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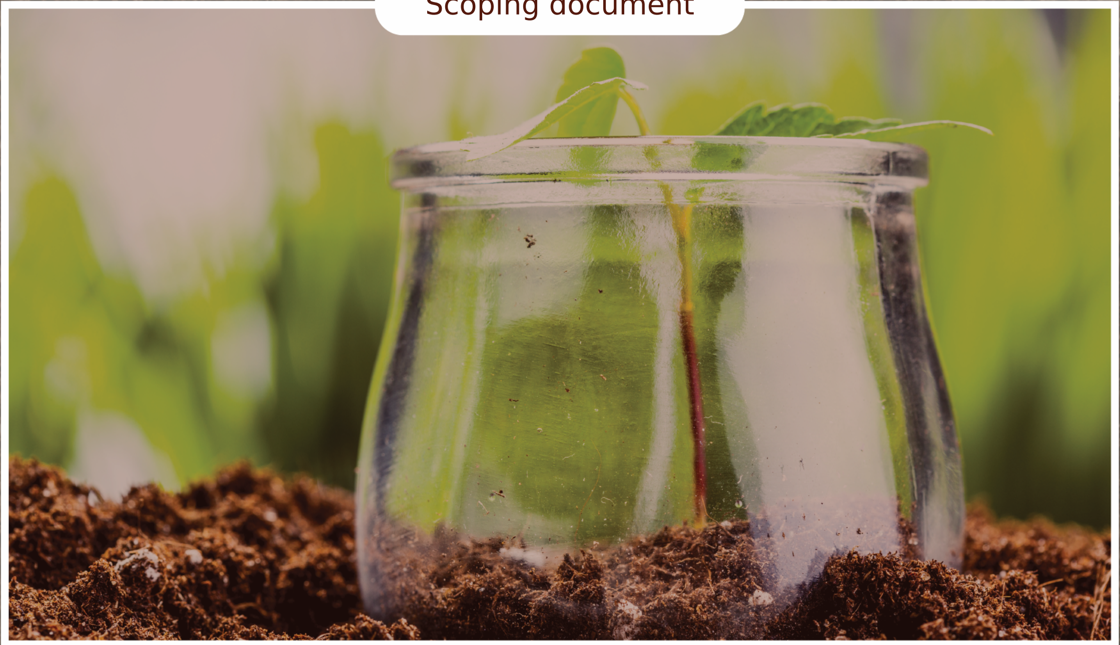
Soil organic
carbon stocks

Scoping document



Preliminary assessment of the knowledge gaps to conserve and increase soil organic carbon stocks

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Preliminary assessment of the knowledge gaps to conserve and increase soil organic carbon stocks

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Introduction

More carbon resides in the soil than in the atmosphere and all plant life combined (Lal 2004). However, soils can act either as a carbon source or sink, and currently represent a net source of greenhouse gas emissions in the EU (European Environmental Agency (EEA 2022). Thus, soil management poses a risk to not achieving European Union climate targets if not addressed appropriately. EU member states reported a total loss of 108 Mt CO_2 from cultivation and drainage of 17.8 Mha of organic soils in the year 2019, whereas only 44 Mt CO_2 were removed from the atmosphere by 387.6 Mha mineral soils (EEA 2022). In Europe and globally, peat soils contains the highest carbon stocks (Batjes 2002, De Vos et al. 2015), but it is essential to manage the water level of peat wetlands to maintain these stocks (Lloyd 2006).

The EU mission: a soil deal for Europe, defines “conserving soil organic carbon stocks ” as one of the 8 mission objectives, addressing the importance of maintaining, or in many situations increasing the soil organic carbon stocks. Soil organic carbon (SOC) is the main component of soil organic matter (SOM) mainly originating from plant debris accumulating and decaying in soil (Hoffland et al. 2020), slowly becoming a product dominated by molecules of microbial signature (Kallenbach et al. 2016) mixed and often adhered to soil minerals (Lehmann and Kleber 2015). A large body of previous research shows that the total input of organic C is a crucial factor in determining the long-term C stock, together with soil properties that control SOC stabilization (Mikutta et al. 2007, Schmidt et al. 2011). In 2017, the soil carbon 4 per mille initiative was launched to investigate the potential in increasing the soil organic matter stocks by 0.4%/year to compensate for anthropogenic release of greenhouse gasses (Minasny et al. 2017). This has fuelled an interesting debate on the complexity of soils, it's use and quality in relation to carbon storage (e.g. White et al. 2018, Moinet et al. 2022, Powlson and Galdos 2023). There is, however, an overwhelming body of evidence that increasing soil organic carbon stock in agricultural soils may help sustain or even improve biological, physical, and chemical soil properties, with benefits for soil organisms, root growth, as well as a range of other functions of soils important for many ecosystem services (Powlson and Galdos 2023). In cropland soils, the soil organic carbon (SOC) stock is often declining, and vulnerable to further losses due to intensive management and climate change. Conserving SOC in soils may support climate change adaptation and resilience to adverse weather conditions (Fan and Wang 2022), but it is challenging to combine global climate change mitigation and adaptation, through soil organic carbon sequestration while at the same time enhancing food security.

The soil mission objective aims at identifying actions that can limit the current carbon losses from cultivated soils and preferably reverse it to a rate of 0,1 - 0,4% increase per year (European Commission n.d.). The mission's objectives are relevant not only for supporting the aim to improve soil health by 2030, but also for the member states to become carbon neutral by 2050 (European Commission, n.d.). This think tank addresses the importance of maintaining, or in many situations increasing the soil organic carbon stocks by addressing the impacts of:

- Management
    - Forestry management
    - Agronomic and land use managements
    - Climate change and adaptation technologies
    - Biodiversity and soil health
- Societal
    - Urbanization and circular economy
    - Education and awareness raising
    - EU-footprints on SOC-stocks outside EU
- Technical
    - Soil carbon measuring and monitoring

In general, changes in soil carbon stocks are slow and management effects will vary depending on climate zones and soil types. Dialog and interaction is essential with all relevant stakeholder including those who own or manage land, agronomic advisors (both governmental and commercial), agricultural supply companies, policy makers, those involved in the food supply chain, and others, for the successful implementation of soil carbon management technologies. Practitioners holds essential knowledge and experience about their own land, and mutual knowledge and practice exchange, will facilitate and stimulate the necessary engagement for innovative technology implementation within the various aspects of soil carbon stocks and improvement of soil health in general.

