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Review article

Climate change in Europe. 2. Impact on soil. A review*

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Abstract – This article reviews major impacts of climate change on soil.

climate change / soil / water / nutrient / carbon / desertification / pH / organic matter / CO_2 / soil biodiversity / soil erosion / soil moisture / soil organic matter

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1. INTRODUCTION

Climate is an important factor in soil development and a major driver of the processes of soil formation. At the same time, changes in the bio-physical nature of soil, due to rising temperatures, changing precipitation intensity and frequency and more severe droughts, are likely to release substantial amounts of greenhouse gases. However quantitative information, from observations and modelling of the impacts of climate change on soil and the various related feedbacks, is very limited. To date, assessments have relied mainly on local case studies that have analysed how soil reacts under changing climate in combination with evolving agricultural and forest practices. Indicators with full European coverage, to help policymakers identify appropriate adaptation measures, are absent, as can be seen from the limited number of indicators in this chapter. There is an urgent need to address this unsatisfactory situation through the establishment of appropriate monitoring schemes.

Soil has many biological, chemical and physical characteristics with a marked spatial and temporal variability. Changing climate will affect these characteristics and may also have

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** Corresponding author: Arwyn.Jones@jrc.it serious consequences for the well-being of people, who are dependent on the broad range of environmental goods and services regulated by soil. Soil is one of the key life-support systems on the planet, responsible for major ecological and other functions such as:

- supply of water and nutrients for plant growth and food production (ecosystems, agriculture and forestry);
- regulation of the water cycle;
- nutrient cycles, storage of carbon and regulation of greenhouses gases;
- trapping of contaminants (buffering capacity);
- source of raw material (e.g. clay minerals);
- preservation of cultural heritage;
- habitats for animal and plant species, maintaining their biological and genetic diversity;
- support to human settlements, providing a basis for buildings and infrastructures, disposal of waste material, slope stability.

The EU's Thematic Strategy for Soil Protection (EC, 2006) has stated that several soil functions are under serious pressure in many parts of Europe. The understanding of soil as an important contributor to water systems, the global carbon cycle and other systems is still evolving and needs to be developed further; so far soil has been perceived mainly in the context of arable land and fertility for crop production. The perception of soil as an environmental medium providing substantial goods and services for all land and aquatic ecosystems has developed over recent decades but still with a focus on economic aspects and valuing different types of land use.

Significant projected changes in precipitation patterns will affect soil formation and functions. Soil as part of the soil-water-plant system contributes and influences changes in groundwater recharge, water quality through buffering capacity, plant growth and evapotranspiration through water available to roots, and run-off through retention capacity. This is vital for land and water management. Better and more quantitative understanding of this system is needed to improve forecasts and possible response actions. Indicators with sufficient resolution in time and space are needed to link observations and new models which include climate change.

Based on the current limited amount of observations and some modelling, the following issues are highlighted in this chapter. Soil organic matter drives the majority of soil functions; any reduction can lead to a decrease in fertility and biodiversity (see Fig. 1), a loss of soil structure, reduced water retention capacity and increased risk of erosion and compaction. Changes in rainfall and wind patterns will lead to an increase in erosion in vulnerable soils which often suffer from low organic matter content. Climate change will further increase the risk of desertification, which is already affecting southern Europe and is expected to move gradually northward (see Fig. 2). Desertification[1] is an advanced stage of land degradation where the soil has lost part of its capability to support human communities and ecosystems. By absorbing water, soil organic matter can contribute to the mitigation of flooding following extreme rainfall events, while storing water in the event of more frequent and severe droughts. However evaluation of the impact of climate change remains difficult. Changes to features such as texture and mineralogical composition will only occur over long 'geological' time spans, while properties such as pH, organic matter content or microbial activity will show a more rapid response. In addition, the response of a particular soil type may be both positive and negative, depending on its function. Rising temperatures and precipitation may support increased agricultural productivity but may also increase the risk of erosion.

Soil can also act as a carbon sink, absorbing carbon dioxide from the atmosphere and thus mitigating global warming. In areas with low temperatures and sufficient moisture, the decomposition of dead biomass (leaves, stems, roots of plants) is reduced, leading to accumulations of soil organic matter. Increasing temperatures will accelerate decay rates, leading to increased carbon dioxide and methane emissions from soil. Appropriate wetland management and land-use practices should thus be enhanced to maintain or enhance soil carbon stocks.

2. SOIL ORGANIC CARBON

Key messages

- Soil in the EU contains around 71 gigatonnes of organic carbon, nearly 10% of the carbon accumulated in the atmosphere. An increase in temperature and a reduction in moisture tend to accelerate the decomposition of organic material, leading to a decline in soil organic carbon stocks in Europe and an increase in CO_2 emissions to the atmosphere. This could wipe out all the savings that other sectors of the economy are achieving to reduce anthropogenic greenhouse gas emissions.
- Losses of soil organic carbon have already been observed in measurements in various European regions over the past 25 years.
- The projected changes in the climate during the 21st century will change the contribution of soil to the CO_2 cycle in most areas of the EU. Adapted land-use and management practices could be implemented to counterbalance the climate-induced decline of carbon levels in soil.

2.1. Relevance

Organic carbon in the soil is a dynamic part of the carbon cycle, which includes the atmosphere, water and constituents of the above- and below-ground biosphere. The main source of organic carbon is organisms that synthesise their food from inorganic substances (autotrophic), such as photosynthesising plants. In this process atmospheric carbon is used to build organic materials and enters the soil layers through decomposition and the formation of humus.

