4.3 Soil carbon change (in mineral soils, organic soils and inorganic carbon)

Soil hosts the largest carbon pool in the terrestrial ecosystem, playing an essential role in the global carbon cycle and the regulation of climate change. Soil carbon is solid carbon stored in soils, existing in organic and inorganic forms. An important distinction between these two forms is that inorganic carbon has a much higher potential for permanence in soils than organic carbon. Soils are characterised as mineral or organic based on their organic matter content.

Mineral soils form most of the world's cultivated land and may contain a trace of or up to 20 % organic matter. Organic soils are naturally rich in organic matter, principally due to vegetation and climate, and are distinguished from mineral soils by meeting specific criteria outlined in the IPCC guidelines for national GHG inventories (Drösler *et al.*, 2014) and Food and Agriculture Organization (FAO) guidelines (FAO, 2006). These criteria include a thick organic horizon, a high organic carbon content, and the possibility of water saturation episodes.

4.3.1 Mineral soils

The SOC content of mineral soils varies across Europe, with the highest levels in woodlands. Croplands exhibit the lowest SOC content, posing challenges to achieving EU climate targets due to ongoing carbon loss. Land use changes, includingthe conversion of grasslands to croplands, have a significant impact on SOC stocks, highlighting the need for sustainable land management practices. Climate change and land use change are major drivers of SOC change, influencing soil fertility, water dynamics, GHG emissions, biodiversity and resilience to climate change. Mitigating SOC loss is essential for maintaining soil health, agricultural productivity, and ecosystem stability, highlighting the importance of implementing strategies to enhance soil carbon sequestration and minimise soil degradation.

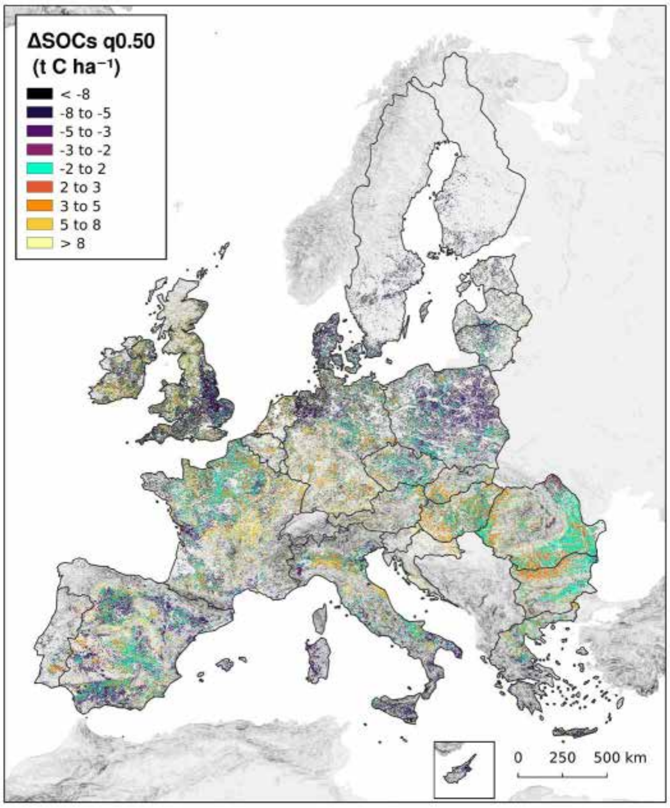
4.3.1.1 Status and trends

Europe exhibits considerable spatial variability in soil types, climates and land uses, leading to diverse patterns in SOC content across regions. Based on the soil measurements from LUCAS, SOC content increases from south-eastern to north-western climatic zones (Fernandez-Ugalde *et al.*, 2022). The highest SOC levels (EU mean = 318 g kg^{-1}) are found in the wetlands of the boreal and Atlantic zones (peatlands). SOC content is also high in woodlands (EU mean = 88 g kg^{-1}), especially in north-western climatic zones (boreal, Atlantic, suboceanic and northern subcontinental). The mean SOC content of grasslands is 40 g kg^{-1}, rising slightly to 55 g kg^{-1} in shrubland. Organic carbon content is the lowest in croplands (EU mean = 18.3 g kg^{-1}) and, unsurprisingly, in bare land (EU mean = 17.3 g kg^{-1}).

Overall, soils are losing carbon as CO_2 (EEA, 2022a), which could hamper the achievement of EU climate targets. SOC changes in agricultural soils across the EU and the United Kingdom from 2009 to 2018 have been comprehensively assessed, showing varied impacts depending on land use and management practices (De Rosa *et al.*, 2023). The total SOC loss from croplands is moderate, representing 0.75 % of their initial stocks and amounting to 70 Mt of carbon from the initial 9.3 Gt of carbon within the first 20 cm of soil. Spatial analysis reveals different changes in SOC across the continent (Figure 6). The median change in SOC content indicates an average decrease of 0.4 t C ha^{-1} for the EU and the United Kingdom combined, with some countries, such as Austria and Slovenia, experiencing increases of up to 3 t C ha^{-1}. The most significant losses, up to – 4.9 t C ha^{-1}, occur in the higher latitudes of northern Europe, where a lower soil clay content correlates with decreased carbon retention capacity.