State-of-the-Art

Forest management

Forest soils store almost half of the total organic carbon in terrestrial ecosystems, and forest management practices can influence the rates of input or release of carbon from soils (Mayer et al. 2020, Mäkipää et al. 2023, Ontl et al. 2020). An important factor for soil C stocks, for Europe and globally, is to maintain existing forest cover and avoid its removal or degradation. Forest management can have various objectives, such as timber production, biodiversity conservation, recreation, carbon sequestration, and other ecosystem services. It is, however, likely that, in many forest situations, the main societal goal will be habitat for wildlife with managements being tailored for different species in different situations. Forest management require thus a holistic approach serving several ecosystem services other than simply exploring its potential in storing soil carbon. Consideration of C stocks will thus be a secondary factor. Many factors influence the interactions between forest management and SOC stocks, such as forest type, disturbance, soil type, climate, time (Ahmed et al. 2012, Jandl et al. 2021) and the carbon use efficiency (CUE; Qiao et al. 2019, Tao et al. 2023).

Several studies underscore the need for sustainable management practices and innovative solutions to meet the growing demand for timber and forest waste as bioenergy in the context of climate change. The demand for wood-based energy is expected to increase, but the carbon impacts of forest bioenergy are uncertain (Giuntoli et al. 2020). Forest residues can also be used for biochar production, with substantial climate benefits even after all environmental costs associated with production and application are discounted through life cycle analysis (Tisserant et al. 2022). This is further complicated by the potential effects of climate change and air pollution on forest productivity and carbon sequestration (Matyssek et al. 2012). The removal of forest residues for bioenergy could also have negative consequences for how forest systems provide and sustain their ecosystem services (Clark 2012).

Agronomic practises

Sustainable food production requires increasing the productivity and efficiency of land, water, and other inputs, while reducing the environmental impact and greenhouse gas emissions of agriculture. Overall, the adoption of recommended agricultural practices, such as reduced tillage, crop rotation, cover crops, including agroecology and intercropping can lead to enhanced SOC storage and restoration of soil quality, and by that strengthen long-term food security. But it must be recognized that the production benefits may not be apparent in the short or medium-term. Soil carbon stocks and quality are influenced by climate, soil minerals and aggregation (Lehmann and Kleber 2015), the rate of plant primary production, plant root interaction with soil and soil biology (Bai and Cotrufo 2022, Kätterer et al. 2011), and various management factors, such as land use, soil management and crop rotation (Cui et al. 2022, Fornara and Higgins 2022, Haddaway et al. 2017). The review of recent studies by Bai and Cotrufo (2022) highlight the essential role of management improvements, restoration and the capacity of plants and soil biology in controlling the formation of mineral associated organic material (MAOM) and particulate organic material (POM) promoting SOC storage, mediating the impacts of climate change. The biogeochemistry of SOC is a dynamic continuum from intact plant residues to highly oxidized carbon in carboxylic acids which requires a mechanistic understanding of the SOC interaction with minerals, the mediation of microbial activity balancing both the stocks and flows of organic matter (Lehmann and Kleber 2015). Agronomic practices vary, and potential impact on soil organic carbon stocks is shortly discussed for some of the emerging once.

Growing cover crops where soil would otherwise be bare, has many benefits including decreased nitrate leaching over winter and decreased soil erosion compared to bare soil. However, their role in increasing SOC may have distinct limitations in many European situations. For instance, in regions of NW Europe with temperate climate, autumn-sown crops are common, which leaves limited scope to include cover crops unless under-sown at an early stage in the development of the main crop. By contrast, in regions with a more continental climate such as much of North America, spring-sown crops are more commonly grown, leaving large areas of soil bare over winter. However, where cover crops can be grown, it is likely that they will lead to some increase in SOC, though the magnitude of increase may well be less than often assumed. For example, a recent review calls into question the often-quoted view that cover crops can increase SOC by about 0.3 tC/ha/yr – see Chaplot and Smith (2023). Depending on climatic region and plant species, cover crops may contribute to increased nitrous oxide emissions in the long term due to accumulation of organic N in the increased stock of soil organic matter. (Guenet et al. 2021 , Lugato et al. 2018).

The effects of tillage practices on SOC at different soil depths are not uniform and depend on various factors, such as soil type, climate, crop type, tillage practices (e.g. no tillage to high intensity, Haddaway et al. 2017), tillage frequency and bulk density (Fornara and Higgins 2022). For example, a review of 351 studies from warm temperate and snow climate zones, found that SOC was significantly higher in no tillage soils compared to high intensity systems in the upper 30 cm soil layers, but no effect was found in the full soil profile. The higher SOC in top soil layers in no tillage systems, may provide resilience to extreme weather conditions though (Haddaway et al. 2017). A recent study from a mediterranean climate, showed among other findings, that tilled wheat had greatest soil C stabilization at intermediate depts (30-60 cm), whereas no-tilled wheat had highest carbon stabilization and microbial biomass at top soil layers (0-30 cm) (Taylor et al. 2024). The increased soil C stabilization in top soil was connected to better plant growth at no-tillage in mediterranean (rather dry) climates. The Fornara and Higgins (2022) study of 500 grassland fields in Northern Ireland, UK, showed that C and N stocks (mg/ha) in the top 30 cm depts were not affected by frequency of tillage + reseeding, as differences in bulk density levels out the stock variation. They report, however, that the concentrations of C (%) and N (%) decreased while bulk density increased by the tillage + reseeding frequency. Thus can soil compaction affect soil C storage more than the frequency of tillage.

