both above ground and below ground, based on a more nature-inclusive, ecological intensive agriculture (Bommarco *et al*., 2013).

Soil (microbial) ecology is increasingly able to determine the composition and potential functioning of the soil biodiversity, while soil food web and network modelling predicts the resilience and stability of soils in their response to extreme weather events and other natural and anthropogenic disturbances. This may be applied in plant breeding to produce varieties that make more effective use of the soil microbiome for plant nutrition and plant protection, as well as plant and microbial traits that promote other ecosystem services, such as carbon storage and reduced dependency on fertiliser inputs. Soil inoculations can be used to introduce plant growth-promoting microbes in crop production systems, or promote natural restoration after taking land out of cultivation. Soil ecological knowledge also has increased understanding of the role of soil biodiversity in promoting diversity in vegetation, and in the natural control of above-ground pests and pathogens, as well as invasive exotic plant species.

Research is also focusing on the interaction between *soil attributes, healthy plants, healthy food, and healthy humans* as envisaged in the SDGs. This is addressing interactions between plants, below-ground and above-ground mutualistic interaction, pest and pathogenic organisms, residues of crop projection chemicals, and shortage of micronutrients in feed and food. Work is also underway on *linking socio-economical and human behavioural research* to better understand the ways in which best practices to control erosion, soil contamination, compaction, eutrophication, consequences of soil sealing, etc. can be applied. Multi-sectoral and multi-actor research approaches help to find out how awareness raising, economic constraints, ownership, the long feedback time between action and reaction, perception, land ownership, or other sociological and psychological factors may encourage or impede effective solutions to soil threats. A key question here is how private owners and land managers can be made aware of the long-term values of soils' natural capital in delivering public goods such as clean water, air, retention of GHGs and, above all, sustainable provisioning of food, feed and fibre/materials.

Effective and efficient monitoring tools are also required in studying changes in soil biodiversity and functions, and to provide a set of simple indicators which can be adopted in the same way as commercially provided soil fertility analyses. Insights into the relationships between soil (abiotic and biotic) properties and soil functioning may assist in such monitoring tools' development. Effective monitoring also requires digital soil mapping tools to provide cost-effective means of determining soil geographical distributions, potentially at fine (30 metre by 30 metre) grid scale.

3 Soil biodiversity and above-ground biodiversity

Soils are characterised by their physical, chemical and biological characteristics, which all influence each other. The diversity of soil physical and chemical properties underlies the wealth of soil types across Europe (Jones *et al*., 2005). Soil biological diversity ranges from microorganisms to macrofauna and underlies many of the key ecosystem services shown in Table 2.1. Soil biological diversity includes many thousands of 'species' of microbes and small invertebrates in one handful of soil, and underpins the provisioning of nutrients to plants, the control and release of GHGs, and the control of plant, animal and human diseases (Bardgett and van der Putten, 2014). This enormous biodiversity supports various types of interactions, for example mutualistic symbionts (such as mycorrhizal fungi that cooperate with plants), pathogens and parasites of plants, animals and humans, decomposers that convert plant litter and soil organic matter into mineral nutrients, and ecosystem engineers, such as earthworms that provide structure to the soil. Soil biodiversity varies from microscopically small viruses, bacteria, fungi and protists, through small animals such as nematodes, micro-arthropods and insects, to larger animals such as earthworms, moles, and other vertebrates that spend part of their life in soil. Also plants are an important component of the soil, as their roots are used for anchoring and the uptake of water and nutrients (Bardgett and van der Putten, 2014; Wall *et al*., 2016).

Among the soil organisms there are numerous potentially useful microbes. For example, symbiotic mycorrhizal fungi provide mineral phosphorus and nitrogen, and nitrogen-fixing bacteria can convert nitrogen in the atmosphere to mineral nitrogen available to plants, reducing the need for mineral fertilisers with their associated high energy costs and use of non-renewable resources. Similarly, soil contains many microbes that produce anti-microbial compounds, such as the antibiotics penicillin and streptomycin, providing protection against plant root pathogens as well as being a potential future source of new antibiotics. Soil microbes have also been used in industrial production processes because of the enzymes that they produce.

The below-ground biodiversity is involved in many processes (illustrated in Figure 3.1) that influence the biomass above ground (de Deyn and van der Putten, 2005). Indeed, the diversity of soil types and their biological diversity underlie the enormous variety of European ecosystems and landscapes that underpins natural and cultural diversity. Soils influence above-ground biodiversity through the following:

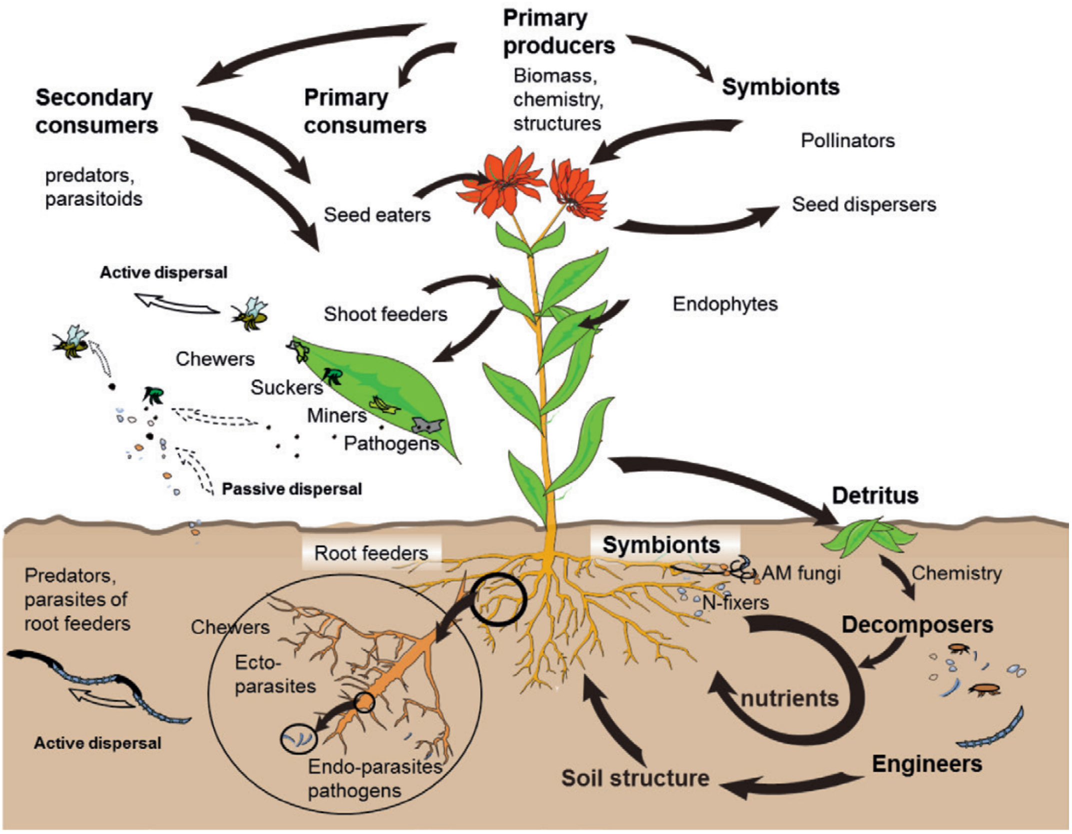

Figure 3.1 Processes linking above- and below-ground diversity (de Deyn and van der Putten, 2005).

- containing seed banks of plant species, some of which have become threatened and are required to restore ecosystems;
- regulating plant community composition by providing soil physico-chemical conditions, and by interactions between plant roots and soil biota;
- controlling plant abundance and invasiveness by positive feedbacks from the abiotic and biotic soil components;
- regulating above-ground pests, plagues and pathogens directly, or indirectly through influencing plant nutrition levels and defensive properties (Bardgett and Wardle, 2010; Wall *et al*., 2012; Moore *et al*., 2017).

Biodiversity above ground is managed under national and EU laws and regulations. The EU has Directives aimed at protecting biodiversity (e.g. Biodiversity, Habitat, Natura and Birds Directives) as well as being committed to implementing measures agreed under the Convention on Biological Diversity. Protecting the (above-ground) biodiversity covered in national and international laws and agreements also requires that the soils within the protected habitats be protected. However, the strong links between above ground and below ground have not yet been included in the EU's Natura 2000 and the Habitats Directive, although the need for better understanding is recognised in the EU biodiversity strategy[6].

To feed the world at the present standard of living (and increasing such for poorer countries), agriculture depends on high production levels that, in turn, depend on high input levels which may not fully exploit and in some cases bypass the natural capacity of soils to support plant growth and plant health. For example, in a cross-EU study, an experiment involving 114 arable wheat fields across Europe showed that adding mineral fertiliser and pesticides had strong effects on yield, but that in fields with higher levels of SOM, the fertilisers had less effect on yields (Gagic *et al*., 2017). Increased SOC can thus lower the fertiliser needs for farmers in current arable systems (Brady *et al*, 2015). This study and others (Bommarco *et al*., 2013; Lechenet *et al*., 2017) point to using the natural capacity of soils to allow a more sustainable and less chemical input-dependent type of land management than is currently the case.

Recent EU-funded studies have identified biological indicators of soil habitat and function (such as EcoFinders (Griffiths and Lemanceau, 2016), ecological–economic modelling in the EU Soil Service (Brady *et al*., 2017b), SoilTrEC (Banwart *et al*., 2017), Landmark and others) and have provided information on soils as habitats and the roles of soil in preserving landscapes and cultural heritage, pointing out that soils also provide archives of human civilisations.

The LUCAS (Land Use/Cover Area frame statistical Survey) initiative resulting from a decision of the European Parliament aims at repeated observations taken at more than 250,000 sample points throughout the EU. This survey will identify changes in land use and provide sampling points for collecting soil samples for further analyses according to standardised measures (Orgiazzi *et al*., 2018).

Also, the Global Soil Partnership and the Global Soil Biodiversity Initiative both provide potential to further disseminate expert-based knowledge, while a Global Soil Biodiversity Assessment is also being planned within the UN and FAO. This increased knowledge and awareness provides an opportunity for refining EU guidelines and directives to take the relationship between below- and above-ground biodiversity into account, as well as applying it in national and local initiatives.

[6] The Commission includes the role of soil biodiversity in delivering key ecosystem services, such as carbon sequestration and food supply, in its research plans related to its biodiversity strategy (EC, 2011).

4 Soils and modern farming

Modern agriculture has made huge strides in productivity to deliver the high yields required to produce food (and other biological resources) to the growing global population. However, the substantial proportion of GHG emissions originating from agriculture, nutrient leaching to ground and surface waters, and biodiversity loss point to the need to find better ways of balancing the maintenance of high yields with sustainability and biodiversity (Vitousek *et al*., 2009). Soils are a critical part of this challenge and are discussed in this chapter.

The interactions between different farming practices and soil have been well documented in previous studies (see, for example, JRC, 2012). Major trends include the fact that intensive farming often leads to the depletion of soil nutrients and SOM, and that the concentration of livestock production in soil-less conditions, such as stockyards (concentrated animal-feeding operations) using feed produced in other areas, produces high volumes of wastes overloaded with nutrients (Herrero *et al*., 2009). Tensions exist between EU regulations that aim to prevent the pollution of ground and surface waters by nitrogen and other nutrients, and the perceived need of farmers to apply the amounts of nutrients considered necessary for product quality and yield. Precision farming, which involves the targeted application of nutrients and pest control measures to relatively small areas (for instance, 30 metre by 30 metre grids) on the basis of location-specific monitoring, offers a means of delivering yield while reducing nutrient losses (Viscarra Rossel and Bouma, 2016).