In contrast, central European regions mostly maintained stable SOC levels over the period studied. The Mediterranean area, characterised by warmer temperatures and less rainfall, showed a broader range of change, from –5 t C ha^{-1} to 1.5 t C ha^{-1}, with the initial SOC levels also being the lowest in the EU. Notably, grasslands in this region played a beneficial role in carbon sequestration, with continuous grassland or conversion from cropland contributing to an increase in SOC. Conversely,

Figure 6. Spatial distribution of the median change in SOC content (ΔSOCs q0.50) at 0–20 cm soil depth, 2009–2018



Source: EUSO, based on De Rosa et al. (2023).

continuous cropland had a net negative impact on SOC levels, attributed to practices such as monoculture and tillage. In addition, soils with a high initial SOC content tended to lose more carbon than soils with lower initial SOC contents.

Overall, SOC trends observed using soil data from LUCAS is approximately confirmed by observations from several national soil monitoring networks (Heikkinen *et al.*, 2013). However, Swedish cropland soils constitute an exception: their SOC content has increased in most parts of the country due to a steadily increasing proportion of ley in rotations (Bellamy *et al.*, 2005; Poeplau and Don, 2015; Knotters *et al.*, 2022).

In the United Kingdom, some studies suggest that there has been a decrease in SOC (which could be linked to changes in the climate (Thomas *et al.*, 2020)), especially in agricultural soils in England and Wales (Bellamy *et al.*, 2005); however, this finding was challenged by a subsequent study (Smith *et al.*, 2007).

Twenty-five years of SOC observations in Swiss croplands show stability overall but some divergent trends (Gubler *et al.*, 2019). The Norwegian Ministry of Agriculture and Food is funding the national programme for monitoring SOC in forests and intensive grasslands. Soil sampling started in July 2023, and these samples will provide information about the levels of, and eventually changes in, soil carbon stores in Norwegian forests and grasslands.

In the western Balkans, it is estimated that the area of land affected by low and declining management in the western Balkans, the loss of SOC is evident in most agricultural soils (Vidojevic *et al.*, 2022). Albanian soils have a relatively low SOC content (≤ 2 %) (Ministry of Tourism and Environment, 2019). Certain research in Bosnia and Herzegovina shows that the SOC content is mostly at a moderate level (3–4 %). SOC content in Kosovo ranges from 0.02 % to 2.79 %, depending on soil type, soil depth, land use, slope, soil cover, etc. There are no data for Montenegro on SOC change. An analysis conducted on many soil samples to monitor the fertility of agricultural land in Serbia shows that most samples had an organic carbon content of between 1 % and 2 %. A major cause of the degradation of agricultural land in the Serbia is a loss of organic matter due to intensive agricultural production, intensive tillage, a lack of organic fertilisation, irrigation, the removal of crop residues or their burning and other SOC stocks is less than 5 % of the total land area and about 10 % of agricultural land (Zdruli *et al.*, 2022). According to a report discussing the state of the art of soil unsuitable cultivation practices.

The soil organic (or total) carbon content is not determined as part of the monitoring and surveying of Ukrainian agricultural land, but the humus content (%) is measured. The weighted average humus content in soils decreased from 3.16 % in the 2015 survey round to 3.07 % in the 2020 round. According to survey results, the lowest humus content was observed in the Polissya zone (2.43 %), while in the forest of the steppe zone it was 3.2 % and in the steppe zone overall it was 3.31 % (Institute of Soil Protection of Ukraine, 2023).

The most recent SOC data for Türkiye, published in 2018 (ÇEM, 2018), indicate that the average SOC content was 47.04 t ha^{-1}. Most carbon reservoirs are located in forests, followed by pastures, which are mostly degraded. After bare and artificial areas, cultivated land has the lowest SOC content. According to FAO's land degradation neutrality decision support system, the SOC content in Türkiye is projected to decline by 2040.

However, the system has reported that SOC levels in agricultural soils are rising due to the increasing use of organic fertilisers and the expansion of drip-irrigated agriculture, compared with the period when re-irrigation practices were intensively used.

4.3.1.2 Drivers

Numerous experiments have investigated the impact of drivers of SOC change, and the findings are being consolidated in an increasing number of meta-analyses (Xu *et al.*, 2020; Beillouin *et al.*, 2023). The main drivers include the following.