Crop rotation is normally practiced in several farming systems, such as organic farming, regenerative agriculture and conservation agriculture, but according to Land et al. (2017) there are not many comprehensive studies designed to unravel the effect of crop rotation on soil organic carbon stocks. Calculation indicate that perennial forages can increase below-ground SOC more than the common crops, especially if crop residues are not returned, or if the perennial forages are discontinued (Bolinder et al. 2007, Bolinder et al. 2012, Land et al. 2017). Perennial crop seems to increase the C storage and flux, more strongly in shallow soil (0-15) compared to deeper soil layers (15-30) (Means et al. 2022) in comparison to annual monoculture crop.

Several of the emerging farming system described under, practice the use of minimal disturbance and reduces tillage, cover crops, crop rotation, plant or animal residue return. Hence does the overlapping practices have shades of the same impacts on soil organic carbon storage. They are however discussed separately for the purpose of the terminologies in use.

Organic farming have the potential to increase soil organic carbons stocks and sequestration rates (Clark and Tilman 2017), offering larger environmental benefits in comparison to conventional agricultural systems (Gattinger et al. 2012). Organic farming generally produce slightly less biomass though, and the effect on soil carbon stock from organic farming is complex and content performance dependent (Seufert and Ramankutty 2017). Organic farming may involve reduced tillage, and reduced tillage have a potential to increase total SOC stocks, if crop management is optimized. Krauss et al. (2022) reported the effect of reduced tillage on SOC stocks in organic farming systems in temperate Europe. They found slight increas in top 10-15 cm, slight decrease in intermediate dept (down to 50 cm), followed by a slight increas again in 70-100 cm depth. The investigation reported in Gaudaré et al. (2023) indicate, though, that unless appropriate farming practices are implemented, expanding organic farming might reduce the potential for soil carbon sequestration. According to Lorenz et al. (2019), the demand for organic products will continue to grow driven by food safety concerns. Due to lower yields, however, natural ecosystems may be increasingly converted to agroecosystems to meet the demand with less well-known consequences for the environment.

Agroforestry and intercropping have shown to significantly impact soil organic carbon stocks in Europe. Mayer et al. (2022) conducted a meta study on temperate climate zones worldwide and found that agroforestry systems sequester significant amounts of SOC in top soils and subsoils. Zuazo et al. (2014) reported that forest, shrubland, and grassland in a Mediterranean agroforestry landscape had higher soil organic carbon stocks compared to abandoned farmland. Kay et al. (2019) further emphasized the potential of agroforestry in sequestering carbon and mitigating environmental pressures in European farmland. It has generally been reported positive effects of diversified arable cropping systems and environmentally friendly farming management on soil organic carbon content in European agroecosystems (Francaviglia et al. 2019).

Regenerative agriculture (RA) may not have an exact definition, and the practice varies between regions and farmers and farming systems. It generally includes reduced tillage, crop residue management, and strong control of fertilization practice. These practices in combination have shown to increase soil organic carbon (SOC) stocks (Chahal and Singh 2020, Rhodes 2017). Regenerative agricultural practices do not only enhance carbon storage but reports also indicate improved soil fertility and crop yields in many situations (Rhodes 2017). In general, it seems likely that agroecological crop management and regenerative practices, particularly reduced or no-tillage and cover crops, have the potential to increase SOC content (Breil et al. 2021).

Conservation agriculture (CA) is based on many of the abovementioned principles. Conservation agriculture simply implies minimal soil disturbance, permanent soil cover, and crop rotation. The effects of CA on SOC stocks are not consistent and depend on various factors, such as soil type, climate, crop type, residue management, and duration of conservation agriculture. A global meta study showed that CA systems including legume residue retention in combination with manure and mineral N-admixing have considerable potential to increase SOC and total N in topsoil layers (Bohoussou et al. 2022). But, as with all the practices considered, research is required to identify opportunities, barriers, and trade-offs with other agronomic environmental goals in a range of environments.

Climate adaptation

The management of soil should focus on sustainability of food and fiber production and sustaining ecosystem services. This puts climate change adaptation as the primary aim for soil management rather than mitigation.

The impact of climate change on food and fiber production depends on the responses and adaptations of farmers, consumers, markets, and policies. These adaptations are the result of complex optimization decisions and general equilibrium dynamics, and thus difficult to measure and predict. Two recent approaches to studying climate change adaptation in agriculture are panel data methods and spatial general equilibrium models (Page et al. 2020). Increased SOC stocks generally favours both mitigation and adaptation as higher SOC in top soil layers in e.g. no tillage systems, provide resilience to extreme weather conditions though (Haddaway et al. 2017).

Plant biodiversity and SOC stocks

Experimental evidence drawn from biodiversity ecosystem functioning experiments has generally shown that higher plant biodiversity leads to both higher aboveground and belowground plant productivity and concordantly higher soil carbon. Already in 1994, Tilman and Downing reported that preservation of biodiversity is essential for the maintenance of stable productivity in ecosystems (Tilman and Downing 1994). It may be the case that in high clay soils where essential elements are limiting that the best yielding monoculture species may be superior to a mixture of plant species for producing biomass and storing soil carbon. However, there are also a host of what ecologists call niche differences that could explain why in some cases a higher number of species would yield greater soil carbon. For example, can plant species differentiate in hot and dry vs cold and wet seasons, exhibiting different rooting depths, producing different types of litter that are differentially processed by the microbial community (Furey and Tilman 2021, Kraychenko et al. 2019, Lange et al. 2015, Lange et al. 2021, Perry et al. 2023, Spohn et al. 2023, Yang et al. 2019).