Production levels of major crops such as wheat and sugar beet have still been increasing in the EU, although there is concern that a ceiling may have been reached: for example, for wheat in France and the Netherlands (Grassini *et al*., 2013). Yields of major crops in major producing countries in the world show a range of trends (Figure 4.1). Globally, there is a concern that the productivity of the land resources of the Earth is declining (Cherlet *et al*., 2018).

4.1 Current challenges to soils in farming

Soil chemical composition

Loss of SOC is a key factor in soil degradation and receives attention because of its role in mitigating climate change (section 6). SOC is influenced by current and past management practices and requires detailed understanding of the occurrence of different soil types (see, for example, Bouma and Wösten, 2016; Pulleman *et al*., 2000). Returning carbon to the soil using treated sewage or other wastes should ensure this does not lead to soil contamination from heavy metals or pharmaceuticals, or raise food safety issues. Although some organic compounds may be biodegraded by the soil biota, amounts should not exceed its assimilative capacity. At the same time, some necessary trace elements (e.g. zinc) and other micronutrients are at insufficient levels in many soils and crops (Black, 2003), and are not well covered by standard soil chemical analyses and fertilisation advice (Marschner, 1995).

Humic and fulvic acids in SOM have a positive influence on soil fertility and the physical integrity of soil, and they increase the availability of nutrients. In addition to manure or compost, the SOM can be increased by applying an oxidised form of lignite (leonardite) (Cavani *et al*., 2003; Ozdoba *et al*., 2001). Europe accounts for roughly 40% of global lignite reserves (the top European producers include Germany, Greece, Poland and the Czech Republic).

Soil physical degradation

Soil compaction results from use of heavy machinery, intensive cropping, short crop rotations and intensive

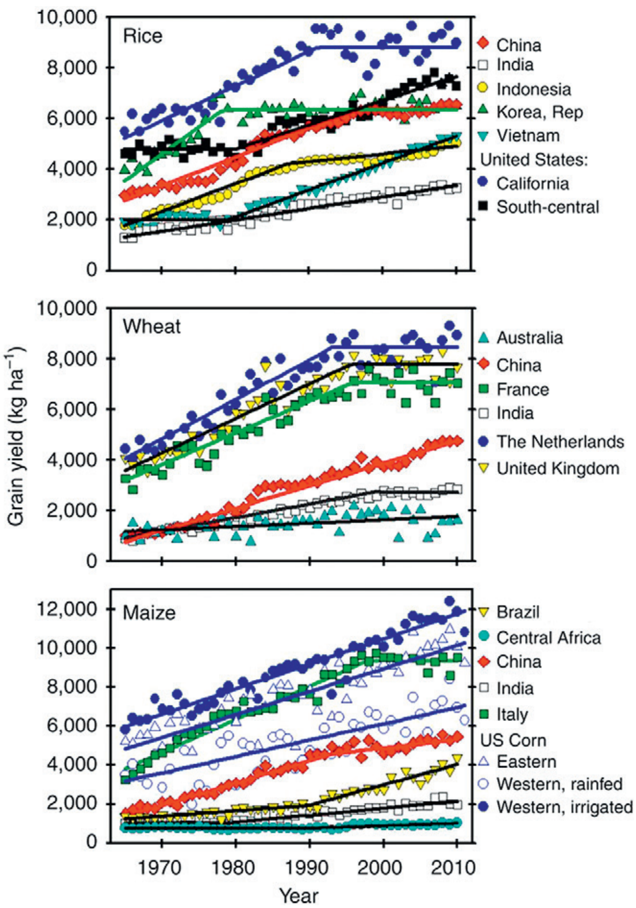

Figure 4.1 Yields of rice, wheat and maize from the 1960s to 2012 in various regions of the world (Grassini et al., 2013).

grazing. It leads to the destruction of soil aggregates and decreases soil porosity, which is crucial for the infiltration of water and the effective growth of plant roots (Hamza and Anderson, 2005; Batey, 2009; Gregory *et al*., 2015). Although there are limited data on soil compaction, Soane and Van Ouwerkerk (1994) estimated that it contributed to the degradation of some 33 million hectares in Europe.

Loss of SOC reduces soil particle cohesion and aggregate stability and increases the risk of soil erosion by water and wind. The physical degradation due to SOC decline combines with compaction and crusting to reduce water infiltration and increase runoff (and erosion). On sparsely vegetated land between cropping seasons or during crop establishment, topsoil may be transported by runoff resulting in losses on site, and off-site impacts such as mud floods, surface water pollution, reservoir sedimentation and damage to infrastructure and property (Boardman and Poesen, 2006). Flat lowlands that are less susceptible to water erosion may still be affected by wind erosion.

Soil biological degradation

Soil tillage, fertilisation, pesticide use and irrigation disrupt soil biota, and increasing land use intensity reduces the average size of remaining soil organisms and causes a decline in diversity (Tsiafouli *et al*., 2015). Soil tillage disrupts mycorrhizal fungal networks and kills earthworms (Briones and Schmidt, 2017), which impedes the formation and maintenance of soil structure. On the other hand, no tillage practices may require increased (chemical) weed control. Fertilisation, in general, promotes microbial life by increased root and root exudate production; however, bacteria can be promoted more than fungi and the effectiveness of the symbiotic relationships between plants and soil microbes can be reduced.

Insecticides targeted at above-ground insect pests may also have lethal or sub-lethal effects on soil organisms and persist across crop cycles (see EASAC (2015) and Giorio *et al*. (2017) for a discussion of the effects on soil organisms of neonicotinoid insecticides). Herbicides and fungicides have the potential to adversely affect soil flora and fungi, with effects poorly quantified because sub-lethal effects on soil organisms are not included in the testing required for regulatory approval. Effects will depend on the degradability of the active ingredient and may be complex: for instance, glyphosate increases some microbial activity while decreasing root mycorrhization, with negative effects on soil water infiltration (Zaller *et al*., 2014). Options to reduce such impacts may include low or no-tillage agriculture, but this may require more herbicide use to compensate for the loss of the mechanical weed control functions of tillage. Inclusion of cover crops in arable cropping systems, especially during periods when soils would otherwise be bare, can have a positive effect on soil biodiversity because soils are covered for much longer periods during the year, and organic inputs are increased through the cover crop roots and litter. Also, set-aside of soils can enhance soil biodiversity (Tóth *et al*., 2016).

Current intensive grassland management, including direct injection of manure into the soil, high stocking rates or zero grazing systems (when the herbage is cut and carried to housed livestock), poor grass species diversity and conversion of long-term pasture land into a pasture–arable crop rotation all degrade grassland soil biodiversity as well as above-ground biodiversity. Parasites from livestock may affect soil fauna, and antibiotic-resistant bacteria from cattle may also be transmitted (e.g. in soils, cattle and farms in Burgundy, *Escherichia coli* producing the enzymes symptomatic of antibiotic resistance (CTX-M lactamases) have been found (Hartmann *et al*., 2012)). The potential for antibiotics to reduce the diversity of soil microbes and open new antibiotic resistance mechanisms has yet to be assessed (Nesme *et al*., 2014).

Lastly, the effects of genetically modified crops on soil biota have been extensively studied. Most impacts did not exceed the normal fluctuations in soil biological properties that result from seasonal changes, crop choice and extreme weather events (Kowalchuk *et al*., 2013). However, genetically modified crops may have indirect side effects of concern for the soil, such as the consequent excessive use of broad-spectrum systemic herbicides like glyphosate. Moreover, locally adapted crop and plant species that withstand variations in climate, etc., and which are better in balance with the local soil conditions, may be out-competed and replaced by such internationally standardised crops.

Emerging threats

Microplastics (plastics smaller than 5 mm, including nanoplastics which are smaller than 0.1 μm) have been increasing in terrestrial ecosystems and may involve larger quantities than the marine environment which has attracted much attention recently. As with marine plastics, adverse effects can be physical, be ingested at different sizes by birds, mammals and other organisms, and may (either directly or by adsorption of other contaminants) exert toxic effects (see Anderson *et al*., 2018; Machado *et al*., 2018). Their potential impacts in terrestrial ecosystems are summarised in Figure 4.2 but remain largely unexplored.

Another trend is that water shortages in the world will increase demand for the use of more wastewater for irrigation, increasing the exposure and risks from contaminants (metals, pharmaceutical residues, etc.) with threats to both soil and water quality.

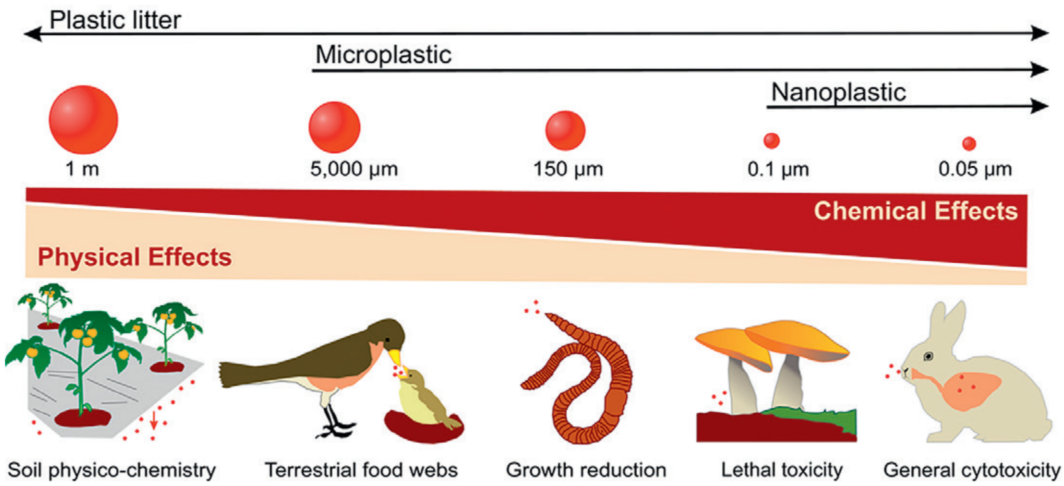

Figure 4.2 Range of potential impacts of plastics contamination of different sizes (Machado et al., 2018).

Economic and social factors

To address the issues described above, several economic and social aspects need to be considered. For instance, ownership structures have an influence on the priorities given to long-term sustainability of soils. These appear to vary within the EU, for example between east and west, but information is scattered (Van Dijk, 2007). Some trends include an increase in the size of individual farms: between 2007 and 2013 the area per farm increased by almost 30%. The average farm size is 16 hectares but there are very large differences between small and large farms (50% of the farms cover less than 2.5% of the EU agricultural area)[7]. Although some investors will seek to maintain or increase the value of their investments through protecting or increasing soil quality, pressures for short-term returns on rented land may risk losing soils' multi-functionality (van Dijk, 2007). Currently, around 44% of the agricultural land in the EU is under tenant farming[8]. Continued intensification may lead to high input of chemicals to control crops, weeds and pest organisms, resulting in losses of multiple ecosystem services and the biodiversity underpinning them (see, for example, Isbell *et al.*, 2017). Communicating and encouraging application of existing expertise remains a challenge where knowledge may be sufficient to address problems about current soil conditions but is nevertheless not applied. Relevant solutions may be sought in the social and economic literature and reflect the more recent growth of information through social media (Bouma, 2018).

4.2 Opportunities in the future Common Agricultural Policy

The Common Agricultural Policy (CAP) of the EC was initiated more than 50 years ago to increase agricultural productivity through technical progress, to ensure a fair standard of living for producers and consumers, and to stabilise the international markets for food (Smędzik-Ambroży and Majchrzak, 2017). It has been reformed regularly, and the 2013 revision (which applies from 2014 to 2020) aims to achieve a better balance between continued food security and safety in Europe while ensuring sustainable use of the land and maintaining natural resources, preventing climate change and addressing territorial challenges (EC, 2013). The revision placed the joint provision of public and private goods at the core of policy, so that farmers would be rewarded for the services they deliver to the wider public, such as landscapes, farmland biodiversity and climate stability, even though they have no quantified market value. This recognised explicitly for the first time the wider public goods provided by ecosystem services (including those provided by soils).