- Climate change. Soils will release more carbon into the atmosphere under future warmer climatic conditions (i.e. resulting in positive feedback loops of soil carbon loss causing climate warming) (Wang *et al.*, 2022; Lugato, 2024). The impact of climate change is not solely confined to direct effects; rather, indirect consequences such as wildfires and changes in snow cover may have a more substantial influence on SOC. With a notable increase in the occurrence of forest fires in Europe, as evidenced by the alarming statistic that 2022 was the second worst year on record in the EU in terms of area burned by wildfires (San-Miguel-Ayanz *et al.*, 2023), it becomes imperative not to underestimate the indirect effects of climate change. While phenomena such as flooding, drought and alterations in snow cover have received limited attention in existing meta-analyses (Koven *et al.*, 2017) there is a noticeable absence of synthesised results on indirect effects (Beillouin *et al.*, 2023). Further investigations are needed to enhance our understanding of the individual and collective impacts of climate change on SOC, particularly across diverse land use types and varying climatic conditions (Beillouin *et al.*, 2023).

- Land use change. The overall effects of land use change and land management on SOC are 7–10 times larger than the direct effects of climate change (Beillouin *et al.*, 2023). Reducing the conversion of grassland to cropland could provide significant climate change mitigation by retaining soil carbon stocks that may otherwise be lost (De Rosa *et al.*, 2023). Conversion of grasslands to croplands typically results in a loss of approximately 36 % of SOC stocks within a 20-year period (Poeplau *et al.*, 2011). Preventing this conversion is crucial for averting soil carbon losses. However, it is essential to acknowledge that the conversion of grassland to cropland often occurs in response to food security challenges. This poses a dilemma, as food security could be compromised, given that more land is required to produce human food from livestock on grasslands than crops on croplands (Lal, 2001; de Ruiter *et al.*, 2017; Clark and Tilman, 2017; Poore and Nemecek, 2018; De Rosa *et al.*, 2023). Future changes in land use and climate have broader implications for land degradation, including effects on vegetation, fire and coastal erosion (IPBES, 2018; IPCC, 2019; Smith *et al.*, 2019). For instance, by 2080, extreme climate change could lead to carbon losses from mineral topsoil in the order of 2.5 ± 1.2 Pg in the EU and the United Kingdom (Lugato *et al.*, 2021).

- Soil erosion. Due to on-site soil losses and off-site sediment transfer and deposition, soil erosion has multiple environmental impacts, with significant negative effects over time (Panagos *et al.*, 2018a; Borrelli *et al.*, 2023). This has implications for biogeochemical processes such as SOC cycling, by increasing CO_2 emissions through enhancing mineralisation and decreasing carbon sinks and sediment burial (Lugato *et al.*, 2016; Borrelli *et al.*, 2017; Panagos *et al.*, 2018a).

4.3.1.3 Impacts

Soil carbon losses have significant and multicausal impacts on the environment, agricultural productivity and overall ecosystem health in Europe. Some of the main impacts include the following.

- **Reduced soil fertility.** SOC is a key component of organic matter, which provides essential nutrients. Its decline can therefore affect nutrient availability for plant growth. Declining soil fertility can lead to decreased crop yields, reduced agricultural productivity and affecting overall forest health, in particular when organic matter declines below 2 %. There is some evidence that crop yields and yield stability enhance with increasing organic matter content, though some studies show equivocal impacts (Lal, 2006).

- **Impaired water retention and drainage.** SOC plays a crucial role in regulating soil water dynamics. The loss of carbon can reduce the infiltration and water retention capacity of soils, making them more prone to waterlogging or, conversely, decreasing water availability during dry periods. This can reduce the efficiency of water use by crops, increase the risk of soil erosion and affect the overall functioning of the forest ecosystem (Niu *et al.*, 2008; Schindlbacher *et al.*, 2012).

- **Increased GHG emissions.** Soil carbon losses contribute to the increased emission of GHGs, particularly CO_2. When organic matter decomposes, carbon is released into the atmosphere. This process not only reduces soil carbon stocks but also contributes to climate change, exacerbating global warming (Bispo *et al.*, 2017; Lugato *et al.*, 2021; Le Noë *et al.*, 2023).

- **Loss of biodiversity.** Soil organic matter is a habitat and food source for various microorganisms, fungi and fauna. A decrease in soil carbon can lead to a loss of biodiversity inthe soil ecosystem, affecting soil functions and services. This can have cascading effects on the entire ecosystem, including above-ground plant communities (Geisen *et al.*, 2019).

- **Soil erosion.** Soil carbon loss is often associated with soil erosion, as it weakens the soils' structural stability and reduces infiltration rates, and thereby soils' ability to resist erosion. Erosion leads to the removal of topsoil, which is rich in organic matter. This, in turn, exacerbates the loss of soil fertility and hinders sustainable agricultural practices (Pimentel, 2006; Borrelli *et al.*, 2017).