The effect of SOC on soil health

The EUSO soil health dashboard reveals that 61% of EU soils are unhealthy (EU Science hub 2023), however gaps remain due to limited data various soil degradation issues. Soil health is closely linked to SOC, as soil organic matter affectes soil sturture, soil life and elemental cycles, which together sustaining essential ecosystem functions such as erosion protection, soil biodiversity, primary production, climate regulation and water quality (Hoffland et al. 2020). Soil carbon is vastly heterogeneous, encompassing everything from last hour's root exudates to persistent humified material, millennia old (Amundson 2001). Soil organic matter is biologically most useful when it breaks down and releases plant nutrients, which is in direct contrast to the aim of storing more carbon in soils (Janzen 2006). Thus has the status of carbon quality, such as particulate and mineral associated fractions in relation to its stability and soil structure in agronomic and forests soils, has been a matter of intense research (Georgiou et al. 2022, Liang et al. 2017).

Many lists of indicators for soil quality and soil health include carbon content and microbial respiration together because they are positively correlated (EU commission 2023). Microbial biomass does provide 'early warning' of slow changes in total SOC (Powlson et al. 1987). But biomass is not the easiest method for routine use. Alternatives exists - see Bongiorno et al. (2019). As microbial activity and nutrient release increase with increasing carbon content, nutrient mining can occur, counteracting ideas of improving soil health. Additional biological indicators may also provide insight about C dynamics and microbial activity (Liptzin et al. 2022).

Circular bioeconomy

In a sustainable bioeconomy, recycling of nutrients from organic residues is imperative (Hellsmark et al. 2016, Sawatdeenarunat et al. 2016). There is a huge diversity in organic residues depending on their origin and/or the type of process involved in their production. Application of organic residues as soil amendment and fertilizer to agricultural land gives the opportunity of recovering the nutrients, primarily nitrogen and phosphorus, and of potentially improving soil quality by adding organic matter. However, such residues may also increase greenhouse gas production through the input of microbial substrates and increased mineralization of N.

Urbanisation

Urbanization is the process of transforming rural areas into urban areas, which can have various effects on food production and soil organic carbon (SOC) stocks. In view of the need for housing increased populations in many European countries, some loss of agricultural land due to urbanization seems inevitable. Generally, there is a major conflict of interest between urbanization and the protection of productive soil. High quality soil for agriculture is a non-renewable resource since it takes centuries to build up few centimeters of productive soil. The conversion of agricultural land to urban land is de facto an irreversible process (Amundson et al. 2015), as new use may decrease the land’s ability and capacity to supply food and other vital ecosystem services (Tan et al. 2009). Historically, urbanization has occurred close to our most productive farmland (Ferrara et al. 2014), and most remaining farmland is located close to urban settlements. Thus, urban sprawl is consuming fertile agricultural land for urban use worldwide (Skog and Steinnes 2016). How to combine increased food production and soil organic matter conservation with increased urbanization and high pressure on productive agricultural land, i.e., multifunctional land use, is a challenge. The EU commission has onset several strategies, such as the biodiversity long-term plan to protect nature and reverse the degradation of ecosystems. The strategy aims to put Europe's biodiversity on a path to recovery by 2030 (EU commission 2020), the EU soil strategy EU commission 2021 to protect and restore soils, and ensure that they are used sustainably and finally the "no net land take " brief, to outline what measures can avoid, reduce or compensate for land take (Science for Environment Policy 2016).

Education and awareness raising

Awareness of the importance of soil health has increased recently. For instance, will the PREPSOIL project support the implementation of the Soil Mission by creating awareness and knowledge on soil needs among stakeholders in regions across Europe. Considering the recognition of soil and its importance to sustain essential ecosystem services, there is a need to improve fellow citizens, land managers, politicians and policymakers common understanding of SOC dynamics and its central role in soil fertility and carbon storage. Soil carbon storage refers to an increase of soil carbon stocks, while soil carbon sequestration implies a net removal of atmospheric CO2. However, these terms are often used interchangeably or ambiguously, which can cause confusion and misunderstanding among different stakeholders and audiences.

Education and awareness on the importance of SOC management for global benefits, particularly in climate change adaptation and is vital role for sustainable food security is challenging to communicate though. In part this is because of the complexity of organic carbon composition and complex fate in soil, and the linkages to soil functions such as soil structure, soil life and elemental cycles (Chenu et al. 2019).

EU footprints of soil carbon outside Europe

The import of food and fiber into Europe has a complex and varied impact on soil organic carbon (SOC) levels in soils outside of Europe. Frank et al. (2015) found that changes in SOC stocks depend on management regime and environmental factors, with a potential for carbon sequestration in European cropland. However, if C sequestration as opposed to food production is prioritized in Europe, this would lead to increased imports of food. Much being likely to be grown on recently cleared land elsewhere in the world with the resulting loss of SOC, and increased CO_2 emissions, in those regions. For instance, if organic farming increases, this may come at the expense of SOC loss at another site (Gaudaré et al. 2023). To improve our understanding on soil organic carbon (SOC) stock outside Europe, standardized estimation methods, comprehensive data sets, and accurate mapping techniques is needed (Aksoy et al. 2016, Lorenz et al. 2019, Lugato et al. 2014, Wiesmeier et al. 2012).

Soil carbon measuring, accounting and monitoring

To effectively address content and quality of soil organic carbon stock, several methods exist ranging from laboratory measurements to remote sensing modelling. In short, the determination of soil organic carbon stocks in soil requires measurements of bulk density, gravel content and soil organic C concentration. Soil organic C concentration can be determined making use of several methods where Visible–Near-Infrared (vis–NIR) Spectroscopy is one, the bulk density by Active Gamma-Ray Attenuation, whereas gravel content may require wet sieving (England and Viscarra Rossel 2018). Careful, repeated field sampling followed by laboratory analysis using dry combustion analysis and bulk density measurement, following standardized and procedural guidelines are, however necessary, for accurate reporting and verification. There is a challeng in developing cost-effective methods for detecting changes in soil organic C resulting from changes in management etc., but a number of direct field applicable methodologies exist, such as laser-induced breakdown spectroscopy (LIBS) (Cremers et al. 2001), inelastic neutron scattering (Wielopolski et al. 2000), Mid-Infrared and Near-Infrared Diffuse Reflectance Spectroscopy (McCarty et al. 2002). For remote sensing eddy covariance is a costy application usefull for measuring respiration and carbon fluxes, provideing insights into regional soil carbon sequstration when used in combination with simulation modelling (Zeng et al. 2020).