These reforms have been referred to as a 'greening' of agriculture because of their inclusion of sustainability and environmental aspects. Specific measures relate to crop diversification (with improving soil quality as a primary objective), maintaining permanent grassland and an obligation on larger farms to have at least 5% of the arable area on their farm as 'ecological focus areas (EFAs)'. The options for EFAs include cover crops, catch crops, buffer strips and field margins, hedgerows and trees, nitrogen-fixing crops and fallow land. There is an aim to apply 30% of direct payments to improving the use of natural resources through these mechanisms. Rural development budgets are also aligned with the CAP's environmental objectives and at least 30% are reserved for voluntary measures that are beneficial for the environment and climate change (for example, agri-environmental-climate schemes, organic farming,

[7] http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farm_structure_survey_2013_-_main_results
[8] http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farm_structure_survey_–_common_land

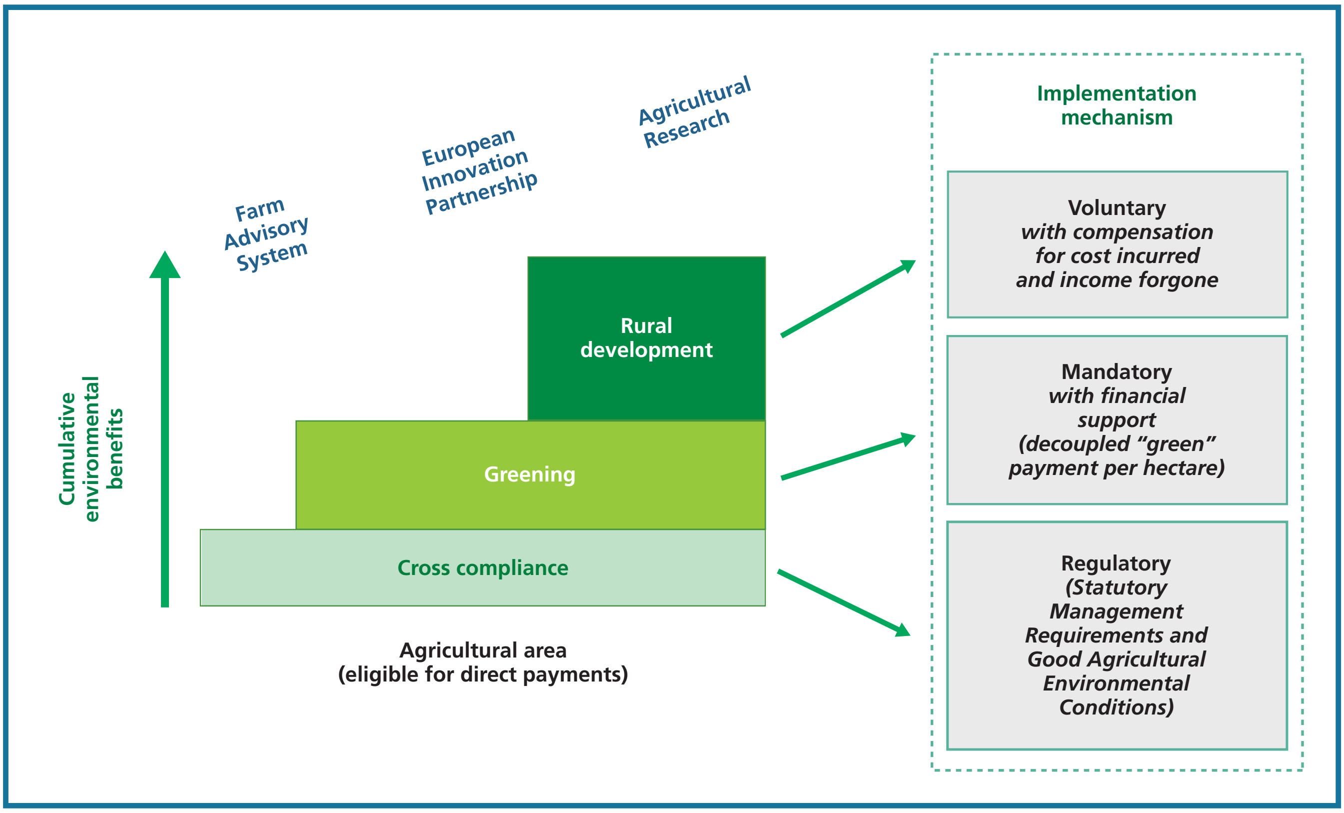

Figure 4.3 The architecture of the CAP greening measures (EC, 2013).

Natura 2000 areas, and forestry measures). The architecture of the new policy is shown in Figure 4.3.

In addition, the 'cross-compliance' conditions require farmers to comply with *Statutory Management Requirements*, and that farmland must be kept in *Good Agricultural and Environmental Condition*. The latter includes requirements to maintain SOM and structure, avoid the deterioration of habitats and to manage water resources. There is a specific rule banning the burning of post-harvest stubble.

The degree to which the current CAP objectives can be achieved is still being studied. The EC published an evaluation of the impact of greening measures after 2 years of implementation (EC, 2017), which showed that crop diversification had led to changes in cropping patterns in around 0.8% of arable areas and may have slowed to some extent the historical trend towards monoculture crops. With permanent grassland, this evaluation detected a disincentive to plough permanent grassland in six Member States. With EFAs, farmers reported higher ratios than legally required (9.7% of arable land included) and EFAs were also seen as encouraging an expansion in nitrogen-fixing crops. These overall beneficial trends did not have any significant effect on the profitability of farmers (EC, 2017).

Gocht *et al*. (2017) modelled the impact of CAP greening and found a small decrease in overall productivity to be associated with a small (1.2%) increase in soil erosion from increased areas of fallow land lacking green cover. Smędzik-Ambroży and Majchrzak (2017) analysed trends in soil productivity[9] between 2007 and 2013 and found an average increase of 22%, with some Members States showing substantial increases (Finland 57%, Ireland 40%, Slovakia 31% and Slovenia 29%). Analysing the distribution of subsidies between EU15 and EU12 countries led the authors to conclude that the CAP has had no effect on soil productivity, and that the gains were due to improved practices independent of the CAP. They also found that soil productivity in the EU15 was about 20% higher than that in the EU12 and that the introduction of better farming practices in the EU12 has yet to improve soil productivity to the same level as in the EU15. They did not, however, explore how far current higher levels of soil productivity were compatible with sustainability of the soils' multifunctional services. Moreover, studies have not yet shown whether the current CAP is improving the biodiversity and functioning of soils.

Most funds from the CAP are channelled to farmers through direct payments, with a smaller proportion flowing via Rural Development Programs (Pillars I and II

[9] Soil productivity is defined as the capacity of soil, in its normal environment, to support plant growth.

respectively). Brady *et al*. (2017a,b) analysed the impact of Pillar I payments and concluded that the CAP is keeping more, mostly marginal, land in production and avoiding land abandonment. On the positive side, this could be seen as preserving the productive potential of land and its associated biodiversity and cultural diversity. However, there was much variability across regions, and structural change and agricultural improvement were also delayed, which Brady *et al*. (2017a) describe as a '*serious goal conflict*'. Negative consequences of direct payments were identified as higher GHG emissions, larger nutrient surpluses and higher rates of pesticide use (with associated reductions in soil quality).

From these initial findings it is clear that achieving environmental sustainability of agriculture is a challenge and further measures and how to implement these remain under debate. The evaluation by the EC (2017) saw a need to amend EFA rules to encourage greater uptake of the most beneficial EFA types. Grassland measures needed to be applied more widely both within and outside the Natura 2000 network to protect habitats. Moreover, there was a need to ensure that suitable advice is available to farmers, not just on administrative and compliance aspects but, more importantly, on the purpose of greening and the ways of optimising their environmental and climate effects. Bowyer and Keenleyside (2017) also stress the need for an independent Farm Advisory System that helps farmers not only to better understand and meet EU rules, but also to develop regional and site-specific incentives linked with national rural development programmes.

In the next reform of the CAP (post 2021), the EU has an opportunity to apply recent research to allow agriculture to more effectively adapt to and mitigate climate change, while improving biodiversity. For instance, minor modifications to the crop diversification rules could benefit soils by encouraging more crop rotation which can increase SOC, improve soil structure, and water and nutrient retention. Crop rotation involving legumes not only improves nutrient supply (reducing need for chemical fertilisers) but also reduces dependency on imported soy protein feeds with their embodied deforestation (Box 3). Innovative approaches to nutrient management being applied in some Member States may also have potential for wider application[10]. Other ideas are that 'soil reports[11]' could be developed to allow the threats and opportunities for individual properties to be formulated by farmers and other land owners to record the status of their soils (SOC, biodiversity, pathogen suppression, etc.). Others advocate more fundamental redesign involving a shift to instruments targeted on desired outcomes based on the 'polluter pays' and 'provider gets' principles (Brady *et al*., 2017a). Such principles would provide incentives to (1) generate public goods that otherwise would be underprovided; (2) mitigate environmentally damaging emissions at the lowest possible cost; and (3) continually strive to improve environmental performance, while not obstructing structural change and agricultural development.

[10] Denmark has created a nitrogen standard quota at the farm level to optimise nutrient flows in agricultural production systems. This has improved soil sustainability and reduced nutrient inputs to marine waters (Riemann *et al*., 2016).
[11] Or, in the Netherlands, 'soil passports'. https://has.nl/en/topproject/soil-passport-producing-healthy-and-safe-food-starts-good-quality-soil

5 Soils, plant health and human health

5.1 Concept of soil 'health'

The connection between the attributes of soils and the condition of plants, and through that connections with human health, makes the term soil 'health' useful in broadening the traditional concept of soil quality (Karlen *et al*., 1997) to incorporate the multi-functionality of soil. The FAO (based on Pankhurst *et al*., 1997) offers a definition as follows: '*Soil health is the capacity of soil to function as a living system, with ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production*' (FAO, 2008). The FAO definition acknowledges soil to be a vital living system that should deliver a continued capacity to support the production of plants and animals, thereby including the composition and structure of soil biodiversity and its relationship to multi-functionality (Wagg *et al*., 2014). As shown in Figure 5.1, soil 'health' relates to the composition and structure of soil biodiversity and can be degraded through mechanisms such as poor land management and climate change, which in turn directly affect ecosystem functioning and reduce the services the ecosystem provides towards human health.

Compared with the broad concept of soil 'health' used by the FAO, the EU's Soil Thematic Strategy is more focused on the problems and costs related to poor soil functioning (erosion, land degradation, etc.). However, taking into account public demand for healthy food from soil-grown crops, it would appear appropriate to consider soils in a much broader context and thus involving food safety, animal and human health as well as the soil's capacity to produce a particular crop (a point also made in a recent EASAC report on food and nutrition security and agriculture in Europe (EASAC, 2017b)). Europe has extensive regulations on plant health and biosecurity, but these do not explicitly link plant health to the condition of the soils on which they are grown. Regarding soil-borne diseases, some can be prevented by crop rotation, but this is not always effective. Moreover, changes in extreme weather conditions and outbreaks of virulent pathogens can reduce or bypass plant resistance, increasing the risk of soil-borne crop diseases. The challenge is to maximise the ability of natural enemies in the soil (e.g. consortia of microbial communities (Raaijmakers and Mazzola, 2016)), to prevent specific soil-borne diseases.