- **Increased vulnerability to climate change.** Agricultural soils with lower organic carbon content are generally more vulnerable to the impacts of climate change, such as extreme weather events, droughts and temperature fluctuations, than those with higher carbon contents. Increasing SOC levels can enhance soil's resilience to these climate stressors (Wang *et al.*, 2023).

4.3.2 Organic soils

European peatlands are facing significant degradation due to agriculture, drainage and peat extraction, leading to significant carbon loss, biodiversity decline and environmental damage. New land use change policies under the common agricultural policy (CAP) reform aim to reduce drainage and implement the rewetting of drained peat soils. The EU Regulation on Nature Restoration, aims to restore degraded peatlands to achieve climate and biodiversity objectives and enhance food security. Restoring drained peatlands is identified as one of the most cost-effective ways to reduce greenhouse gas emissions in the agricultural sector.

4.3.2.1 Status and trends

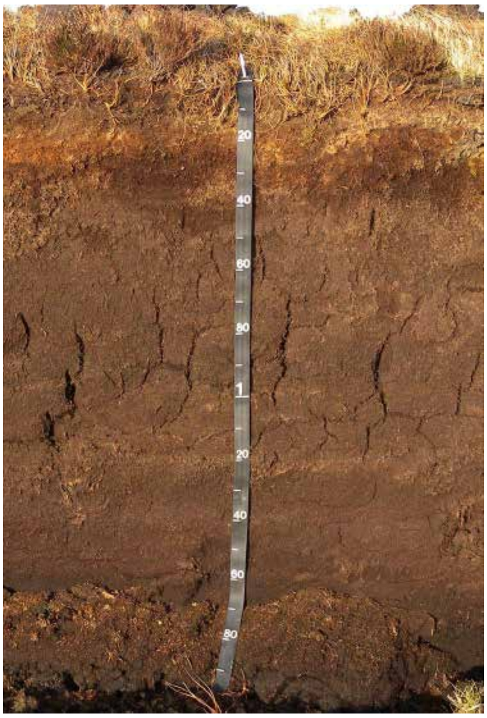
Peatlands are unique ecosystems that store significant amounts of carbon. In Europe, peatlands store approximately five times more carbon than forests (Limpens *et al.*, 2008) and about half of Europe's total SOC. The corresponding organic soils, also known as Histosols, are important SOC stores.

Organic soils store much more carbon per unit area than mineral soils. The amount could be more than 10 times the carbon stored in mineral soils, depending on peat thickness. As acidic and waterlogged conditions restrict decomposition (low temperature can also be a factor), peatlands hold more carbon per hectare on average than all other ecosystems, making them the largest carbon stock of the entire terrestrial biosphere (Temmink *et al.*, 2022).

A map of peatlands in Europe (Tanneberger *et al.*, 2017) reveals a strong northern bias in the distribution of organic soils across Europe, generally reflecting climatic conditions. Peatlands cover a large portion of the land area in the Nordic countries. Almost one third of European peatland is in Finland, and more than a quarter is in Sweden. The remainder is in Iceland, Poland, the United Kingdom, Norway, Germany, Ireland, Estonia, Latvia, the Netherlands and France. Small areas of peat and peat-topped soils occur in Lithuania, Hungary, Denmark, Czechia, Belgium, Italy, Austria and Spain (Kløve *et al.*, 2017; Tanneberger *et al.*, 2022).

Data from peatlands, particularly heavily degraded ones, are relatively limited (Evans *et al.*, 2022). Measuring the depth of the organic horizon helps quantify the amount of carbon stored in the soil, which is essential for understanding the role of peatlands in climate regulation and carbon sequestration (Beaulne *et al.*, 2021). The depth of the organic horizon was measured at 1 050 sites as part of the soil data collected in the 2018 LUCAS soil module (Fernandez-Ugalde *et al.*, 2022), with 30 % recording a depth of 40 cm or more. However, most of the sites selected for depth assessments appear not to fulfil the depth criteria for Histosols. The assessment failed to analyse the very shallow organic soils, such as those found on bedrock. The implication could be either that many of these locations are mineral soils with well-developed organic horizons, or that peatlands have been eroded back to the underlying mineral base (Fernandez-Ugalde *et al.*, 2022).

Photo 4. Peat profile.



Source: A. Jones.

Monitoring changes in the depth of the organic horizon over time can help assess the extent of peatland degradation due to factors such as drainage, land use change and climate change. Germany has initiated a peatland monitoring programme (implemented from October 2020 to May 2025) utilising a standardised approach aimed at the long-term investigation of site-specific and land-use-related influences on peatland development. The programme aims to fulfil existing reporting obligations concerning peatlands, containing peat and other organic soils, within the land use, land use change and forestry sectors and the agricultural sector. It seeks to achieve this by providing measurements and enhancing methods for regionalising the primary factors determining emissions.