Climatic conditions strongly influence both the trends and rates of accumulation and transformation of organic substances in the soil. Increases in temperature and aridity (see

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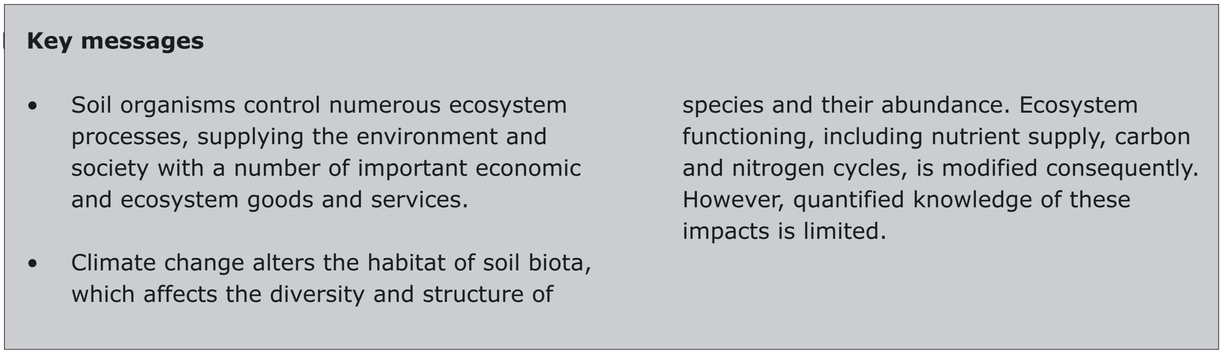
[1] Desertification is defined by the United Nation Convention to Combat Desertification (UNCCD) as 'land degradation in arid, semiarid and sub-humid areas resulting from various factors, including climatic variations and human activities' (UNCCD, 1997).

Figure 1. The impacts of climate change on soil biodiversity.



Key messages

- Soil organisms control numerous ecosystem processes, supplying the environment and society with a number of important economic and ecosystem goods and services.
- Climate change alters the habitat of soil biota, which affects the diversity and structure of species and their abundance. Ecosystem functioning, including nutrient supply, carbon and nitrogen cycles, is modified consequently. However, quantified knowledge of these impacts is limited.

Soil biodiversity controls several processes such as organic matter and nutrient cycling, degradation of organic pollutants, nitrogen biotic fixation, plant-microbe symbiotic nutrient uptake, plant growth promotion and plant protection, maintenance of soil physical structure and pollination. Perhaps the most important potential impacts of climate change on soil relate to below-surface biodiversity, which ranges from bacteria, fungi, microbes, microscopic invertebrates to larger invertebrates such as ants, earthworms and termites. Because the majority of soil and sediment biodiversity is hidden beneath the surface, this species richness remains mostly unknown, poorly mapped, and rarely considered in models of climate change or adaptation plans (Behan-Pelletier and Newton, 1999; Paustian et al., 2000; Wolters et al., 2000). Yet, the biological diversity of soils is estimated to be greater than that in above-ground systems (Wall and Virginia, 2000). This vast biodiversity is critical to the well-being of all life, both below and above the surface: it provides ecosystem services such as filtering of air and water, control of erosion, regulation of the global cycles of nutrients, carbon, nitrogen, and phosphorus (Brussard et al., 1997), waste recycling through decomposition, bio-control of plant and human pests, and soil fertility.

The SCOPE Committee on Soil and Sediment Biodiversity and Ecosystem Functioning recently synthesized knowledge on below-ground species diversity and ecosystem functioning in a series of international workshops (Behan-Pelletier and Newton, 1999; Brussaard et al., 1997, 2007; Hooper et al., 2000; Wolters et al., 2000). Most of the stages involved in soil ecosystem processes are performed by groups of species from many phyla, resulting in high species redundancy (different species performing same ecosystem process). Some critical processes are performed by a few 'keystone' taxa (e.g. mostly larger invertebrates such as termites, earthworms, enchytraeids).