5.2 Plant health and food quality

Discussions about food quality include assertions that current food crops are less nutritious, or less healthy, than in the past (Udo de Haes *et al*., 2012; EASAC, 2017b). Indeed, some reviews and meta-analyses have demonstrated a correlation between micronutrients

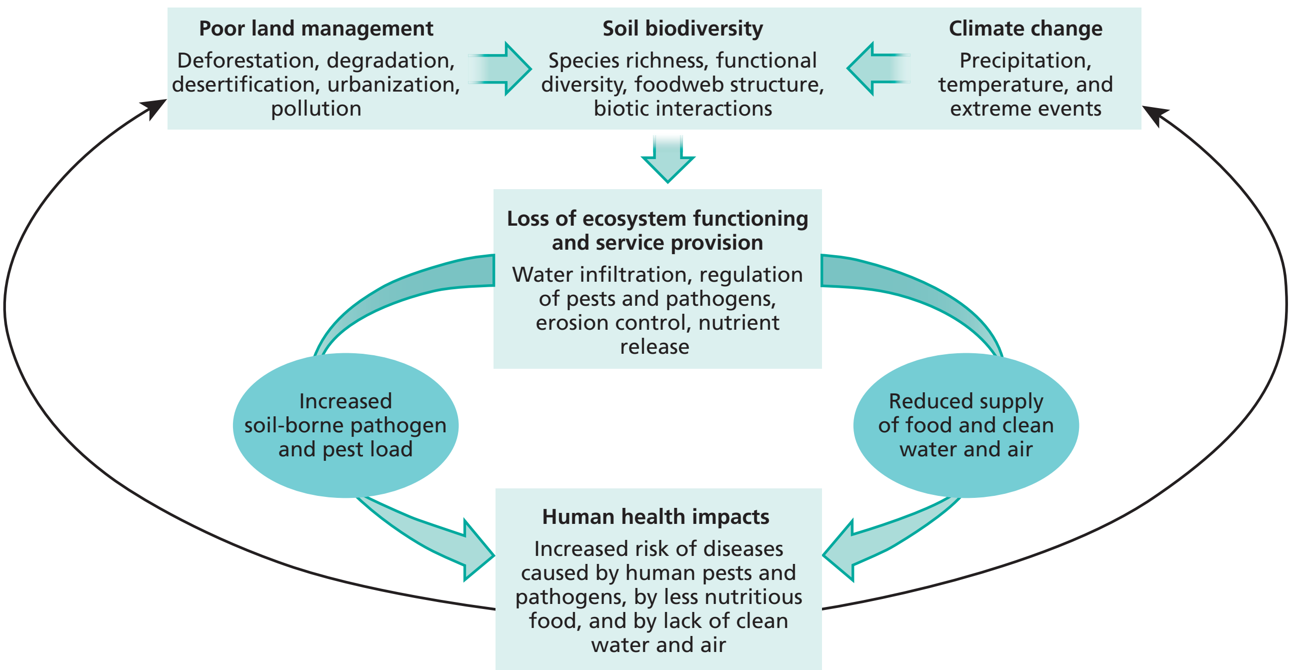

Figure 5.1 Soil biodiversity and its relationships to human health (Wall et al., 2016).

and reduced incidence of specific human diseases (Acamovic and Brooker, 2005; Crozier *et al*., 2009). It has been reported that current crops do contain less micronutrients than earlier and that this can affect both human and animal health (Udo de Haes *et al*., 2012). For instance, the Broadbalk experiment at Rothamsted, UK, has shown that since the 'Green Revolution' yields have greatly increased but the micronutrient content of wheat grain has decreased. This seems due to the introduction of semi-dwarf, high-yielding cultivars, as in comparison the concentrations in soil have either increased or remained stable (Fan *et al*., 2008; Zhao *et al*., 2009). It seems as if current crop varieties that have been bred to produce higher yields may, in the process, have diluted micronutrient concentrations.

Biological soil composition may also influence the amounts contained within the plant of secondary metabolites including amino acids and compounds that influence plant defences against pest insects and pathogens (Bezemer and van Dam, 2005). It has been proposed that 'healthy' soils can increase food quality. As an example, tomatoes grown in organic soils have more flavonoids (Colla *et al*., 2002). However, the concept of healthy soils for healthy food needs to be further established. In addition, the spatial diversity of land use (Hanson *et al*., 2016) and natural elements such as flower strips in field margins will influence the availability of natural enemies of above-ground pest and plague organisms (Tscharntke *et al*., 2012). Therefore, soil attributes, crop diversity and natural habitat elements in agricultural landscapes may all promote crop plant health and ultimately healthy food. As there is a feedback loop between soil and plants that is reinforcing the health status of the cropping systems, healthy plants may also benefit the soil. For example, plants with little pathogen infestation will also prevent pathogen build-up in the soil from the residues remaining after harvesting.

5.3 Soils and human health

Wall *et al*. (2016) described how soils and soil biodiversity contribute to healthy food, clean drinking water and air, as well as helping to prevent human allergies and to control outbreaks of human pathogens and helminths (parasitic worms). The role of soils for human health is recognised by the United Nations, the World Health Organization and the Convention on Biological Diversity, through the Global Soil Partnership of the FAO. In Europe, the effects of soil *contamination* on human health are well recognised in EU research programmes[12]. But here we consider soil-borne *pathogens* as a potential threat to human health, as well as to soils as a source of allergens, and as a route for transmission of radioactive compounds.

At least 39 diseases resulting from soil-borne pathogens[13] are known to occur globally (Jeffery and van der Putten, 2011), and the World Health Assembly of the UN has emphasised the need for increased medical intervention to minimise soil-transmitted diseases[14]. As observed in a recent review by the United Nations Environment Programme (UNEP, 2017), bacteria in water and soil naturally possess a huge diversity of resistance genetic traits, with pathogens able to acquire resistance genes from environmental bacteria, offering a means through which resistance can spread (Ashbolt *et al*., 2013; Finley *et al*., 2013; Wellington *et al*. 2013). For example, antibiotics in animal manure interact with soil particles in different ways: in some cases the soil particles may neutralise the antibiotic but in others they may exert selection pressures on the bacteria already in the soil (Subbiah *et al*., 2011). The growing use of antibiotics and other medicines for humans and animals thus poses a potential risk to soil biodiversity, and to the resistance to antibiotics found in soil microorganisms. The processes of gene transfer and their extent are still incompletely understood and further research is required to establish the role of soil biodiversity in suppressing human, animal and plant pathogens and mitigating pathogen outbreaks through biological control (Boxall *et al*., 2012; Berendork *et al*., 2015).

Soil and land management have a substantial influence on the control and spread of soil-borne human diseases (Wall *et al*., 2016), and loss of soil biodiversity has been linked with increased risk of human infectious diseases such as Lyme disease, anthrax and hookworm (Patz *et al*., 2004). The potential of soil biodiversity to suppress human, animal and plant pathogens and to mitigate pathogen outbreaks through biological control is particularly important in the light of international trade and global markets increasing the risk of introducing novel soil-borne human pathogens. In combination with climate warming, soil-borne human pathogens that have been introduced from warmer climate regions have the potential to proliferate.

Microbes in soil naturally produce and use antibiotics to compete with each other, and it is estimated that only about 0.03% of the antibiotics that may be useful for human healthcare have been discovered (Bérdy, 2012). The possibility of discovering novel antibiotics remains,

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[12] See, for example, http://ec.europa.eu/environment/integration/research/newsalert/pdf/IR5_en.pdf.
[13] Soil-borne human pathogens are considered those pathogens whose life cycle can be completed in soil. Soil-borne human diseases have been defined by Jeffery and van der Putten (2011) as '*human diseases resulting from any pathogen or parasite, transmission of which can occur from the soil, even in the absence of other infectious individuals*'.
[14] For example, the anthrax outbreak in 2016 in Komi Republic, Russia, after permafrost melting and exposure of the old livestock burial places.

while the widespread use of antibiotics since the mid-1900s both in people (to combat infections) and in farm animals (to increase growth) has resulted in such antibiotics entering the soils and enhancing antibiotic resistance genes in soil microbial communities. Antibiotic-resistant bacteria or soil microbes acquiring resistance may have prolonged and increased survival in the soil (Sanderson *et al*., 2016), but the possible health impact of the survival and promotion of resistance genes in the soil microbiome, and the possible transfer to humans through water, crops and animals as food, are not well understood. Apart from these compounds, the soil microbiome contains many other bioactive compounds, such as orthoformimycin (Monciardini *et al*., 2014), and many other microbial products wait to be discovered.

People may also be exposed to allergens in the soil following soil erosion and exposure to soil dust. For example, the moulting exoskeletons of oribatid mites can cause severe allergic reactions (Krivolutsky, 1995), and allergens produced by plants and microorganisms (such as pollen and fungal spores) can spread over large distances through the air, so that degraded land can affect human allergic responses at distances of up to several hundred kilometres (Skjøth *et al*.2013). Potential for reducing exposure to possible allergens in dust exists by urban greening[15], since vegetation cover, even in cities, may decrease fine dust levels in the air and thereby reduce cases of asthma and other respiratory diseases. Other solutions to reduce dust and erosion involve better agriculture practices, especially focusing on preventing agricultural soils from being uncovered by vegetation for extended periods.

Like many other chemical compounds, radioactive elements (radionuclides) can accumulate in soils. Their mobilisation, immobilisation and concentration are largely due to activity of soil fauna (see Zaitsev *et al*., 2014). For example, owing to the 1986 accident in Chernobyl, fallout had strong effects on both agricultural and natural soils in Belarus, Russia and Ukraine, as well as in many other European countries (including upland pastures in the UK). Plants and animals took up radionuclides in some areas, and they were subsequently found in milk, meat, forest food products, freshwater fish and wood[16]. Soil degradation and disruption of soil communities, due to soil tillage or digging activities for example, may also release long- and short-lived radionuclides, leading to a transfer over a wide region by wind or water.

[15] There are over 55 million hectares of urban land in the EU with an annual increase of about 1 million hectares (Bardgett, 2016). Green urban areas also demonstrate positive effects on human mental health (de Vries, 2010; Gascon *et al*., 2015; Egorov *et al*., 2016).
[16] See http://www.europarl.europa.eu/RegData/etudes/BRIE/2016/581972/EPRS_BRI(2016)581972_EN.pdf

6 Soils and climate change

6.1 General considerations

Despite the Paris Agreement of 2015, current emissions of carbon dioxide and other GHGs are on a trajectory to raise the mean global temperature by 2.7°C (relative to pre-industrial levels) by the end of this century (Gütschow *et al*., 2015). Even at the most challenging target of 1.5°C, releases of carbon dioxide or methane from thawing permafrost carbon stocks are expected (Hansen *et al*., 2016), and land carbon losses are also reported from tropical forests owing to the combined effect of climate change and land-use change (Baccini *et al*., 2012). In contrast, temperate forests in Europe have been increasing carbon stocks (Luyssaert *et al*., 2010). Soils are an important storage of carbon and organic matter (Jobbagy and Jackson, 2000; Lal, 2004; Lal *et al*., 2015; FAO, 2017a–c) and the amounts of carbon contained in below- and above-ground biomass are highly significant[17]. The fate of carbon in soils is thus a critical factor in determining rates of carbon releases to the atmosphere and the extent of warming, and it has been estimated that since the start of agriculture some 12,000 years ago, soils have lost 133 gigatonnes of carbon to the atmosphere (Sanderman *et al*., 2017).

The Global Soil Partnership has compiled a Global Soil Organic Carbon Map (FAO/ITPS, 2018) and this can be expressed as a percentage loss in relation to the natural content (IPBES, 2018a) as shown in Figure 6.1. Almost half of European soils have low organic matter content, principally in southern Europe, but also in areas of France, the UK and Germany (Rusco *et al*., 2001). Several reports mention decreasing SOC contents in northwestern Europe as well, for example in Norway (Riley and Bakkegard, 2006), the UK (Bellamy *et al*., 2005; Barraclough *et al*., 2015), the Swiss Alps (Leifeld *et al*., 2009) and the Flanders region in Belgium (Mestdagh *et al*., 2004; Sleutel *et al*., 2007). In France, SOC content decreases of about 50% have been observed in some regions (see, for example, Arrouays *et al*., 1995) when soils were converted from native vegetation to croplands. These decreases were quite sharp during the first decade but they still continued at a slower rate over many subsequent decades. Recent studies showed that French cultivated soils are considerably depleted in organic matter (Meersmans *et al*., 2012) and thus their theoretical SOC sequestration potential is high (Angers *et al*., 2011; Chen *et al*., 2018) if the underlying processes that caused the SOC loss can be reversed.