European peatlands are facing significant degradation. Some 48 % are already degraded (excluding European Russia), primarily due to agriculture, drainage and peat extraction, leading to significant carbon loss, biodiversity decline and environmental damage. Within the EU, the proportion is 50 % (120 000 km^2) (Tanneberger *et al.*, 2021a). The EUSO Soil Degradation Dashboard shows EU peatlands that are likely to be degraded due to agriculture-related pressures (2 % of the total area of the EU) based on the United Nations Environment Programme's Global Peatlands Assessment , whose data are retrieved from the Global Peatland Database compiled by the Greifswald Mire Centre.

In Europe, the degree of peatland degradation clearly increases from Arctic to temperate regions. In central Europe, more than 90 % of all peatlands have been utilised for agriculture, forestry or peat extraction for centuries (Joosten, 2010).

Drained peatlands in the EU emit around 220 Mt-CO_2eq per year (around 5 % of EU emissions), mainly from agriculture on drained peat soils. This land makes up only 2.5 % of the total agricultural area but generates around 25 % of the total agricultural GHG emissions in the EU (including CH_4 from enteric fermentation and N_2O from fertilisation). The contribution is even larger in peatland-rich countries such as Finland (62 %), Poland (42 %) and Germany (37 %), based on national inventory reports data for 2019 (Tanneberger *et al.*, 2021b). In 2019, Member States reported a loss of carbon from 17.8 million hectares of land with organic soil (4.2 % of the total land area), corresponding to emissions of 108 Mt CO_2 (EEA, 2022a).

Ukrainian peat soils are situated in the southernmost region of eastern Europe's peat soil expanse. Shaped by warmer climates, they boast an age surpassing their northern counterparts. These soils previously achieved an equilibrium, including a carbon balance, under natural conditions (Truskavetskii, 2014). However, human intervention has disrupted this equilibrium, resulting in a negative carbon balance. Various researchers (Bradis *et al.*, 1973; Tanovitskii, 1980; Succow and Jeschke, 1986; Bambalov and Rakovich, 2005; Truskavetskii, 2014) highlight the disappearance of valuable flora and fauna, a reduction in biodiversity, and a trend towards the desertification of areas adjacent to extensive peatlands.

4.3.2.2 Drivers

The main factors driving peat loss are intricately connected, each influencing and exacerbating the effects of the others. These vary depending on the type of peatlands involved. Certain threats are more relevant to specific peatland types; for example, arable agriculture poses a particular risk to lowland peat.

- Land use change. The impact of humans on northern peatlands dates back centuries, to well before the industrial revolution (Holden *et al.*, 2004). Since then, there has been evidence of changes stemming from agricultural cultivation, the expansion of grazing pastures, forestry activities and the extraction of peat for fuel. The population growth from the 1700s to the 1900s increased the need for more arable land. In the early 1800s, the pressure for land resulted in its reclamation for agriculture or other uses, which continued with many large drainage projects at the end of the century (Kløve *et al.*, 2017). In Finland, a lack of coherence in forest, agricultural and environmental policies has led to increased drainage activity on peat soils since the beginning of the 20th century, which is linked to targets of increasing farm size and productivity and to developments in the CAP. The area of cultivated peat soils has grown, although fields cleared since 2004 have not been eligible for area- based subsidies (Regina *et al.*, 2016).

- Drainage. Drainage is the key driver of the degradation of peat soils (Swindles *et al.*, 2019). In the Nordic countries, between 3 % and 40 % of the original peatland area has been drained for agricultural purposes (Kløve *et al.*, 2017; Szajdak *et al.*, 2020). In countries such as Denmark, Germany, the Netherlands, Poland and Ireland, more than 80 % of peatlands have been drained for these reasons (Tanneberger *et al.*, 2021a). Agricultural uses vary from extensive pastures to intensive cultivation, for example vegetable production in Switzerland and the United Kingdom; the growth of maize for fodder and biogas generation in Germany; and dairy farming on grassland in the Netherlands.

- Peat extraction. Peat extraction for horticultural and energy purposes directly removes carbon-rich peat from organic soils, leading to the irreversible loss of soil carbon. Peatlands have always been important for farmers as a source of fuel (Runefeldt, 2010). Peat extraction for electricity production and heating continues in a small number of northern European countries, while the mining of peat to provide growing media (e.g. potting composts sold globally) occurs mainly in Ireland and some Baltic states (Girkin *et al.*, 2023).

- **Climate change.** Climate-driven drying of European peatlands is likely to have been exacerbated by direct human impacts in recent centuries (Swindles *et al.*, 2019). During a period of significant population growth throughout Europe (McEvedy and Jones, 1978), coupled with the expansion of cropland and intensified land use (Ramankutty and Foley, 1999), hydrological shifts took place. Distinguishing between the impacts of climate change and direct human influences becomes challenging, as these factors overlap and interact with each other.