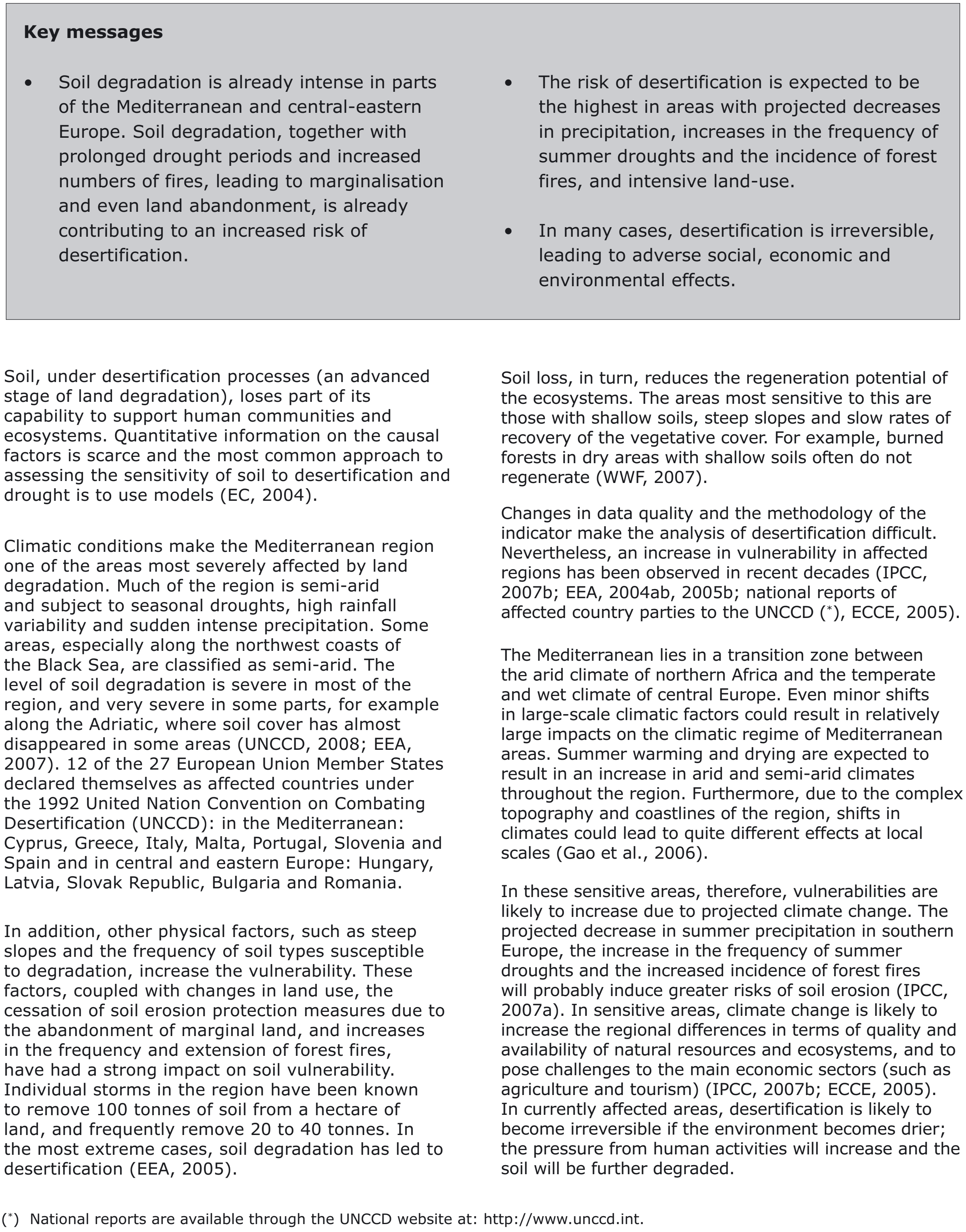
Soils contain a large amount of carbon, and CO_2 release to the atmosphere depends to a large degree on the activities of soil biota. Soil biota regulate the decay process or decomposition, which directly affects carbon level in soils. Climate-induced loss of key invertebrates in a variety of low-diversity ecosystems that are widespread throughout the world can contribute to significant changes in carbon cycle and hence carbon pools and fluxes through the modification of ecosystem functioning (Ayres et al., 2008; Barrett et al., 2008; Poage et al., 2008).

Our understanding of the soil species involved in decomposition and whether individual soil species have an effect on ecosystem processes is limited. For example, the relationship between the number of species of any soil group and an ecosystem process, such as the rate of decomposition, has not been established in field studies. Thus when soils are degraded, knowledge of the effects on their biological diversity and ecosystem services is largely missing.

Climate change can affect soil biodiversity directly, by altering the soil temperature and moisture, and indirectly, altering vegetation communities and productivity, and the rate of organic matter decomposition. Not all soil biota, however, will be affected by climate change to the same extent; according to Wall and collaborators (2001), termites and enchytraeids will be the most affected. Effects of warming may be larger in ecosystems that are currently limited by temperature, such as the arctic tundra and semi-polar deserts (Swift et al., 1998; Convey et al., 2002), and mountain areas. In research carried out in the Swedish Lapland using the environmental manipulation approach, it has been demonstrated that a temperature rise results in an increase in bacteria, fungi and nematode density, but a reduction of biodiversity (Ruess et al., 1999).

The interrelation between soil fauna and vegetation, for example forests, is critical (Binkley and Cristian, 1998; Gonzalez and Seastedt, 2001; Hooper et al., 2000). The Global Litter Invertebrate Decomposition Experiment (http://www.nrel.colostate.edu/projects/glide/) shows that the soil litter and organisms found under different tree species are highly specific. The loss of tree species due to climate change might cause the loss of the associated soil biodiversity. These ecosystem transformations can affect the capacity of the soil to store carbon. Once soil biodiversity and the species and services it provides are lost or damaged, remediation and restoration takes an extremely long time and in some instances the loss of some species is irreversible.

Figure 2. Soil degradation and loss under desertification.



Key messages

- Soil degradation is already intense in parts of the Mediterranean and central-eastern Europe. Soil degradation, together with prolonged drought periods and increased numbers of fires, leading to marginalisation and even land abandonment, is already contributing to an increased risk of desertification.
- The risk of desertification is expected to be the highest in areas with projected decreases in precipitation, increases in the frequency of summer droughts and the incidence of forest fires, and intensive land-use.
- In many cases, desertification is irreversible, leading to adverse social, economic and environmental effects.

Soil, under desertification processes (an advanced stage of land degradation), loses part of its capability to support human communities and ecosystems. Quantitative information on the causal factors is scarce and the most common approach to assessing the sensitivity of soil to desertification and drought is to use models (EC, 2004).

Climatic conditions make the Mediterranean region one of the areas most severely affected by land degradation. Much of the region is semi-arid and subject to seasonal droughts, high rainfall variability and sudden intense precipitation. Some areas, especially along the northwest coasts of the Black Sea, are classified as semi-arid. The level of soil degradation is severe in most of the region, and very severe in some parts, for example along the Adriatic, where soil cover has almost disappeared in some areas (UNCCD, 2008; EEA, 2007). 12 of the 27 European Union Member States declared themselves as affected countries under the 1992 United Nation Convention on Combating Desertification (UNCCD): in the Mediterranean: Cyprus, Greece, Italy, Malta, Portugal, Slovenia and Spain and in central and eastern Europe: Hungary, Latvia, Slovak Republic, Bulgaria and Romania.