Soils in areas with high animal farming intensities do not show such declines (Reijneveld *et al*., 2009), although much of the carbon and nutrient supplied originates from imports of animal feed and crop residues. According to current estimates, there are still about 70–75 gigatonnes of carbon in European soils (Jones *et al*., 2005), and there is potentially even more carbon up to depths of 1 metre that is not accounted for by national inventories which, for example, collect data up to 30 centimetres in grassland soils (Ward *et al*., 2016).

Estimates indicate that SOC globally is being lost at a rate equivalent to 10–20% of total global carbon dioxide emissions (Olivier *et al*., 2015). Without additional measures, further losses of SOC are projected through deforestation and forest degradation, the drying and burning of peatlands, excessive disturbance and insufficient return of organic matter in cultivated soils and rangelands, removal of forest residues in intensive forestry, and from loss of soil carbon sequestration potential by urbanisation and mining activities (van der Esch *et al*., 2017)[18].

Organic matter decays more rapidly at higher temperatures (European Environmental Agency, 2012) providing that there is sufficient moisture, so increasing temperatures will exacerbate the release of GHGs (carbon dioxide or methane) owing to increased decomposition (Crowther *et al*., 2016) and thawing permafrost. Photosynthesis rates may also increase but a recent overview (Crowther, 2017) suggests that warming generally stimulates decomposition more than photosynthesis, and that rising temperatures thus stimulate a net loss of soil carbon. Particularly vulnerable to this trend are the soils in the Northern Hemisphere (Figure 6.2).

As described in Boxes 1 and 3, well-structured soils with higher SOC have greater capacity to both absorb and retain water that will be available to crops under drought, while also slowing the effects of heavy rain. Positive relationships between soil and climate can be influenced by soil policies that encourage farmers, foresters, municipalities and other land owners to make their soils more resilient to climate change (European Environmental Agency, 2015). Soils also play a special role in the northward spread of plant and animal species in a warming climate (Saxe *et al*., 2001; Parmesan and Yohe, 2003), since many wild plant species are controlled by natural pathogens and facilitated by

[17] The 1,500 gigatonnes of organic carbon in soils (mostly in the top metre) exceed that contained in the atmosphere (760 gigatonnes) and vegetation (560 gigatonnes) combined.
[18] Up-to-date estimates of carbon fluxes to/from soils are available at http://www.globalcarbonproject.org/

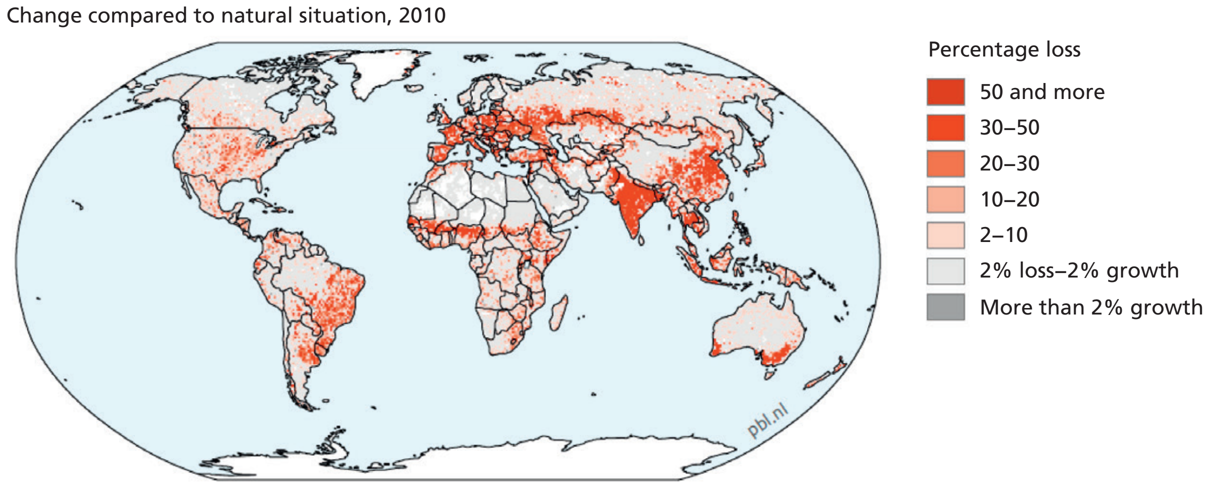

Figure 6.1 SOC losses in 2010 (relative to their natural content) (IPBES 2018a).

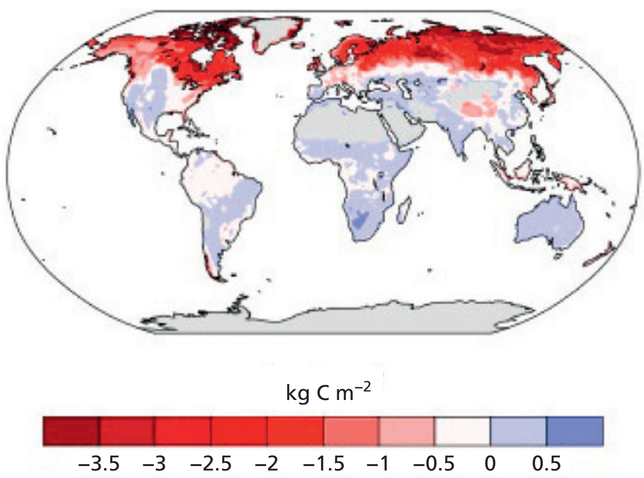

Figure 6.2 The spatial variation in projected surface soil carbon stock changes (0–15 centimetres) expected under a 1°C rise in global average soil surface temperature (Crowther, 2017).

natural mutualistic–symbiotic soil biota. Successful range-expanding species (including invasive species that have been introduced into Southern Europe (Walther, 2010)) that escape their natural enemies may dominate, while other species that depend on specific soil biota may have difficulties surviving in the new range (Engelkes *et al*., 2008).

Decreased winter chilling (Way, 2011; Way and Montgomery, 2015) and increased thawing will also cause contraction of tundra vegetation (Elmhagen *et al*., 2015) which will be taken over by boreal forest. Along the southern range edge, boreal forests will contract to be succeeded by grasses and southern opportunists (Walther *et al*., 2009) that are more prone to fire (Tooth and Leishman, 2014; Coates *et al*., 2016). Warming and drying of the boreal forests' peaty soils will also increase the occurrence of fire, further enhancing the replacement of forest by invading grasses, which would cause northern soils to lose organic matter and carbon storage capacity (Craig *et al*., 2015). Peat soils in particular will encounter desiccation and erosion risks due to a shift to warmer, drier climate (Li *et al*., 2016).

Other potential interactions between climate change and soils include the following.

- Climate change scenarios predict increased wind velocities for North and Central Europe towards the end of this century (relative to the 1971–2000 period) (Tobin *et al*., 2015), which will increase wind erosion, especially on sandy soils with poor vegetation cover (Borrelli *et al*., 2014).
- Increased frequency and intensity of severe rainfall events will increase the incidence of rapid-moving landslides, so that the number of people who are exposed to landslide risk is predicted to increase (Gariano and Guzzetti, 2016).
- Climate change will reduce the availability of water in southern areas of the EU and will lower production of food and fibre owing to a drier climate and increased risk of salinisation (Kreuzwieser and Gessler, 2010).
- In the northern part of the EU, warming may increase yields (with a positive effect on root biomass). On the other hand, the predicted increase in precipitation may increase nutrient loss through leaching (Brinkman, 1982). Accelerated weathering of rocks and minerals will be promoted by higher atmospheric carbon dioxide concentrations, temperature (which enhances weathering), intensive rainfall (which facilitates surface runoff and leaching), heat waves and extended periods

of drought, which change rocks and minerals physically (Qafoku, 2014). These changes have already been observed in recent decades (Gislason *et al*., 2009).

- The adoption of new crops, such as warm-tolerant maize which may be grown at higher latitudes under climate warming, could increase soil erosion rates (Mullan, 2013), especially in erosion-prone sites, owing to the low vegetative soil cover after seeding and the linear structure of the maize rows (Vogel *et al*., 2016).

- The risk of soil compaction may increase because of an increase in the number of days that soils are waterlogged and thus more vulnerable to compaction from heavy machinery (Batey, 2009).

- Urbanisation and urban sprawl, which cause soil sealing and degradation of the remaining vegetation (Liu *et al*., 2015), create urban heat island effects that, together with general climate change, tend to increase precipitation in heavily urbanised areas (Dore, 2005; van Heerwaarden and Vilà-Guerau de Arellano, 2008).

Various options exist to respond to the above threats. In this context, climate adaptation and mitigation measures for soil have a no-regret component: increasing the SOC contributes to improving soil structure and greater water holding capacity, preventing erosion and restoring degraded land. All these factors make positive contributions to the multi-functionality of soil ecosystems. Furthermore, soils are sources of other GHGs, especially nitrous oxide and methane, and their emissions may be reduced by soil management (e.g. by adding certain types of organic matter (Jones *et al*., 2014; Ho *et al*., 2015)). However, advice on good soil management and enhancing resilience of soils to climate change has to be customised for different areas and soil types. Local approaches are thus crucial, considering the enormous variety of landscapes and soil conditions in Europe.

Synergy is also possible in combination with other commitments. Measures to support Europe's commitment to the Convention on Biological Diversity by improving the diversity of plant or tree species in natural vegetation and forests improves soil, while linking fragmented habitats and isolated nature reserves also facilitates species migration in response to climate changes. Protecting and restoring wetlands to support the Habitat Directive and the RAMSAR Convention will also enhance peat stocks (see section 6.2). There is also synergy with other climate change mitigation actions. For instance, limiting urban sprawl, using permeable materials for roads, car parks, etc. and using water harvesting and recycling systems reduces flood risks and washing-out of nutrients, heavy metals and other contaminants into surface and ground waters (Valtanen *et al*., 2014, 2015; Sillanpää and Koivusalo, 2015). Environmentally sensitive development techniques such as green roofs (Kuoppamäki *et al*., 2016), urban vertical gardens (Bass and Baskaran, 2003) and permeable surfaces also help compensate for soil-provided ecosystem services harmed by soil sealing (Guan *et al*., 2015). At the same time, various types of urban greening differ in their climate change effects; while mixed vegetation cover may be beneficial for maintaining soil quality and other ecosystem services, maintaining simple urban lawns requires considerable amounts of energy and may increase emissions of GHGs.

Optimising synergy between various policy objectives requires soil data at both national and European scales, better tools to assess vulnerability of the SOM in different ecosystems under future climate change, an international reference framework on solutions to enhance climate and water resilience in urban regeneration[19], and novel ways of combining production of food, feed and bioenergy with restoring degraded land and returning carbon back to the soil.

6.2 Specific issues on peatlands

A particularly important reservoir of carbon stocks is in peatlands[20]. The current area of peatland in the EU is estimated at more than 380,000 square kilometres, 20% of which have been drained for agriculture, 28% for forestry and 0.7% for peat extraction (Schils *et al*., 2008). Montanarella *et al*. (2006) calculated a carbon stock of 18.7 gigatonnes of carbon, but peatland ecosystems are very sensitive to climate change (Dise, 2009), as increasing temperatures and a lowered water table will remove oxygen constraints on the decomposition of a carbon store holding 455 gigatonnes of carbon globally (Freeman *et al*., 2001).