- **Fire.** Wildfires on peatlands are becoming a common phenomenon during summer throughout Europe, because dry peat is a fossil fuel. When peatlands are drained, prolonged droughts turn peat into highly combustible matter that can easily be ignited through carelessness. Increased wildfire frequency and severity are expected to increase carbon loss from peatlands, contributing to a shift from carbon sink to carbon source (Nelson *et al.*, 2021). Changes to the structure of vegetation can increase the amount of wildland fire fuels available and can alter the hydrological connectivity of the landscape (Thompson *et al.*, 2019), thereby increasing fire risk and post-fire burn severity (Wilkinson *et al.*, 2018).

4.3.2.3 Impacts

Loss of soil carbon from organic soils, particularly in peatlands, in Europe can have profound impacts on the environment, ecosystems and society. Peatlands provide a wide range of ecosystem services, including carbon sequestration, water regulation, biodiversity conservation and recreational opportunities. Loss of soil carbon in peatlands diminishes their capacity to provide these services, compromising their ecological and socioeconomic value to society (Fluet-Chouinard *et al.*, 2023).

- **Climate change.** Loss of carbon through drainage, degradation and fires accelerates climate change in a positive feedback loop. Changes in temperature and precipitation patterns associated with climate change can alter soil carbon dynamics. Warmer temperatures can enhance heterotrophic activity and accelerate decomposition rates (Briones *et al.*, 2022), while changes in precipitation patterns can influence soil moisture levels, affecting decomposition rates and carbon storage. Drainage of wetlands and peatlands for agriculture, forestry or development purposes accelerates decomposition of organic matter by increasing oxygen availability. This process enhances biological activity, leading to increased decomposition rates and loss of soil carbon (Ma, Zhu *et al.*, 2022). Without rewetting, drained peatlands will continue to lose SOC and climate change will induce further peat loss from undrained peatlands (Tanneberger *et al.*, 2022).

- **Biodiversity loss.** Peatlands are unique ecosystems that support a rich diversity of plant and animal species, many of which are specially adapted to these environments. The loss of carbon from soil in peatlands can disrupt these ecosystems, leading to the loss of habitat and decreased biodiversity. Rare and specialised species, such as bog mosses, are particularly vulnerable to habitat degradation. Indeed, many European peatlands have already undergone shifts in vegetation composition over the last 300 years, including changes in Sphagnum communities (Gałka *et al.*, 2015), andincreases in grass, sedge (Gogo *et al.*, 2011) and shrub (e.g. Calluna vulgaris) cover (Turner *et al.*, 2014) . Typical peatland biodiversity, in particular that of groundwater-fed fens in temperate Europe, has been devastated by drainage (Hans *et al.*, 2017; van Diggelen, 2018).

- **Reduced water quality.** Peatlands play a crucial role in regulating water flow, filtering pollutants and maintaining water quality (Holden *et al.*, 2004; Millennium Ecosystem Assessment, 2005; Zedler and Kercher, 2005). The loss of carbon from soil in peatlands can degrade water quality by increasing sedimentation, nutrient run-off and contamination from agricultural chemicals (Clutterbuck and Yallop, 2010). Drained peatlands with agricultural uses in the EU are also a source of 1–5 Mt of NO_3 annually (Tanneberger *et al.*, 2021b). This can harm aquatic ecosystems, reduce water quality for human consumption and increase treatment costs for water utilities. Further negative consequences of drainage are a reduction in water quality through the discharge of nutrients to ground and surface water (Tanneberger *et al.*, 2021b), and increasing water acidity in the case of sulphide-bearing peat drainage (Saarinen *et al.*, 2013).

- Increased flooding and erosion. Peatlands act as natural sponges, absorbing and storing water during periods of heavy rainfall and releasing it slowly over time. Loss of carbon from soil in peatlands reduces their ability to retain water, increasing the risk of flooding and soil erosion. This can lead to damage to infrastructure, the loss of arable land and the degradation of aquatic habitats (Lieffers and Macdonald, 1990; Cleary *et al.*, 2005; Rooney *et al.*, 2012; Nieminen *et al.*, 2018).

- Cultural and archaeological losses. Peatlands contain valuable cultural and archaeological sites, including ancient human settlements, artefacts and well-preserved organic materials. The loss of carbon from soil due to drainage, degradation and extraction activities can damage or destroy these sites, resulting in the loss of important cultural heritage and historical information (Bain Bonn *et al.*, 2011; Flint and Jennings, 2020; Historic England, 2021).

- Economic costs. The impacts of peatland degradation and loss of carbon from soil impose significant economic costs on societies. These costs include the loss of ecosystem services, increased flood damage, reduced agricultural productivity and expenditure on restoration and conservation efforts. Drainage of peatlands also leads to land subsidence (1–2 cm yearly), which increases drainage costs and flooding risk, and results in the loss of productive land (Joosten *et al.*, 2012; Bonn *et al.*, 2016) and damage to infrastructure.