In addition, other physical factors, such as steep slopes and the frequency of soil types susceptible to degradation, increase the vulnerability. These factors, coupled with changes in land use, the cessation of soil erosion protection measures due to the abandonment of marginal land, and increases in the frequency and extension of forest fires, have had a strong impact on soil vulnerability. Individual storms in the region have been known to remove 100 tonnes of soil from a hectare of land, and frequently remove 20 to 40 tonnes. In the most extreme cases, soil degradation has led to desertification (EEA, 2005).

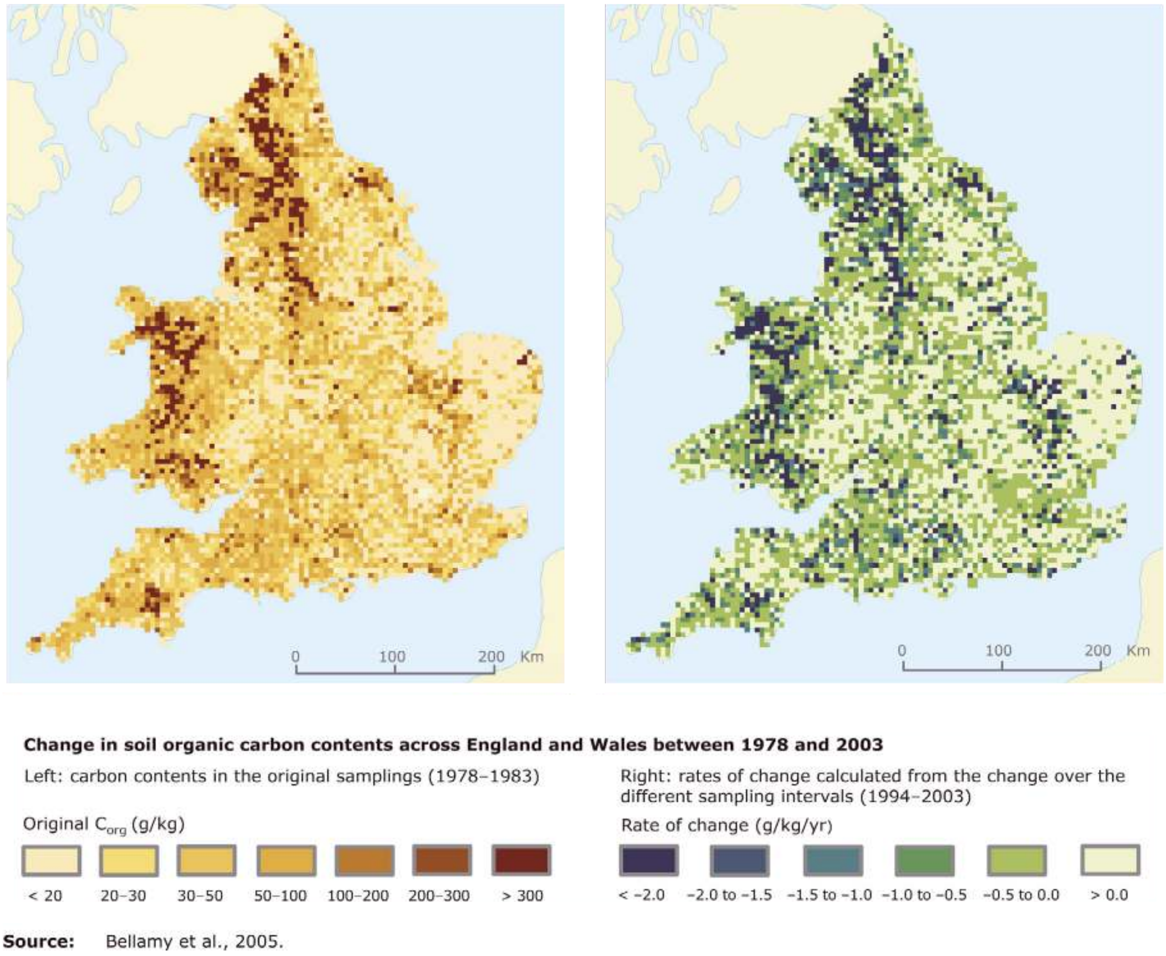
Soil loss, in turn, reduces the regeneration potential of the ecosystems. The areas most sensitive to this are those with shallow soils, steep slopes and slow rates of recovery of the vegetative cover. For example, burned forests in dry areas with shallow soils often do not regenerate (WWF, 2007).

Changes in data quality and the methodology of the indicator make the analysis of desertification difficult. Nevertheless, an increase in vulnerability in affected regions has been observed in recent decades (IPCC, 2007b; EEA, 2004ab, 2005b; national reports of affected country parties to the UNCCD (*), ECCE, 2005).

The Mediterranean lies in a transition zone between the arid climate of northern Africa and the temperate and wet climate of central Europe. Even minor shifts in large-scale climatic factors could result in relatively large impacts on the climatic regime of Mediterranean areas. Summer warming and drying are expected to result in an increase in arid and semi-arid climates throughout the region. Furthermore, due to the complex topography and coastlines of the region, shifts in climates could lead to quite different effects at local scales (Gao et al., 2006).

In these sensitive areas, therefore, vulnerabilities are likely to increase due to projected climate change. The projected decrease in summer precipitation in southern Europe, the increase in the frequency of summer droughts and the increased incidence of forest fires will probably induce greater risks of soil erosion (IPCC, 2007a). In sensitive areas, climate change is likely to increase the regional differences in terms of quality and availability of natural resources and ecosystems, and to pose challenges to the main economic sectors (such as agriculture and tourism) (IPCC, 2007b; ECCE, 2005). In currently affected areas, desertification is likely to become irreversible if the environment becomes drier; the pressure from human activities will increase and the soil will be further degraded.