Knowledge Gaps

In general, there is a need for more knowledge on long-term trends in European cultivated and non-cultivated soils (such as forests, peat, pasture, natural gras and heath lands) and documentation on consequences of land use changes, impacts of urbanization and new technologies on soil properties and soil organic carbon stores.

This is best achieved by a combination of

1. detailed studies to investigate mechanisms of C turnover and stabilization.
2. continued interpretation and re-interpretation of data from long-term experiments.
3. surveys of organic C changes in realistic commercial situations.

This “think tank” has specifically identified knowledge gaps connected to forestry, agriculture, climate change impacts, biodiversity, soil health, circular economy, urbanization, education and awareness raising, as well on methods for carbon measuring, accounting and monitoring and very shortly on EU footprints of soil-C outside Europe:

Forestry and practices

Research on forestry and practices require more long-term soil monitoring, experimental studies, and synthesis of existing data to provide evidence-based guidance for climate-smart forest management practices. Such as:

- How different forest management practices affect soil carbon stocks and greenhouse gas emissions in different forest types, climates, and soil conditions.
- How forest management practices can be integrated into existing modelling tools and accounting systems to better estimate the mitigation potential of forest soils
- How forest management practices balance the trade-offs and synergies between soil carbon sequestration, biomass production, ecosystem services, and socio-economic benefits.
- The carbon impacts of forest bioenergy are uncertain due to optimistic assumptions about forest management.
- It is also unclear how the potential effects of climate change and air pollution will affect forest productivity and carbon sequestration.
- Will the removal of forest residues for bioenergy have negative consequences on ecosystem services and long-term sustainability. And will this be detrimental for insects and wildlife?
- The effect of bioenergy demands on timber markets, carbon, and land use is complex and requires further studies.
- There is a need to evaluate the effect of biomass removal (especially forestry residues) for bioenergy and biochar on soil carbon stocks in forest, soil nitrogen/nutrients, and possibly biodiversity.
- When considering carbon stocks, there is also a need to better account for time perspectives, as new equilibrium for SOC will take a couple of decades to be reached, while for example biochar effects are cumulative over the long term. Different use scenarios can produce very different climate impacts as a function of the projected time we are considering.

Agronomic practices

There are several knowledge gaps on various aspects of agronomic practices for managing soil organic carbon stocks in agricultural soils, and long-term field experiments trying to elucidate the effect of different soil management practices on soil carbon stocks need long-term perspectives (and appropriate financing possibilities):

Soil management

- Many studies focus on varying one or two management practices (e.g., different tillage intensity, fertilization strategies or straw management), and how they influence soil carbon stocks. While the picture gets clearer for some aspects, others require more systematic long-term studies, e.g., fertilizer strategies for more novel organic fertilizers (biogas digestates, fish sludge etc.).
- The optimal combination of tillage and crop rotation for SOC sequestration depends on the specific context and objectives of each system. There is no one-size-fits-all solution, but rather a need for site-specific and adaptive management that considers the trade-offs and synergies between SOC, crop yield, and other ecosystem services. This involves work to better understand and define drivers and impacts at a mechanistic level as a basis for prediction to other situations.
- How can we make use of cover crops to increase SOC in areas with climatic limitations to include cover crops in rotations?
- What is the potential of different plant species and mixtures to increase SOC in different climatic regions and farming systems, and how do different plant species and mixtures affect greenhouse gas production?

System approaches

- There is need for more long-term studies on a system level, e.g., comparing different types of agronomic systems in different climate zones and on different soil types with respect to processes affecting carbon stocks.
- Consumer demand for organic products will continue to grow driven by food safety concerns and increasing affluence, but due to lower yields in organic farming, natural ecosystems may be increasingly converted to agroecosystems to meet the demand with less well-known consequences for the environment.
- There is an urgent need to strengthen the database on environmental impacts of organic agriculture by establishing and studying long-term field experiments in all major biomes and principal soils.
- Agroforestry systems (AF) play a crucial role in shaping soil organic carbon (SOC) stocks practices on SOC, and AF have the potential to benefit several ecosystem services, but there is still a need to investigate the impact of soil properties, tree age and managements practises on carbon stability, its vertical distribution, processes, and mechanisms driving carbon sequestration in short and long term.
- Regenerative agriculture (RA) often includes periods of pasture or herbal leys within mainly arable cropping, so system level consideration including impacts of animals is required. But quantifying the magnitude of SOC changes resulting from specific RA interventions remains a knowledge gap. Long-term studies and standardized monitoring protocols are necessary to assess the SOC dynamics under different RA approaches.

- Various organic farmers practise conservation agriculture (CA) in Europe but assessing SOC changes resulting from specific CA practices remains challenging. Long-term studies and standardized monitoring protocols are necessary to understand SOC dynamics under different CA approaches. Understanding regional variations and management systems is vital.