Peatlands contribute to biological diversity, the water cycle and regulation, global carbon cycling relevant to climate change, and are used as fuel, a growing

[19] Related projects include International Union for Conservation of Nature 'World Environmental Hubs' and 'URBES' ('Urban Biodiversity and Ecosystem Services') programmes, as well as EU Programmes (e.g. http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/scc-02-2016-2017.html)

[20] Peat is defined as dead and partly decomposed plant remains that have accumulated *in situ* under waterlogged conditions. Peatlands are landscapes with a peat deposit that may currently support vegetation that is peat-forming, that may not, or that may lack vegetation entirely. The presence of peat, or vegetation capable of forming peat, is the key characteristic of peatlands.

medium for plants, and as a material source or as a provider of other ecosystem services. Peatlands also provide information about past landscapes, climates and cultural activity (since the anaerobic conditions of the peat provide an ideal environment for preserving a range of historical and ancient information and artefacts). Globally, peatlands store twice as much carbon as all forest biomass (Parish *et al*., 2008), while in Europe peatlands store approximately five times that stored in Europe's forests (Limpens *et al*., 2008; Berredo *et al*., 2012) and account for about half of Europe's total SOC (Byrne *et al*., 2004; Montanarella *et al*., 2006; Panagos *et al*., 2013). Most European countries include areas of peatlands, although the majority is concentrated in the northern half of the continent or on mountains; Russia and the Nordic and Baltic countries alone provide more than 60% of the European peatland resources (Wetlands International, 2010).

Many European peatlands have been degraded by peat extraction for horticulture and fuel, drainage, agriculture and forestry, resulting in substantial carbon and nitrogen emissions (Barthelmes *et al*., 2009). Such degraded peatlands are less able to bind carbon, and degraded peatlands have become net carbon sources and have resulted in the EU becoming the world's second largest carbon dioxide emitter (after Indonesia) from degraded peatlands (Holden *et al*., 2011). This has brought with it habitat loss, and increased erosion and fire risk with potential effects on downstream catchment areas through reduced water quality and increasing flood risk (Green *et al*., 2014). Exploitation of peat (for example as a fuel or growing medium) can conflict with maintaining ecosystem services such as carbon storage and sequestration, biodiversity and landscape value. Peat is still used for domestic fuel in some regions; for example, it provides 6.2% of Finland's annual energy production, second only to Ireland. Peat has been extracted on a large scale as a growing medium for horticulture, with some being taken from peatland areas with high wildlife value. Peatlands provide habitat for rare and threatened species (many of the bird species breeding on peatlands have European conservation designations and legal protection), and their contribution to biodiversity is important.

Conversion of peatland to agriculture has been going on in Europe for centuries, and today an estimated 125,000 square kilometres are used for agriculture. Well-managed peatland soils are among the most productive agricultural lands available, but a recent assessment found a significant increase in the contribution to GHG emissions because of land management in general and wetlands converted to croplands in particular (Petrescu *et al*., 2015). The importance of wetlands, particularly peatlands, was recognised in a recent review of natural climate change mitigation solutions (Griscom *et al*., 2017) which noted that per unit area, wetland areas hold the highest carbon stocks, and that by avoiding the loss of wetlands, substantial carbon stocks can be protected and costs reduced, since conservation tends to be less expensive than wetland restoration (Barbier *et al*., 2011; Bayraktarov *et al*., 2016).

EU policy regimes relevant to peatlands have been extensively reviewed (see, for example, Peters and Von Unger, 2017) and reveal both positive and negative impacts. Related EU policies include nature protection, infrastructure planning, water policy, agriculture and the CAP, rural development and structural funds, LIFE funding, energy policy and climate change regulations. However, peat-specific considerations are generally lacking. In some cases, different policies are mutually inconsistent (e.g. the parallel availability of grants to manage peatland habitats and to fund drainage systems which degrade peatlands). The lack of an EU regulatory framework for soil also impedes the recognition of the value of these organic soils.

The role of peats in climate policy is still emerging, with the EU gradually obliging GHG accounting of peatlands, but only where used as forest, cropland or grazing land. Proposals for land use, land-use change and forestry (LULUCF) accounting are not currently creating incentives for reducing emissions from peatlands, nor rewards for peatland restoration. Other policies on biofuel and biomass can increase pressures to drain peatlands for crops such as maize and rapeseed, causing carbon loses from land-use change. Similarly, no clear regulatory framework for energy use from peat and its limitations is in place across the EU.

Various options are available to improve this situation.

- On horticultural use, the voluntary European eco-label standard and the certification system of 'Responsibly Produced Peat' should be strengthened.
- The Strategy for Responsible Peatland Management launched in 2010 by the International Peat Society offers a framework for managing peatlands responsibly for their environmental, as well as their social and economic values.
- EU Structural Funds could be used for peatland rewetting and paludiculture development (detailed guidance on restoration is available (see, for example, Similä *et al*., 2014)).
- Revising LULUCF accounting to create incentives to reduce emissions from peatlands, and rewards for peatland restoration.
- Work is needed to build an accurate inventory of peatland GHG emissions and to evaluate peatland rewetting as a cost-effective mitigation measure.

6.3 The '4 per mille' initiative

During the Conference of the Parties (COP) 21 meeting of the UNFCCC, France launched the '4 per mille' initiative under the banner of 'Soils for Food Security and Climate' (Chabbi *et al*., 2017, Soussana *et al*., 2017). The aim of this initiative is both to promote food provisioning for a growing world population and to mitigate climate change; it is part of the Global Climate Action plan adopted by the UNFCCC at COP 22 as a follow-up to the COP 21 Lima-Paris Plan of Action. The Executive Secretariat of the '4 per mille' initiative is hosted by the Consultative Group on International Agriculture Research. If global carbon stocks of managed land could grow with a rate of 0.4% per year, this would offset much of the anthropogenic-driven increase in annual atmospheric carbon dioxide concentrations. The '4 per mille' initiative called on all fields (agroecology, agroforestry, conservation agriculture, integrated soil fertility management, landscape management, etc.) to initiate practical actions to enhance carbon storage in managed soils.

As described earlier, improving SOC promotes other ecosystem services such as water holding capacity, soil structure, nutrient provisioning and control of soil-borne pathogens; thus it has direct benefit to farmers and other land users. The '4 per mille' initiative has thus been widely embraced and the FAO organised a Global Symposium in 2017 to combine agendas for sustainable management of soils, climate change mitigation and adaptation, combatting land degradation and food security[21]. The initiative also plays an important role in the forthcoming special Intergovernmental Panel on Climate Change report on Climate Change and Land[22] and contributes to the Global Research Alliance on agricultural GHGs, which aims at reducing agricultural GHG emissions and increasing soil carbon sequestration while ensuring food security objectives[23]. Finally, the current restructuring of the Common Agriculture Policy in the EU will include the potential use of SOC as an indicator for smart practices (Minasny *et al*., 2018).

A major attraction of the '4 per mille' initiative is that measures to enhance SOC are well known. Loss of soil (especially agricultural soils) through sealing should be avoided, while enhancing SOC levels through green manuring, preventing soil remaining bare at any stage of the growing season, cover cropping, adding compost, sewage sludge, manure or other sources of organic matter, keeping grass or grass–clover in the rotation, minimum tillage, promoting (re)forestation, avoiding losing forest SOC after forest cutting, promoting cattle grazing, etc. Moreover, this objective may also be met by developing perennial grains whose deep roots can increase soil carbon and other soil ecosystem services[24]. However, some of these measures, such as manuring, are moving carbon from one piece of land to another, rather than binding carbon dioxide (Powlson *et al*., 2011). Moreover, it is not only the quantity but also the quality of the SOM in which the carbon is incorporated that will determine which ecosystem service, and how much of it, will be influenced.

SOM is a complex biogeochemical mixture derived from organic material in all stages of decomposition, with plant litter compounds remaining in the soil for periods ranging from a few days to decades (Paul *et al*., 2002; von Lutzow *et al*., 2006). Longer-term stabilisation is generally the result of interactions with soil minerals that reduce degradation by enzymes (see, for example, Schmidt *et al*., 2011), while microbial biomass is an important source of the accumulated SOC (Miltner *et al*., 2012). The surface area of the soil mineral fraction (e.g. clay, silt or sand content) may set an upper limit for the amount of SOC that a particular soil can hold (Six *et al*., 2002).

The '4 per mille' initiative has triggered much debate on the feasibility of the targets and best means of implementing carbon-enhancing measures. Minimum critical thresholds for SOC, optimum levels and potential maximum levels of SOC are still a matter of scientific debate. Historical literature suggests a minimum threshold of 2% SOC, and intensively cultivated soils in Europe have already fallen below this level in many cases (Huber et al., 2008). The practical mitigation potential has been estimated as being from 0.07 to 0.7 tonnes of carbon dioxide equivalent per year per hectare (Smith *et al*., 2007), and Minasny *et al*. (2017) found that, under best management practices, up to 10 per mille of carbon sequestration can be achieved for soils with low initial SOC stock (for the first 20 years after implementation). They estimated that if '4 per mille' were to be applied in the top 1 metre of global agricultural soils (3,900–4,900 million hectares), SOC sequestration potential would be between 2 and 3 gigatonnes of carbon per year. However, other studies suggest a more limited capability at the global scale (Powlson *et al*., 2014; Zomer *et al*., 2017), while clearly the annual increase in SOC will decline as it reaches equilibrium (White *et al*., 2017).

Lal (2016) points to several challenges in implementation of the '4 per mille' initiative including limited scientific data, the finite capacity of soil carbon

[21] http://www.fao.org/about/meetings/soil-organic-carbon-symposium/en/
[22] http://www.ipcc.ch/report/sr2/
[23] http://globalresearchalliance.org/about/
[24] Kernza is a perennial intermediate wheatgrass and a wild relative of annual wheat (https://landinstitute.org/our-work/perennial-crops/kernza/).

sinks, the reversibility of SOC enhancements achieved, how to engage resource-poor farmers and small landholders as well as financial commitments. Overall effects on climate also need to consider the potential release of other GHGs with a higher warming potential (e.g. methane and nitrous oxide). A conclusion that may represent the current view is that the '4 per mille' initiative is more about the concept than about the numbers (Lal, 2016) and it appears unlikely to deliver a uniform increase in SOC across all global soils.

It is also necessary to see the initiative in the wider picture, where most agricultural soils are still losing rather than gaining carbon (Mestdagh *et al*., 2004; Bellamy *et al*., 2005; Riley and Bakkegard, 2006; Sleutel *et al*., 2007; Reijneveld *et al*., 2009) and are vulnerable to continued warming (section 6.1). Failure to apply measures to prevent soils losing carbon (for example in drained peat areas) may well outweigh actions to increase carbon levels in other soil types. Furthermore, in southern Europe, soils store carbon poorly because of high decomposition rates (Zdruli *et al*., 2004). Increased demand for a more bio-based economy, such as producing biofuels and biomaterials, also needs to take into account policy on enhancing SOC and to ensure that returning carbon to the soil is not in competition with providing carbon for the bio-economy[25]. Urban sprawl also removes the soil, and with it the potential to increase its carbon content.

Overall however, along with the scientific debate, there is a general consensus that policies, incentives and practices focusing on increasing SOC levels are highly commendable, as they provide a no-regret solution to both mitigation and adaptation to climate change, as well as for (climate) smart food, feed and fibre production. However, science-based insights are still needed to prevent unwanted side effects of policies aimed at increasing SOC and to prevent initiatives that are ineffective. Moreover, the current view is that some of the estimates of the potential of soils to counteract substantial proportions of global emissions may be too optimistic.

[25] For instance, by using perennial grasses which retain soil carbon in their root structures.