(*) National reports are available through the UNCCD website at: http://www.unccd.int.


Change in soil organic carbon contents across England and Wales between 1978 and 2003

Left: carbon contents in the original samplings (1978–1983)

Right: rates of change calculated from the change over the different sampling intervals (1994–2003)

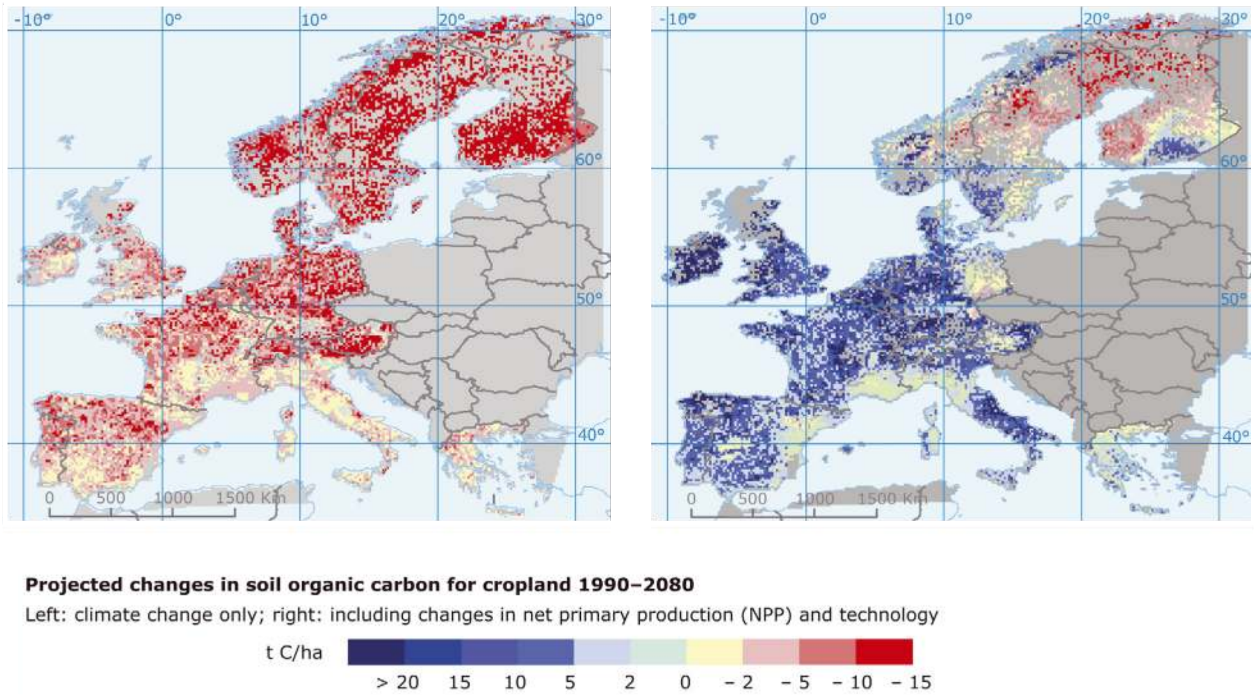
Source: Bellamy et al., 2005.

Figure 3. Changes in soil organic carbon content across England and Wales between 1978 and 2003.

Fig. 2) lead to a decrease in the amount of organic carbon in soils in affected areas. Lower levels of organic carbon in the soil are generally detrimental to soil fertility and water retention capacity and tend to increase soil compaction, which leads to increases in surface water runoff and erosion. Other effects of lower organic carbon levels are a depletion of biodiversity and an increased susceptibility to acid or alkaline conditions. The projected changes will accelerate the release of CO_2 from the soil, contributing to higher concentrations in the atmosphere (Janssens, 2004; Bellamy, 2005). The main measures to reduce the detrimental effect of higher temperatures combined with lower soil moisture on the amount of soil organic carbon are changes in land cover and adaptation of land-management practices (Liski et al., 2002; Janssens et al., 2004; Smith et al., 2005, 2006). Under given climatic conditions, grassland and forests tend to have higher stocks of organic carbon than arable land and are seen as net sinks for carbon (Vleeshouwers and Verhagen, 2002). Land-management practices aim at increasing net primary production and reducing losses of above-ground biomass from decomposition. Adaptive measures on agricultural land are changes in farming practices, such as a reduction in tilling or retaining crop residues after harvesting.

2.2. Past trends

Figure 3 shows the change in soil organic carbon content between 1978 and 1983 (Bellamy et al., 2005). The study showed an estimated annual soil carbon loss for England and Wales of around 4.4 million tonnes. Initial results indicate that the dominant driver of soil carbon loss was changes in land use or land management practices, primarily by the conversion of land for the production of agricultural crops. A survey of Belgian croplands (210 000 soil samples taken between 1989 and 1999) indicates a mean annual loss in organic carbon of 76 $gC\,m^{-2}$ (Sleutel et al., 2003). A large-scale inventory in Austria estimated that croplands were losing 24 $gC\,m^{-2}$ annually (Dersch and Boehm, 1997). The general intensification of farming in the past is likely to have exceeded the effect of changes in the climate on soil organic carbon on agricultural land. Peat lands in Europe have been a significant sink for atmospheric CO_2 since the last glacial maximum. Currently they are estimated to hold about 42 Gt carbon, about 60% of all carbon stocked in European soils, and are therefore a considerable component of the European carbon budget (Byrne et al., 2004). The annual loss of carbon due to drainage of peat lands is in the range of 0 to 47 $gC\,m^{-2}$ (Lappalainen, 1996).