Climate change and climate adaptation strategies

The knowledge gaps on climate adaptation to sustain food and fibre production, while maintaining or even increasing soil organic stocks is a broad and interdisciplinary field of research, involving various disciplines, methods, and perspectives concerning soil health, quantification of SOC stocks, regional variability, mitigation strategies and integration with agricultural polices:

- Despite efforts, many European soils remain unhealth, failing critical thresholds for soil health indicators. Thus, is developing specific indicators that correlate with SOC storage and climate resilience essential.
- While different initiatives aim to increase SOC storage, quantifying the actual progress remains challenging. Thus, is monitoring and assessing SOC stocks across diverse European landscapes necessary. Lack of consistent data and standardized methodologies hinders accurate measurements.
- Europe has diverse climates, soils and land use practise, and regional-specific knowledge is essential for tailoring adaptation strategies to understand how SOC responds to different management practises in specific European contexts, is a gap.
- Identifying effective mitigation strategies to enhance SOC storage is critical, and research should focus on practices that promote SOC accumulation while considering local conditions. However, balancing trade-offs between climate adaptation, food security and other ecosystem services is challenging.
- What significance do extreme weather events have on organic carbon stocks? Climate change-related events such as droughts, forest fires, etc. are expected to occur more often in the next decades and will have an impact on soils. Modelling is needed to assess those effects on the soils and its capacity to sequester carbon.
- Integrating SOC considerations into existing agricultural policies is essential. Policy coherence between climate adaptation, soil conservation, and sustainable land management is lacking. This requires collaboration between policymakers, scientists and practitioners.

More indirect knowledge-gaps are:

- What is the effect of climate adaptation measures, e.g., breeding of more resilient varieties with larger root systems, longer-lasting plant covers.
- How can forest management practices enhance the resilience and adaptation of forest soils to climate change, biodiversity loss, and other environmental changes.
- What incentives will be useful to make farmers and forest owners adapt different production strategies? It should be recognised that measures that are beneficial in

these respects may not deliver benefit to farmers in the short – or medium term but may even represent a cost.

Biodiversity

The "Convention on Biological Diversity (CBD)" defines soil biodiversity as “the variation in soil life, from genes to communities, and the ecological complexes of which they are part, that is from soil micro-habitats to landscapes.” It encompasses the variety of life belowground, including microorganisms, microfauna, mesofauna, and macro/megafauna. Soil biodiversity plays critical roles in delivering ecosystem goods and services, such as nutrient cycling, water regulation, and soil structure maintenance. Biodiverse ecosystems may enhance SOC storage capacity and research can identify which plant species or microbial communities promote SOC accumulation. Plant communities enhance SOC through root exudates, litter quality and mycorrhizal associations, and investigating these feedback loops may help designing effective climate adaptation strategies. Moreover, does biodiversity affect SOC response to land use changes, and the relationships vary across ecosystems, climates, and soil types. There is an intricate relationship between SOC, soil biodiversity and ecosystem resilience in Europe, and some of the unknowns are:

- There is a need for more knowledge on the relationship between biodiversity and soil organic stocks as biodiversity influence soil processes, nutrient cycling, and ecosystem functioning.
- There is also a need to understand how different species interact with SOC can enhance our knowledge on ecosystem resilience and stability.
- Despite it's importance, quantifying soil biodiversity remains challenging
- Methods for studying biodiversity range from assessing invisible microorganisms to invertebrates and vertebrates, and developing standardized indices and monitoring system is essential to understand the relationship between soil biodiversity and ecosystem services.
- There is also a need to explore how more biodiverse biota contributes to SOC stocks and various ecosystem services.
- There is also a global gap in biodiversity data, particularly in northern latitudes, central Asia and Central Africa, and understanding the regional variability and context-specific soil biodiversity patterns is crucial for effective conservation and adaptation strategies.

More specific examples of unknowns are:

- Does the benefit of plant biodiversity on soil carbon storage depend on soil texture and parent material?
- Are monocultures of high-yielding plants superior to mixtures when the soil is heavily fertilized and irrigated?
- Are experimental results, e.g. in respect to changes in SOC stocks, that manipulate the number of species or groups of species in natural systems applicable to agricultural systems that are often higher in soil fertility, fertilized and have improved cultivars of plants compared to native species?

- Does belowground biodiversity affect SOC stocks? Does more diversity imply more activity and vice versa, or is one better than the other in terms of soil heath and SOC stocks?
- Does a diversity of carbon inputs, from a mixture of plant species, promote greater stability of soil carbon than a monoculture of a high yielding species that has high inputs but all of the same litter quality?
    - And can different species be harvested at the same time?

Soil health - one health

The EUSO soil health dashboard, reveals that 61% of EU soils are unhealthy. However, gaps remain due to limited data on various soil degradation issues, including contamination. Developing comprehensive and updated knowledge for identifying healthy and degraded soils is essential. Essential knowledge gaps are:

- While we know that EU soils are both gaining and loosing carbon, the specific factors driving these changes remain a knowledge gap.
- Which carbon fractions are most relevant for stabilisation of carbon, which are the most relevant for the many aspects of soil health? As carbon stocks in soils change slowly, there is a need for developing and/or more extensive testing of more dynamic proxies for carbon sequestration.
- Can we both conserve soil carbon and benefit from its decay? How do we achieve increased decomposition of organic matter and increased stabilization of carbon at the same time? Should we seek to increase throughput of organic C in soils rather than concentrate solely on increasing stock as a better strategy?
- How do we determine the health of soils in terms of carbon content and which indicators are most related to soil functioning?
- How can soil organic carbon stocks be assessed in an overall health concept that also includes healthy plants (food and feed), clean water, healthy animals, and people?

Circular economy

The soil plays a key role in a circular economy and sustainable society, but there is significant lack of knowledge concerning safe and energy-efficient recycling of waste materials in soil, and its impact on soil organic carbon stocks and soil health. We cannot make use of organic waste transferring contaminants, pathogenic organisms, and unwanted plant residues such as weed in healthy soils. While circular economy principles emphasize resource efficiency, their direct influence on SOC stocks remains an area of study.

- Research is needed to understand how circular economy practices, such as recycling, remanufacturing, and waste reduction, affect soil carbon sequestration.
    - Identifying synergies between circular economy strategies and SOC preservation is crucial.