7 Implications for policy

7.1 Sustainability of soils

As described in previous sections, the unsustainable use of soils has been under active debate within the EU since 2002, but proposals for a Soil Framework Directive were withdrawn in 2014 owing to opposition from several Member States (partly related to contaminated land issues but also out of concerns that the subsidiarity principle should apply). Recognition of the need to manage soils in a more sustainable manner is included in the Seventh Environment Action Programme (Box 2).

Section 2 summarised the many recent actions at the global level, and international attention continues with the G20 summit in Argentina (July 2018) having included a special meeting on soils[26]. The IPBES has also published its global assessment of land degradation and restoration (IPBES, 2018a). The nexus of actions related to soil sustainability is thus shifting from the EU to the global dimension and it is important that the EU plays an active role in the international sphere. The nexus now includes the UN Convention to Combat Desertification, FAO's Global Soil Partnership, the '4 per mille' initiative, IPBES actions on land degradation, a forthcoming UN and FAO Global Soil Biodiversity Assessment, the International Union for the Conservation of Nature's Bonn Challenge Initiative on deforested and degraded lands[27], and grassroots organisations such as the Global Soil Biodiversity Initiative. Previous activities of the latter Initiative can provide a foundation on which to build the global soil biodiversity assessment (Ramirez *et al*., 2015).

In EU and international discussions there is a wide consensus that soils should be sustainable, and the ITPS has provided useful criteria for determining whether a landscape is functioning effectively and whether soils are being managed sustainably. These criteria are as follows:

- leakage of nutrients is low;
- biological production is high relative to the potential limits set by climate and water availability;
- levels of biodiversity within and above the soil are relatively high;
- rainfall is efficiently captured and held within the root zone;
- rates of soil erosion and deposition are low, with only small quantities being transferred out of the system;
- contaminants are not introduced into the landscape and existing contaminants are not concentrated to levels that cause harm;
- systems for producing food and fibre for human consumption do not rely on large net inputs of energy;
- net emissions of GHGs are zero or less (when the soil is a net sequester of carbon).

Such criteria should inform a review of EU-wide measurement and monitoring coordination between Member States and establish locally appropriate benchmarks to allow policy makers and land managers to determine whether they are moving towards sustainability.

7.2 EU soils policy framework

One question is whether recent research has implications for regulation on soil sustainability issues. Firstly, on the basic question of whether there is any change to the case for an EU Soil Directive, recent science has improved understanding of the extent to which soils' multiple ecosystem services provide benefits to European society as a whole which could be relevant to the applicability of the subsidiarity principle. In any case, we note that, even in the absence of a Soils Directive, there are other mechanisms that may contribute to soil protection (Frelih-Larsen *et al*., 2016), including the Habitat Directive, Natura 2000, Europe's contribution to the Convention on Biological Diversity, and policies focusing on food safety, climate change mitigation and adaptation which could acknowledge the role of soil and its physics, chemistry and biology.

The reviews by JRC (2012) and ITPS (2015) concluded that there are shortcomings to available data arising from different national monitoring systems. The EU Thematic Strategy (Morvan *et al*., 2008; EC, 2012a) also noted that assessing the state of Europe's soils would be improved if consistent and comparable data could be gathered. The European Soil Data Centre has already been established to provide a single reference

[26] The Agriculture Ministerial Meeting on 27–28 July 2018 had a central theme of food and nutrition security which released a statement on 'Improving soils and increasing productivity' with three recommendations on good soil governance, soils knowledge in specific areas, and increasing international scientific cooperation.

[27] This initiative aims to apply forest landscape restoration to over 150 million hectares of deforested and degraded lands by 2020.

point and holds all relevant soil data at the European level, and this provides an appropriate mechanism for improving coordination and harmonisation between Member States' actions on soil measurement and monitoring. Maintaining long-term data centres such as the European Soil Data Centre facilitates the use of data both from research actions and from EU monitoring schemes, and its value is increased by providing open access data.

One of the four pillars of the Soil Thematic Strategy is related to research needs, and the expert group has identified several high-priority areas where lack or deficiency in knowledge may limit our ability to sustainably manage soils. These are in Table 7.1 and, although by no means exhaustive, they can be considered when themes in Framework Programme 9 are prioritised.

7.3 Soil sealing

In section 2 the threat to soils from sealing was introduced. There is a particular conflict between urban and infrastructural development and the location of high-quality agricultural land. Gardi *et al*. (2014) calculated that the loss of agricultural land from 1990 to 2006 through sealing in EU countries had the productive capacity equivalent to 6 million tonnes per year of wheat.

Loss of agricultural production within the EU is against the background of increasing demand globally, which has already put most productive soils into agricultural use and has been driving conversion of forests and drylands to agriculture (Box 3). The loss of EU productive capacity, by increasing demands for imports, merely adds to the pressures in supplier countries to clear remaining areas of forest to meet demand. This 'embodied deforestation' is estimated at over 9 million

Table 7.1 Some major knowledge gaps

Theme	Knowledge gaps
Agriculture	How to combine food production with soil protection and multi-functional land use. How modern agricultural practices and increased yield may influence (micro) nutritional food quality. (Soil) sustainability of conventional, organic, regenerative, ecological-intensive and other forms of agriculture. How to make agriculture 'climate smart' (Paustian *et al*., 2016): contributing to mitigation while adapting to climate change. Long-term trends in European agriculture (e.g. the Broadbalk experiment); and consequences for soil properties and land use function in conversion towards ecologically intensive agriculture (Mäder *et al*., 2002; Schrama *et al*., 2018).
Biodiversity	How are European soil biodiversity and soil functions related to local climate, soil type, physico-chemical soil conditions, as well as current and historical land use.
Human health	How may soil attributes relate to a 'one health' concept embracing healthy plants, healthy food (and feed), healthy animals and healthy people. How to map risks of certain soil-borne diseases, how to map consequences of climate change, land-use change, and invasive species for human health, and how to mitigate these effects. Mobility of antibiotic resistance genes. Microplastic effects in soil on ecosystem services, plants and human health.
Climate change	How to motivate land owners, such as farmers, to carry out climate-smart agriculture, horticulture and forestry. How to guide towards novel communities and novel ecosystems that may develop as a consequence of climate warming-induced range shifts, including internal controls of species abundance and how to optimise multi-functionality. How to assess the quality of SOM for producing multiple ecosystem services. How to integrate biomass production into arable production to achieve effective contributions to climate change mitigation.
Urbanisation	What is the role of soil in urban areas and the need for an international reference framework on nature-based solutions to enhance climate mitigation and water conservation in cities.
Education	The need for educational programmes that create awareness of the role of soil in the life of individuals, communities and European society as a whole.
Circular economy	Soils play a key role in a more circular and sustainable society, but there is still a major knowledge gap about how to recycle waste materials after human consumption to soils without reducing sustainability and soil multi-functionality.

hectares deforested between 1990 and 2008 to meet the EU's imports of crops and livestock[28]. In view of soil sealing being one of the drivers of increased EU demand for imports, the EU analysis of community action required to reduce global deforestation should recognise soil sealing (whether for housing, infrastructure, mining or, more recently, solar farms) as a potential driver.

Soil sealing involves the loss of soils' multi-functionality and ecosystem services (Table 2.1) to accommodate the social and economic demands of development. In view of the staus of soil as a non-renewable resource, this is an effectively permanent loss and should be minimised as far as possible. The EC has published guidelines on best practices to limit, mitigate or compensate for soil sealing (EC, 2012b), which are broadly consistent with guidelines offered by the ITPS. They include the following:

- minimising conversion of green areas;
- re-use of already built-up areas, such as brownfield sites;
- using permeable cover materials instead of concrete or asphalt;
- supporting green infrastructures (green roofs, vertical gardens, green spaces with trees and shrubs, etc. where vegetation growth reduces net losses of SOC); and
- providing incentives to urban developers to minimise soil sealing.

The strong economic and social pressures for urban development have dominated the political discourse and made it difficult to consider the value of soil and its services when seeking an optimal trade-off with pressures for urbanisation. However, recognition of the shortage of agricultural land and the threats to the world's remaining natural ecosystems from agricultural expansion (see Cherlet *et al*., 2018) make it imperative for politicians and land use planners to minimise soil sealing and improve management during construction works (for example, saving and sorting removed soil for reuse, reclaiming soils and returning to agriculture/gardening when urban areas are abandoned, and minimising compaction). Minimising the demand for new surface mining can be achieved by recycling minerals and construction materials.

Recent research can help include the value of soils in the planning process (Siebielec *et al*., 2010; Prokop *et al*., 2011). In particular, valuing the functions of soil strengthens the attractiveness of using empty buildings or brownfield sites. Some Member States have regulations that protect good agricultural land or apply a use tax which increases with the quality of the land taken. Some cities provide tax incentives or funding schemes for green roofs, permeable surfaces for parking areas, etc. Studies of city designs (see, for example, Claessens *et al*., 2014) can determine location-specific ways in which the soil can contribute to urban adaptation to climate change, through the role of unsealed soil and green spaces in increasing water storage capacity, preventing flooding and providing a cooling effect in hot and dry conditions.

Greater awareness of the value of soils' ecosystem services is essential when debating the threats of urban sprawl to sustainable food and fibre production, and the pressures to irreversibly destroy agricultural, forest and natural soils[29]. Stricter regulations on planning to minimise urban sprawl and protect remaining soils require public understanding and support, which would be facilitated by increased awareness among European citizens about the importance of soil functions for a healthy and sustainable society (section 7.7). Across Europe, such awareness initiatives exist but most are largely local. Linking such initiatives and enhancing awareness through, for example, urban farming, citizen science projects and internet-based information in all national languages may help to protect and safeguard soils.

7.4 Soil organic carbon

As explained in section 6, SOC is a key player in the global carbon cycle and there is a broad consensus that further reductions in SOC should be avoided and past losses of SOC reversed. Section 6.3 described uncertainties in the scale of carbon sequestration that might be achieved through the '4 per mille' initiative. Combined with the likelihood that the rate of SOC loss will increase with further warming, some of the estimates of the ability of increasing SOC to offset substantial proportions of carbon dioxide emissions may be over-optimistic. Increasing SOC is just one of several potential approaches to improving land stewardship towards achieving Paris Agreement goals of holding warming to below 2°C (Griscom *et al*., 2017).

A comprehensive guide to incorporating carbon stock enhancement has been provided by Paustian *et al*. (2016) and systematic reviews have synthesised how agricultural management influences soil carbon (see, for example, EIP-Agri, 2015; Haddaway *et al*., 2015, 2016; and Mistra EviEM systematic review protocols[30]).

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[28] http://ec.europa.eu/environment/forests/impact_deforestation.htm
[29] The need to promote good soil governance to limit urban sprawl to protect soils was included in the recommendations from the July 2018 G20 meeting.
[30] Mistra EviEM systematic review protocol SR4 (farming effects on SOC of arable soils- http://eviem.se/en/projects/soil-organic-carbon-stocks/) and SR10 (effects of tillage on SOC- http://eviem.se/en/projects/soc-tillage/).

Advice on good soil management to increase SOC and enhance resilience of soils to climate change can be customised for different areas and soil types, and local advice is essential to ensure effectiveness of SOC-enhancing measures. The need of farmers for such independent advice on this issue, as well as on other soil management questions, strengthens the case for re-establishing independent advisory and extension services which have declined in many Member States in recent years. Currently, an advisory service for farmers is implemented through the CAP as the Farm Advisory System[31], but it may need expanding to take on these more local and specific agricultural needs.