Projected changes in soil organic carbon for cropland 1990–2080

Left: climate change only; right: including changes in net primary production (NPP) and technology

Source: Smith et al., 2005.

Figure 4. Projected changes in soil organic carbon for cropland 1990–2080.

2.3. Projections

The amount of organic carbon in the soil is determined mainly by the balance between net primary production (NPP) from vegetation and the rate of decomposition of the organic material. Without an increase in NPP, soil carbon for cropland may decrease by 9 to 12 $\mathrm{t\,C\,ha^{-1}}$. When taking account of changes in NPP and technological advances, the amount of organic carbon on cropland could increase by 1–7 $\mathrm{t\,C\,ha^{-1}}$ (Smith et al., 2005). Figure 4 shows that climate change may cause loss (red) of soil organic carbon for most areas in Europe. This decline could be reversed (blue) if adaptation measures in the agricultural sector to enhance soil carbon were implemented. It should be noted that these modelled projected changes are very uncertain.

3. SOIL EROSION BY WATER

Key messages

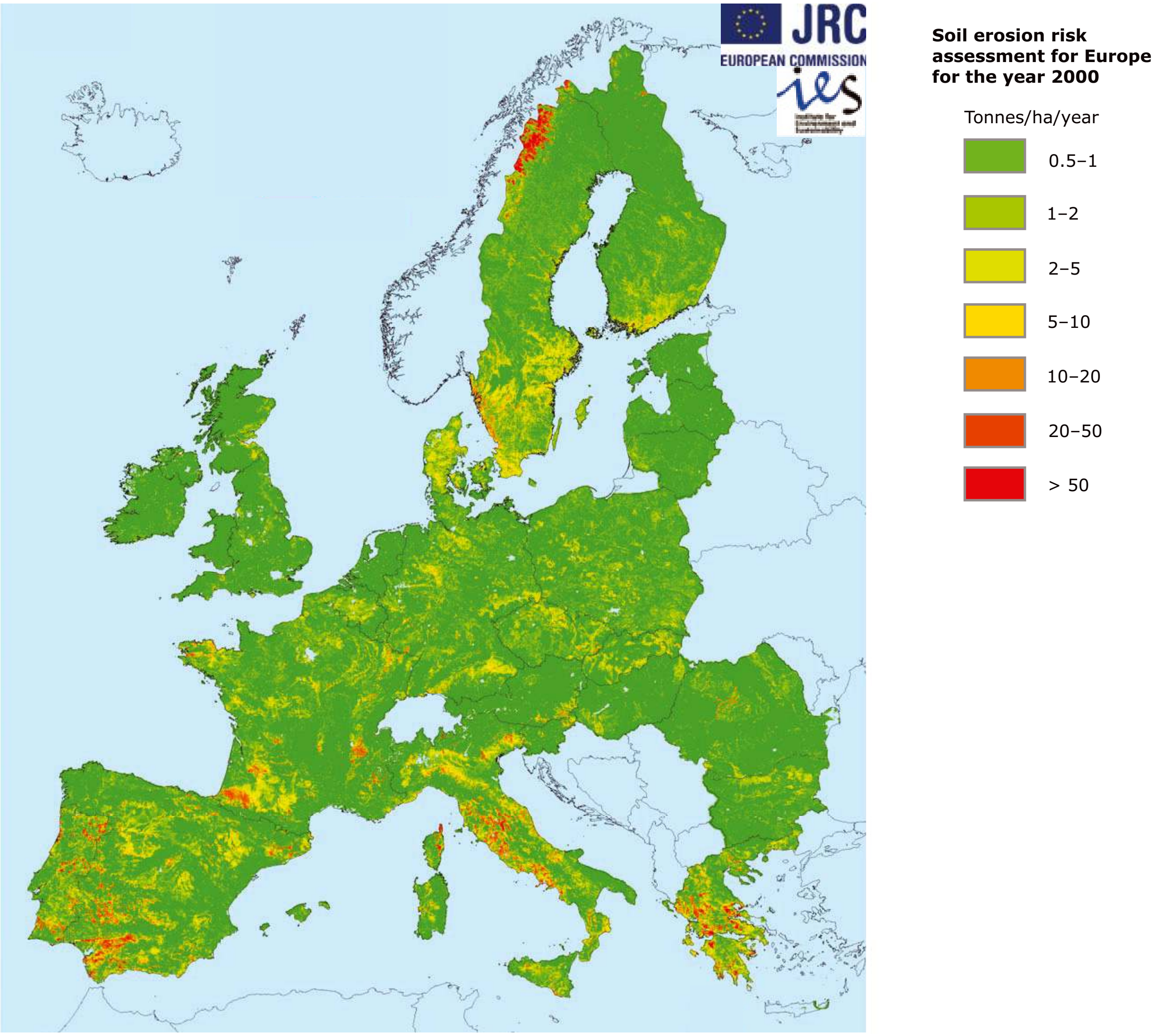
- An estimated 115 million hectares, 12% of the total EU land area, are subject to water erosion.
- The projected changes in the climate during the 21st century, with increased variations in rainfall pattern and intensity, will make soils more susceptible to erosion.
- The off-site effects of soil erosion will increase with climate change and related changes in rainfall pattern and intensity.