- Circular economy models involve material flows across sectors (e.g., agriculture, industry, and waste management), but new knowledge to quantify the impact of these material flows on SOC dynamics is essential.
    - Researchers must explore how circular economy practices alter carbon cycling, organic matter inputs, and decomposition rates in soils
- LCAs evaluate environmental impacts across product life cycles, and integrating soil carbon considerations into LCAs can provide insights into circular economy practices.
    - There is also a need to develop robust methodologies for assessing soil carbon changes due to circular economy interventions.
- Urban agriculture contributes to circular economy goals by utilizing local resources and reducing waste. However, its impact on SOC stocks in urban soils is not well understood.
    - Investigating the role of urban agriculture in maintaining or enhancing SOC levels is necessary.
- Circular economy policies often focus on material flows and waste reduction, but integrating soil health and carbon sequestration goals into circular economy policies is an emerging challenge.
    - Policymakers need evidence-based guidance on aligning circular economy strategies with soil conservation efforts.
- Indirect knowledge gaps related to circular economy, are:
    - How to deal with heterogeneity of organic waste samples and its following post treatment. This has implications for sorting and applicability.
    - Many knowledge gaps still exist on how to treat issues like persistent organic pollutants (POPs) or contaminants of emerging concern (CEC).
    - How the different sources and qualities of organic waste relates to soil carbon stocks and other soil health parameters.
    - There is a potential in recycling organic waste as valuable soil amendments and source for mineral nutrients. But the implications for GHG production is still uncertain.

Urbanisation

Urbanization significantly alters land use patterns, leading to changes in soil properties, and SOC stocks vary widely across different urban environments (e.g., parks, sealed surfaces, green spaces). Furthermore, does urban soils face unique challenges due to compaction, pollution, and limited space. Urban systems involve material flows (e.g., waste, organic matter) that impact SOC dynamics. Thus, will integrating soil health and carbon sequestration goals into urban planning and policies be challenging. Several unsolved questions remain though:

- Understanding how urbanization affects different SOC pools (e.g., particulate organic matter, mineral-associated fractions) remains a gap. Preservation of high-quality soil should be an important principle. In some situations moving soil may be considered the last option when other measures to protect the productive land have failed. Hence:

  - Researchers need to explore the dynamics of SOC storage and turnover in urban soils.
  - Is there a potential to increase SOC carbon stocks in urban soils (e.g. urban agriculture)?
  - How does moving of soil to an alternative location affect SOC stocks, both in the short and long-term?
  - What are the potential trade-offs' effects on SOC stock (e.g., change hydrology/drainage)?
  - What is the potential of constructed soils (also called techno soils) to fulfil urban needs? And how can they be designed to maximize soil C sequestration?
- Heterogeneity across urban soils is a challenge, hence investigating the factors contributing to this heterogeneity is essential.
  - Thus, may identifying patterns and drivers of SOC distribution within cities become a priority.
- Quantifying the influence of urban material flows on SOC inputs and losses is a knowledge gap.
  - Investigating carbon cycling pathways within urban landscapes is thus essential.
- Developing effective soil management practices for urban areas is crucial.
  - Research should focus on strategies to enhance SOC stocks while considering urban constraints.
  - How can food production and other roles of soils and land use (such as flood control, nature conservation) figure more strongly in local and national planning?
- Policymakers need evidence-based guidance on sustainable urban development that considers SOC preservation.
  - Hence is balancing urbanization with soil conservation efforts is a critical area for further research.
- There is a need to develop knowledge and models to evaluate the consequences decreasing agricultural production due to urban sprawl have on food systems elsewhere. Any food not grown within Europe due to land loss is likely to be imported from elsewhere in the world often grown on land recently cleared of natural vegetation and thus emitting C.

Education and awareness raising

Ongoing projects, such as the PREPSOIl, target the need to create awareness and knowledge on soil needs among stakeholders in regions across Europe. There is a great need for education that increases awareness and knowledge of the conservation of soil organic carbon stocks in sustaining life and natural resources from the individual to the societal level. Soil is generally strongly under-communicated in society, including institutes of education at all levels, and there is an obvious link to the 8th mission objective on soil literacy in society, focusing on soil in general but also on its carbon stocks. .

- There is a lack of awareness and appreciation of the multiple benefits and co-benefits of increasing and maintaining soil carbon stocks.
    - Not only for climate change mitigation, but also for soil health, food security including its adaptation to climate change, biodiversity.
    - Also, how soil maintain ecosystem services and by that contribute to the achieve multiple sustainable development goals.
- The trade-offs and synergies between soil carbon and other environmental and socio-economic objectives, and how to optimize and balance them in different contexts and scenario is generally poorly understood in the society.
- The spatial and temporal variability and uncertainty of soil carbon stocks and carbon-storage capacity are not well quantified and communicated, which hinders the assessment and monitoring of soil carbon changes and the evaluation of the potential and effectiveness of soil carbon sequestration practices.
- The lack of clear and consistent use of definitions and concepts of soil carbon storage and soil carbon sequestration, and knowledge on the differences in education and policy making seems pertinent to address.
- The lack of effective and engaging communication and outreach strategies and tools to raise awareness and educate different target groups and sectors on soil carbon issues and solutions.
    - Many existing communication and outreach activities on soil carbon are not tailored to the specific needs, interests, and preferences of different audiences, such as farmers, consumers, policymakers, educators, or media.

EU footprints of soil carbon outside Europe

Current knowledge gaps to improve our understanding on soil organic carbon (SOC) stock outside Europe highlight the need for standardized estimation on the effect of global land use change, European carbon fooprints, how policy making affect SOC coservation, global bodiversity, the importance in having access to comprehensive data sets and accurate mapping techniques.

- European imports of agricultural products can indirectly influence land use changes and soil carbon dynamics in exporting countries, and there need to provide knowledge on:
    - Quantifying the extent of carbon leakage (i.e., when reduced emissions in Europe lead to increased emissions elsewhere due to trade) caused by European imports.
    - Understanding how trade patterns affect land use decisions (e.g., deforestation, conversion of natural habitats) in exporting regions.
    - The importance of pedo-genetic SOC inventories for accurate estimation of land use changes.