In the focus on '4 per mille', however, it is important not to overlook the potential for losses of soil carbon through continued unsustainable use of peat soils (section 6.2) or degrading wetlands, which could easily outweigh any benefits from increasing SOC in arable soils. European peatlands' carbon stocks are very sensitive to a warming climate and lowered water table, and protection and restoration of peatlands is thus critical to maintaining and increasing SOC in the EU. Various options described in section 6.2 include encouraging the wider use of the voluntary European eco-label standards, 'responsible produced peat' certification and 'responsible peatland management' schemes, rationalising grant schemes to incorporate the carbon stock value of peat, expanding the funding options (e.g. EU Structural Funds) to be used for peatland rewetting and paludiculture, and providing incentives and rewards through LULUCF accounting rules. At the same time, an accurate inventory of peatland GHG emissions is needed to evaluate peatland rewetting as a cost-effective mitigation measure. In this last context, restoration of higher water tables in peat areas not only slows carbon loss but may also promote their value for above-ground (plant, insect, bird) biodiversity and support Europe's commitment to the Convention on Biological Diversity and the RAMSAR Convention.

7.5 Soils' multi-functional ecosystem services

As described earlier, soils' ecosystem services are directly and indirectly related to the soil biota and biodiversity. A better understanding of the multiple ecosystem services provided by soils extends the range of stakeholders affected by degradation of soils much beyond the agricultural sector. For instance, many business supply chains also depend on soil (Davies, 2017), so the current global trend of soil degradation across 12 million hectares per year (UN Convention to Combat Desertification, 2016) threatens businesses' ability to meet the growing global needs for food and resources as populations grow and diets change. Soils underpin many industries that use plant or animal products in their supply chains: not only food and energy but also clothes and pharmaceuticals. This combines with public interest in healthy food, protection from disease and cultural interest in green parks, natural habitats and wildlife to significantly broaden the stakeholders with a link to soil and its sustainability (Figure 7.1).

While this link is increasingly recognised in the UN through FAO activities, these wider linkages are yet to be recognised by other bodies. For instance, the World Economic Forum risk perception survey[32] includes extreme weather, water scarcity and climate change but not soil sustainability. The vulnerability of supply chains to loss of soil functions (Davies, 2017) suggests that soil sustainability status should at least be included in supply chain risk assessments and sustainability reporting.

Neither is soil sustainability a specific SDG; its importance is mentioned in four targets (including sustainable food production and zero land degradation), but not as an individual factor to be considered in water security or climate change. Soils' interdisciplinary ecosystem services contribute to the SDGs, but many agronomic, hydrological and climatological models use standardised, elementary soil data or no reliable soil data at all. An interdisciplinary approach involving soil scientists as research partners is needed to characterise the dynamic and living soil–water–plant–atmosphere system, and in identifying ways of meeting the SDGs.

IPBES (2018a) noted that the strong two-way interaction between climate change and land degradation, with their effects on ecosystem services, means that these issues are best addressed in a coordinated way. Some activities aimed at climate change mitigation can increase the risk of land degradation and biodiversity loss, for example expansion of bioenergy crops. Planting trees where they did not historically occur (afforestation) can have an impact similar to deforestation, including reduction in biodiversity and loss of food production and water yield.

7.6 Soils and agricultural policy

As discussed in section 4.2, the CAP, as well as the European Innovation Platform initiatives[33], can contribute to increasing soil biodiversity and SOC in agriculture. Additional environmental incentives such as requiring soil surfaces to be always covered with vegetation could be considered in a coming reformulation of the CAP beyond 2020, seeking

[31] https://ec.europa.eu/agriculture/direct-support/cross-compliance/farm-advisory-system_en
[32] The Global Risks Report 2018, 13th Edition.
[33] https://ec.europa.eu/eip/agriculture/en/focus-groups

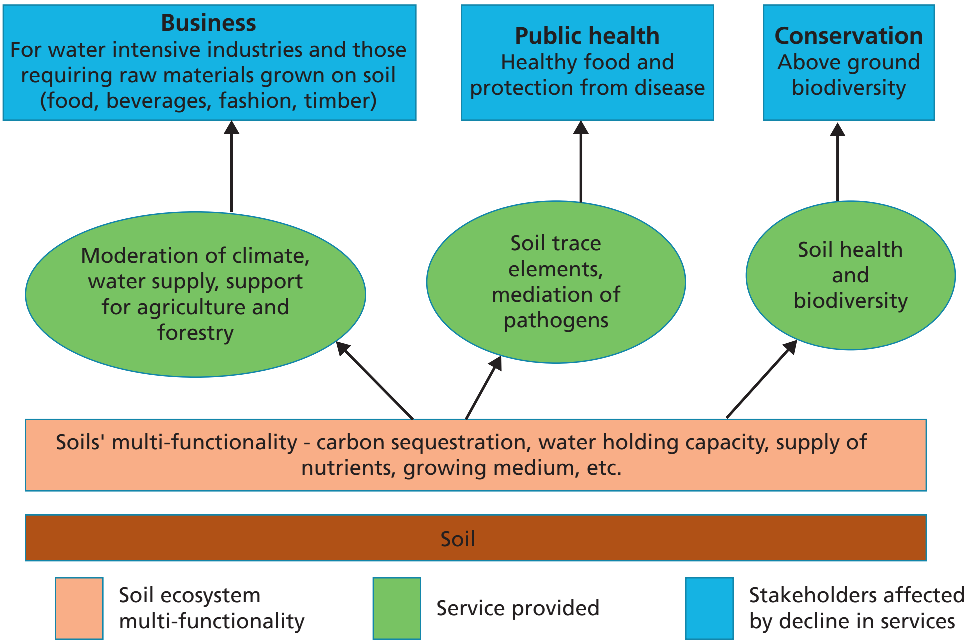

Figure 7.1 Links between soil conditions and stakeholders in society.

to build on the many examples of successful soil conservation and innovative management plans that have already been applied (see, for example, Schwilch *et al*., 2012), as well as findings from evaluations of the current CAP greening (Brady *et al*., 2017a; EU, 2017) and emerging global knowledge on sustainable land management (e.g. within the World Overview of Conservation Approaches and Technologies (Cherlet *et al*., 2018)). The implementation of the new CAP offers opportunities to integrate science and to develop policies such that maintaining the required high rates of food production will not lead to soils being damaged.

Specific approaches that emerge from the expert group and the analysis in section 4.2 include the following.

- The 2013 CAP revision placed the joint provision of private and public goods at the core of policy, a theme endorsed by this report. Evidence of the extent to which these aims are being achieved is now emerging from initial evaluations. Options to improve performance and beneficial effects on soils include encouraging crop rotation within the crop diversification requirement and incorporating wider areas of grassland in the permanent grassland protection requirement.

- Encouraging local production enables people and food producers to relate to and commit to local food production with local soils (as well as reducing food transportation). A regained interest in regional products (see, for example, Schmitt *et al*., 2017, 2018) could be facilitated by ensuring that EU regulations do not disadvantage local production.

- Encouraging labelling schemes which show that farmers have managed their soil to reduce erosion, enhance fertility and maintain good soil structure in a sustainable and environmentally sensitive way (e.g. the UK's LEAF (Linking Environment And Farming)).

- We have already noted (section 7.4) the increased demand for expert advice. Farmers' awareness of soil health, functions and soil enhancement approaches varies and influences their willingness to apply new practices, with the level of support and sense of community positive factors (Sautter *et al*., 2011). Good personal relationships with trusted advisers are a key factor in encouraging uptake of good soil management (Morris *et al*., 2014), thus strengthening the case for re-establishing expert advisory and extension services. These can disseminate examples of good soil management practice and effective monitoring approaches (see, for example, Dolman *et al*., 2014).

- In the discussion of research needs and new technologies, we note:

  - The role of precision agriculture that can enhance crop growth efficiency; linking databases enables information storage at scales as small as patches within fields and applies not just to high input-output farming, but also in organic and ecologically intensive farming.

  - There is a role for leading centres where innovative agricultural production systems combine economic, social and environmental requirements and identify management strategies to optimise the whole dynamic soil–water–plant–climate system.

- Socio-economic studies are needed to identify incentives that stimulate farmers to produce both food and multiple ecosystem services, and how multi-functional contributions of soil to public goods and services might be accounted for in prices for renting or selling.

- Research on how degraded soil can be restored for multi-functional use (Allan *et al*., 2015).

7.7 Raising awareness of soil natural capital

Although the ITPS review of global soils saw Europe's soils as being less degraded than other regions, JRC (2012) estimated that in the 1990s 105 million hectares were affected by water erosion and 42 million hectares by wind erosion. Indeed, a model of soil erosion by water constructed by the JRC estimated that the surface area affected by water erosion in the EU-27 countries was 1.3 million square kilometres, with almost 20% subject to soil loss in excess of 10 tonnes per hectare per year. Conventional wisdom is that farmers have a direct interest in maintaining the productivity of their soils (an argument often used politically as to why there is no need for governments to intervene), but the scale of erosion suggests that soil conservation measures are not being properly adopted or implemented. This may be because conservation measures do not necessarily directly increase yields or efficiencies in the short term, since they are aimed at avoiding detrimental effects that in general only become visible over longer time-scales. Maximising yields over the short term may reflect a market failure to cater for longer-term soil sustainability, as a result of which society loses the common goods and services when soils and their natural capital are neglected (Brady *et al*., 2015).

Addressing this requires recognition that protecting the value of soil needs long-term investment as soil fertility and soil carbon take decades to build. The values of soil capital also need a mechanism through which they can be transferred to farmers and their profits with appropriate incentives (TEEB, 2015). IPBES (2018a) points to the need to avoid incentives that promote soil degradation and to devise positive incentives to reward sustainable land management. Such incentives should ensure that the environmental, social and economic costs of unsustainable land use and production practices are reduced at the same time as making farmers' businesses sustainable. Incentives for safeguarding soil health and mainstreaming the values of ecosystem services can help to avoid, reduce and even reverse land degradation. Such incentives are partly present in the CAP but not yet implemented to a degree that ensures healthy and sustainable soils. Mainstreaming the values of soil natural capital and the resulting soil ecosystem services into decisions taken by farmers will have cascading results for society in reducing costs of environmental damage.

Such measures can also be helped by a greater awareness of the extent and seriousness of land degradation. Here, the increasing spatial disconnect between consumers and the ecosystems that produce the food and other commodities on which they depend can lead to a lack of awareness and understanding of the implications of consumption choices for land degradation. Previous information campaigns associated with 2015's International Year of Soils[34] helped to raise awareness that activities preventing or combating land degradation, soil erosion and desertification are also beneficial to human well-being and are all interlinked with climate change, agriculture, water conservation, air quality and physical planning. The EU, national agencies and local authorities could provide a supportive policy environment for a soil awareness and education strategy (using social media, practical exercises for home and gardens, etc.) to reach all age groups, and demonstrate the ways in which soils contribute to human well-being, thus strengthening community support for stakeholders to manage soils sustainably.

[34] The International Year of Soils (2015) generated many initiatives for outreach on the role of soils. For example, in the Netherlands a citizen science project takes place around 4 October (World Animal Day) and encourages a wider audience to count soil animals in private gardens. The UK Urban Garden Movement, Czech parks, and education in schools increase awareness of the importance of fully functional soil and how best to manage it (Bardgett, 2016).

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Annex 2 Glossary

CAP	Common Agricultural Policy
COP	Conference of the Parties (UNFCCC)
EASAC	European Academies' Science Advisory Council
EC	European Commission
EFA	Ecological focus area
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
ITPS	Intergovernmental Technical Panel on Soils
JRC	Joint Research Centre (EU)
KNAW	Royal Netherlands Academy of Arts and Sciences (Koninklijke Nederlandse Akademie van Wetenschappen)
LIFE	Funding programme of the EU
LULUCF	Land use, land-use change, and forestry
RAMSAR	Convention on wetlands of international importance especially as waterfowl habitat
SDG	Sustainable Development Goals (United Nations)
SOC	Soil organic carbon
SOM	Soil organic matter
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

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