New land use change policies under the CAP reform aim to reduce drainage and the implement of rewetting of drained peat soils (Anon, 2020). Restoration also offers potential gains with respect to water quality, flood management, habitats and biodiversity, the protection of buried paleo-archaeological features and recreational enjoyment (Moxey and Moran, 2014). The EU Regulation on Nature Restoration (EU, 2024) aims to enable the restoration of degraded ecosystems, helping to achieve the EU's climate and biodiversity objectives and enhance food security. As restoring drained peatlands is one of the most cost-effective ways to reduce emissions in the agricultural sector, EU countries must restore at least 30 % of drained peatlands by 2030 (at least a quarter should be rewetted), 40 % by 2040 and 50 % by 2050 (when at least one third should be rewetted). However, rewetting will remain voluntary for farmers and private landowners. Successful peatland restoration in Europe requires knowledge transfer among academics, practitioners and policymakers (Zak and McInnes, 2022).

4.3.3 Inorganic carbon

The distribution of Soil Inorganic Carbon (SIC) in Europe varies geographically, concentrating in areas with Mediterranean climates and calcareous parent materials. Human activities such as fertilization, irrigation, management of soil organic matter, and reclamation practices impact SIC levels. Loss of SIC can have wide-ranging impacts, including reduced carbon sequestration capacity, soil fertility decline, land degradation, desertification, changes in water resources, and biodiversity loss. Research on SIC dynamics is essential to develop management strategies for carbon sequestration and soil condition improvement, in particular in the areas with Mediterranean climates.

4.3.3.1 Status and trends

SIC distribution in Europe varies geographically, concentrating in regions with Mediterranean climates and calcareous parent materials. Consequently, large areas of southern Europe, particularly those with Mediterranean climates, are characterised by carbonate-rich soils with pH values exceeding 7.5. Other areas located on calcareous lithology also show relevant concentrations in the soil profile in humid and subhumid temperate areas, such as the French regions of Champagne and Charente. Recent research (Lu *et al.*, 2023) has compiled the data from LUCAS 2015 regarding SIC concentrations in European topsoils, presenting them in digital maps. There is high variability in the values observed, ranging from 0 g kg^{-1} to more than 300 g kg^{-1}. No information is available on the trends in SIC concentration or storage in European soils, although data from the more recent rounds of LUCAS could be used to estimate such changes.

4.3.3.2 Drivers

The most relevant natural factors contributing to SIC concentration are soil parent material and climate. However, some other factors, such as position in the landscape and even vegetation can also play a role in the final allocation and typology of soil carbonates. As a result, SIC can be present in soils in varying amounts, vertical distribution in the profile, size distribution and pedofeatures (infillings, coatings, pendants, etc.). Carbonates can also be present as cementing agents, forming petrocalcic horizons. In addition, SIC is known to be affected by different factors in soil management. The most relevant ones are as follows.

- Fertilisation. Mostly as a source of acidity, mineral fertilisation with N salts can induce the dissolution and progressive loss of soil carbonates, while releasing CO_2 (Zamanian *et al.*, 2016). Fertilisation can also result in changes in the proportion of pedogenic compared with lithogenic carbonates (Bughio *et al.*, 2016).

- Irrigation. By changing the soil water regime, affecting primary productivity and biological activity, and acting as a source of calcium and/or bicarbonate, irrigation interferes with many aspects of SIC cycling. In addition, the partial pressure of CO_2 in soil solution is affected by irrigation, which influences bicarbonate leaching (Greenway *et al.*, 2006). Thus, irrigation has been observed to increase the emission of CO_2 from soils (Hannam *et al.*, 2016), and to reduce the amount of carbonates in the silt and clay fractions, while increasing the proportion of pedogenic carbonates (de Soto *et al.*, 2017).

- Management of soil organic matter. Some forms of organic matter added to agricultural soils can be sources of acidity, and therefore enhance natural acidification processes (Raza *et al.*, 2021). However, organic fertilisation has also been observed to induce carbonate neoformation in some soils (Liu *et al.*, 2023).

- Reclamation of sodic calcareous soils. The use of gypsum for reclamation of this type of soil can result in the formation of calcium carbonate, while the use of S to dissolve carbonates in sodic soils can result in the loss of carbonates by acidification (Virto *et al.*, 2022).

4.3.3.3 Impacts

- Carbon sequestration. The retention of SIC helps maintain the soil's capacity to sequester carbon, potentially mitigating increases in atmospheric CO_2 levels and alleviating the effects of global warming. In addition, because of the role of SIC in organic matter stabilisation, changes in SIC concentration, typology and physical distribution in soils can have consequences for SOC storage and protection in agricultural soils (Raza *et al.*, 2021). Fertiliser-induced soil acidity and leaching loss in agricultural ecosystems may cause irreversible changes in soil carbon (e.g. organic and inorganic) levels, and SIC stocks could be lost entirely as CO_2 (Zamanian *et al.*, 2018; Zamanian and Kuzyakov, 2019).