3.1. Relevance

Climate change will influence soil erosion processes. Excess water due to intense or prolonged precipitation can cause tremendous damage to soil. Sheet-wash, rill and gully development can strip the topsoil from the land, thus effectively destroying the capability of the soil to provide economic or environmental services. Favis-Mortlock and Boardman (1995), using the Erosion Productivity Impact Calculator (EPIC) model (Williams and Sharpley, 1989), found that a 7% increase in precipitation could lead to a 26% increase in erosion in the United Kingdom. In high mountain regions like the Alps, decreasing permafrost (observed and projected) can lead, for example, to more landslides with substantial impact on infrastructure (roads, railways, cable cars) and economic sectors like tourism.

Many of the soil erosion risk models contain a rainfall erosivity factor and a soil erodibility factor that reflect average-year precipitation conditions. However, currently available values for the rainfall erosivity and soil erodibility factors may inadequately represent low-probability return-period storms and the more frequent and intense storms under projected climate change.

The relationship between climate change and soil erosion is complex and needs to be better defined, investigated and monitored in order to have a clear picture of future trends. Measurements and models with more detailed temporal and spatial distribution of precipitation and impacts on soil erosion or risk of erosion should be developed, as should indicators for assessing appropriate measures.



Note: Results obtained with application of two models (PESERA and RUSLE, JRC). Areas with yellow and red shades are highly vulnerable to soil erosion by water.

Source: Joint Research Centre (JRC), INRA (France), (http://eusoils.jrc.it/ESDB_Archive/serae/Serae_data.html).

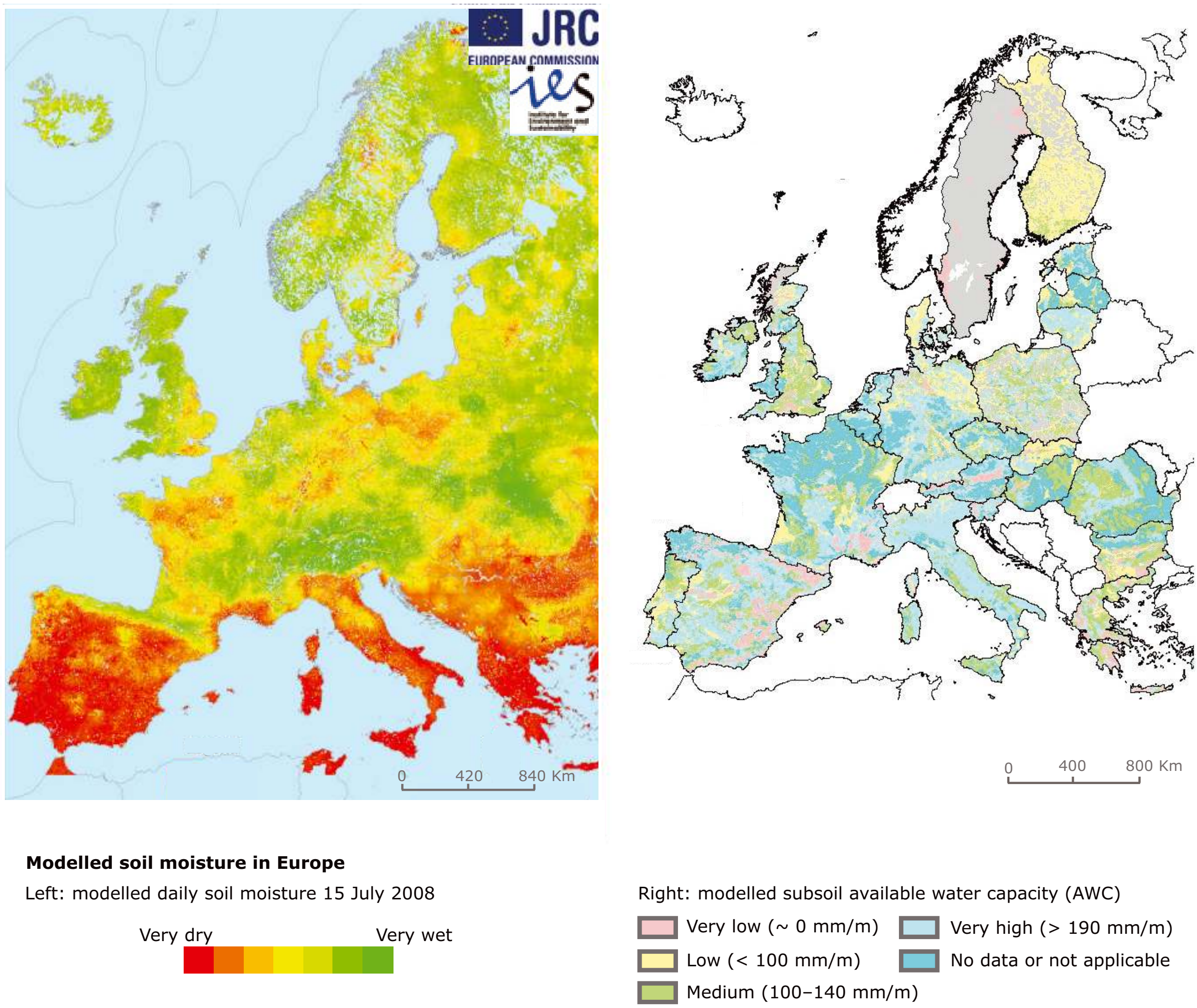
Figure 5. Soil erosion risk assessment for Europe for the year 2000.

3.2. Past trends

Past trends for erosion are not available on the European scale. Based on EU-wide modelling, an estimated 115 million hectares or 12% of the total EU land area is (in 2000) subject to water erosion (see Fig. 5). In this assessment the risk of erosion by water was calculated by using yearly average values for precipitation. However such risks are in fact to a large extent determined by extreme precipitation events (e.g. daily, hourly). The uncertainty of this modelled erosion risk is therefore high, especially at the local level.