- Climate change. SIC levels can change with the climate, and the consequences are crucial for crop production, soil quality and land management practices (Lal, 2004, 2011; Rasmussen, 2006; Banger *et al.*, 2009; Bughio *et al.*, 2016; Gao *et al.*, 2017). However, the acknowledgement of changes in SIC in response to changes in temperature and CO_2 concentrations, and the corresponding influence on soil characteristics and SOC, are minimal (Ferdush and Paul, 2021).

- Soil fertility decline. Inorganic carbon contributes to soil pH regulation and nutrient availability. The loss of SIC can lead to soil acidification, or have the opposite effect, which can reduce soil fertility by reducing the availability of essential nutrients such as calcium and magnesium. This can impair plant growth and productivity, ultimately reducing agricultural yields (Ferdush and Paul, 2021). Furthermore, the pH range of calcareous soils (7.5–8.5) limits the availability of some other nutrients, for example iron and P, although various crop and fertilisation strategies can be used to counteract these effects (Ahmad *et al.*, 2022; Ahmadi *et al.*, 2023).

- Land degradation and desertification. SIC can act as a substantial carbon reservoir in dryland soils, especially those derived from sedimentary parent material (Deane McKenna *et al.*, 2022). Continued loss of SIC can contribute to land degradation processes such as desertification, particularly in arid and semi-arid regions. Given the overall increase in aridity in a warming world, drought may exacerbate loss of SIC from dryland soil under warming conditions (Li *et al.*, 2024). The dissolution of SIC is more important than previously thought in regulating atmospheric CO_2 concentrations (Zamanian and Kuzyakov, 2019), and if future climate change accelerates aridity in drylands (Dai, 2013), the contribution of SIC-derived CO_2 to total CO_2 emissions may become even more substantial (Li *et al.*, 2024).

- **Impacts on water resources.** SIC loss can affect soil water dynamics, leading to changes in groundwater (Kim *et al.*, 2020). From a wider geographical perspective, changes in SIC associated with increased fertilisation can also result in changes in riverine alkalinity at the watershed level (Perrin *et al.*, 2008).

- **Biodiversity loss.** As plants and soil organism distribution is known to be pH-dependent (Lauber *et al.*, 2009; Rousk *et al.*, 2010), changes in soil properties due to the loss of SIC can impact microbial communities, fauna and plant species composition in soil. This could disrupt ecosystem functioning and reduce habitats' suitability for various organisms, leading to biodiversity loss and ecological imbalances. Research on the dynamics of carbonates in soils is still much below the level that will allow practitioners to implement strategies to manage CO_2 sequestration as SIC. Some of the possible research paths are using non-acidifying fertilisers on calcareous soils, developing practices other than liming to combat acidification and to use calcifying or oxalogenic plants (Hirt *et al.*, 2023) or soil organisms using calcium from sources other than carbonates, such as gypsum (Laudicina *et al.*, 2021).

4.4 Soil erosion

Soil erosion poses a significant threat to soil health and agricultural sustainability in Europe. Water erosion is particularly prevalent, affecting 24 % of EU land at unsustainable rates, surpassing soil formation rates and impacting soil quality and land productivity. Projections of future trends in soil erosion in Europe are emerging, as the increase in rainfall erosivity may lead to an increase of up to 25 % in soil loss. Soil erosion in Europe, driven by factors such as poor land management, deforestation, climate change and wildfires, poses significant threats. It leads to loss of soil fertility and agricultural productivity, while also causing sedimentation, flooding and landslides, affecting water quality and causing economic losses. Loss of soil fertility, sedimentation and agricultural production losses are among the most obvious impacts of soil erosion, but other off-site impacts such as risks to cultural heritage sites, land abandonment, desertification and biodiversity loss should not be neglected. Addressing soil erosion necessitates holistic approaches integrating policy interventions and sustainable land management practices tailored to regional conditions.

Erosion is considered one of the most significant threats to European soils and the ecosystem services they provide. It threatens all major functions of soils, leading to a decline in land productivity and multiple off-site effects (Lal, 1998; Patault *et al.*, 2021; Panagos *et al.*, 2024a). More specifically, soil erosion reduces the fertility of soil, alters its structure, changes its biological activity and reduces its water holding capacity. In addition, it causes nutrient loss to water, and can reduce SOC pools (Quinton and Fiener, 2024). The spatially distributed and ephemeral nature of erosion makes its prediction and monitoring challenging, hindering proper risk assessment and policy mitigation. Worldwide, very few national survey programmes for soil erosion exist. Notable excep-

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