3.3. Projections

Several studies have been conducted to model the effects of future climate change on soil erosion (e.g. Kirkby et al., 2004). These show a non-linear spatial and temporal response of soil erosion to climate change, with relatively large increases in erosion during wet years compared with dry years, and sporadic increases spatially. Erosion is projected to increase with increases in precipitation amount and intensity, and to decrease with increases in ground cover and canopy cover (IPCC, 2007a).



Note: Left: example of a forecast of topsoil moisture (15 July, 2008), right: subsoil available water capacity derived from modelling data.

Sources: European Soil Data Centre (ESDAC), http://eusoils.jrc.ec.europa.eu/library/esdac/index.html (left); and European Flood Alert System (EFAS) http://efas.jrc.ec.europa.eu/ (right).

Figure 6. Modelled soil moisture in Europe.

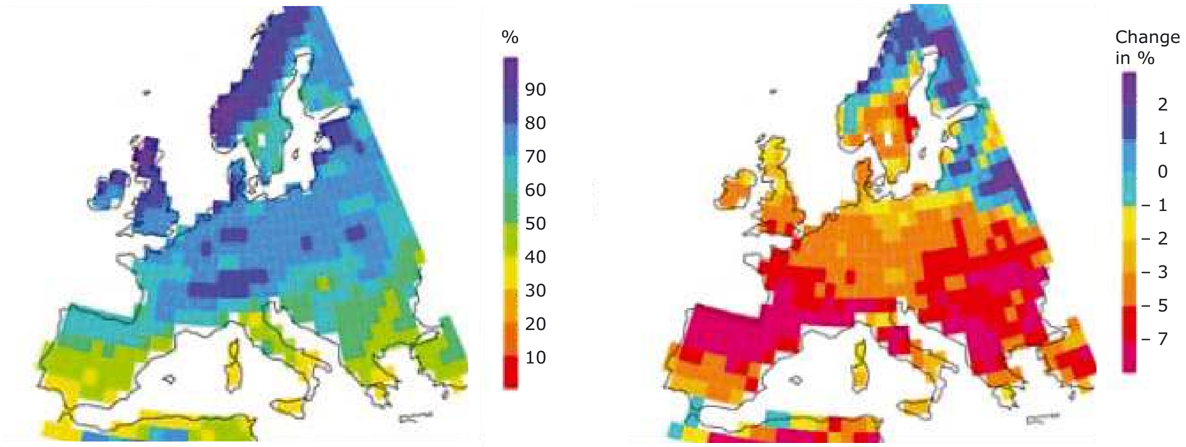
4. WATER RETENTION

Key messages

- Water retention capacity and soil moisture content will be affected by rising temperatures and by a decline in soil organic matter due to both climate change and land-management changes.
- Projections (for 2070–2100) show a general reduction in summer soil moisture over most of Europe, significant reductions in the Mediterranean region, and increases in the north-eastern part of Europe.
- Maintaining water retention capacity is important to reducing the impacts of intense rainfall and droughts, which are projected to become more frequent and severe.

4.1. Relevance

Soil water retention is a major soil hydraulic property that governs soil functioning in ecosystems and greatly affects soil management. Soil moisture forms a major buffer against flooding, and water capacity in subsoil is a major steering factor for plant growth. The effects of changes in soil water retention depend on the proportions of the textural components and the amount of organic carbon present in the soil. At low carbon contents, an increase in carbon content leads to an increase in water retention in coarse soils and a decrease in fine-textured soils. At high carbon contents, an increase in carbon content results in an increase in water retention for all soil textures (Rawls et al., 2003). Soil organic matter can absorb up to twenty times its weight in water. Changes in temperature



Note: Simulated soil moisture by ECHAM5/T106L31 for the baseline period (1961–1990) (left) and relative changes in % under the IPCC A2 scenario (2070–2100) (right).

Source: Calanca et al., 2006.

Figure 7. Modelled summer soil moisture (1961–1990) and projected changes (2070–2080) over Europe.

result in changes in evapotranspiration, soil moisture, and infiltration. These will also influence groundwater recharge by changing the ratio of surface run-off to infiltration. Projections for climate change indicate greater droughts in some areas, which might lead to substantial reductions in summertime soil moisture, and more rainfall – even too much – in others, and also increases in the off-site impacts of soil erosion. Maintaining or even enhancing the water retention capacity of soils can therefore play a positive role in mitigating the impacts of more extreme rainfall intensity and more frequent and severe droughts. Harmonised time-series on relevant soil properties are not available but should be developed. The development of projections for the soil characteristics presented here (subsoil available water capacity and topsoil moisture), which depend entirely on soil properties, is difficult due to lack of data to validate the models. Further research is needed using satellite information and linking this to representative observed data.

4.2. Past trends

There is no clear indication on past trends for water retention across the EU except for local field data. However several models can be used to assess soil moisture, for both subsoil and topsoil. Figure 6, right shows the subsoil available water capacity derived from modelling data. Capacity is high in north-western and central Europe and low in parts of the Mediterranean. Forecasts of soil moisture trends (an example for 15 July 2008 is shown in Fig. 6, left) show very wet topsoils in north-western and central Europe and dry topsoils in the Mediterranean.

Long-term past trend analysis of these modelled characteristics is not possible due to lack of information over a sufficient time-period for the main soil properties that are the input parameters for the models used.

4.3. Projections

Figure 7 presents summer soil moisture over continental Europe for the IPCC A2 scenario (2070–2100), compared with 1961–1990. The projections show a general reduction in summer soil moisture over most of Europe and significant reductions in the Mediterranean region, while the north-eastern part of Europe will experience an increase in summer soil moisture.

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