- Imported goods carry an “embodied carbon” footprint, which includes the carbon emissions associated with their production and transportation, and there need to provide knowledge on:
    - Assessing the carbon content of different imported products (e.g., food, textiles, timber) and their impact on global soil carbon stocks.
    - Identifying strategies to reduce the carbon intensity of imported goods.
- European trade can lead to both positive and negative effects on soil carbon stocks globally. Positive effects include promoting sustainable practices (e.g., organic farming, agroforestry) that enhance carbon sequestration. Negative effects may arise from increased emissions due to intensified production or land use changes driven by trade demands. Knowledge gaps in this context are:
    - Balancing trade-related emissions with efforts to enhance soil carbon sequestration.
    - Evaluating trade-offs between economic growth, food security, and environmental sustainability.
    - Lifecycle studies on imported food as compared with food grown within Europe.
    - The impact of climate change on SOC stocks and the lack of regional data
- Harmonizing trade policies with climate and soil conservation goals is essential, and thers is need to develop more knowledge on:
    - Developing policies that incentivize sustainable trade practices while considering soil carbon implications.
    - Establishing robust monitoring systems to track the impact of European imports on soil carbon stocks globally.
- Trade can affect biodiversity, which, in turn, influences soil carbon dynamics, and thers is need to develop more knowledge on:
    - Investigating how changes in land use due to trade impact soil microbial communities, organic matter decomposition, and nutrient cycling.
    - Understanding the role of biodiversity in maintaining healthy soils and carbon storage.
- In general, threre is a need for consistent global estimation methods, data comparability and accessabiity.

Soil carbon measuring, accounting, and monitoring

Several studies collectively point to the need for standardized, cost-efficient, and reliable methods that can be applied at various scales, and the potential of data-driven approaches and global frameworks to address these gaps:

- Temporal Variability: Soil carbon levels can fluctuate seasonally and annually due to factors like weather, land use changes, and management practices. Research should focus on understanding these temporal variations and their impact on long-term carbon sequestration.

- Spatial Heterogeneity: Soils exhibit significant spatial variability in carbon content. Developing efficient methods to account for this heterogeneity across different landscapes and soil types is essential.

- Depth Profiles: Soil carbon is distributed across various soil layers. Improving our understanding of carbon distribution with depth is critical for accurate accounting and monitoring.

- Measurement Techniques: Current methods for soil carbon measurement (e.g., soil sampling, spectroscopy, remote sensing) have limitations. Research should explore novel techniques that balance accuracy, cost-effectiveness, and scalability.

- Carbon Sequestration Potential: Identifying the most effective land management practices for enhancing soil carbon sequestration remains an open question. Research should assess the impact of practices like cover cropping, agroforestry, and reduced tillage.

- Carbon Loss Mechanisms: While we focus on sequestration, we must also understand carbon loss mechanisms (e.g., erosion, leaching, microbial decomposition). Quantifying these losses is crucial for accurate accounting.

- Data Integration: Integrating data from various sources (field measurements, satellite imagery, modelling) is challenging. Developing robust frameworks for data fusion and synthesis is necessary.

- Baseline Determination: Establishing accurate baseline soil carbon levels is essential for assessing changes over time. Defining consistent baselines across diverse ecosystems is a knowledge gap.

- Feedback Loops: Soil carbon interacts with other ecosystem components (e.g., vegetation, microbes). Investigating feedback loops and their impact on carbon dynamics is vital.

- Policy and Decision Support: Bridging the gap between scientific research and policy implementation is critical. Developing user-friendly tools for decision-makers to assess soil carbon impacts is needed.

References

- Ahmed YAR, Pichler V, Homolák M, Gömöryová E, Nagy D, Pichlerová M, Gregor J (2012) High organic carbon stock in a karstic soil of the Middle-European Forest Province persists after centuries-long agroforestry management. European Journal of Forest Research 131 (6): 1669-1680. https://doi.org/10.1007/s10342-012-0608-7
- Aksoy E, Yigini Y, Montanarella L (2016) Combining Soil Databases for Topsoil Organic Carbon Mapping in Europe. Plos One 11 (3). https://doi.org/10.1371/journal.pone.0152098

- Amundson R (2001) The Carbon Budget in Soils. Annual Review of Earth and Planetary Sciences 29 (1): 535-562. https://doi.org/10.1146/annurev.earth.29.1.535
- Amundson R, Berhe AA, Hopmans JW, Olson C, Sztein AE, Sparks DL (2015) Soil and human security in the 21st century. Science 348 (6235). https://doi.org/10.1126/science.1261071
- Bai Y, Cotrufo MF (2022) Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science 377 (6606): 603-608. https://doi.org/10.1126/science.abo2380
- Batjes NH (2002) Carbon and nitrogen stocks in the soils of Central and Eastern Europe. Soil Use and Management 18 (4): 324-329. https://doi.org/10.1079/sum2002138
- Bohoussou YN, Kou YH, Yu WB, Lin BJ, Virk AL, Zhao X, Dang YP, Zhang HL (2022) Impacts of the components of conservation agriculture on soil organic carbon and total nitrogen storage: A global meta-analysis. Science of the Total Environment 842 https://doi.org/10.1016/j.scitotenv.2022.156822
- Bolinder MA, Janzen HH, Gregorich EG, Angers DA, VandenBygaart AJ (2007) An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agriculture, Ecosystems & Environment 118: 29-42. https://doi.org/10.1016/j.agee.2006.05.013
- Bolinder MA, Kätterer T, Andrén O, Parent LE (2012) Estimating carbon inputs to soil in forage-based crop rotations and modeling the effects on soil carbon dynamics in a Swedish long-term field experiment. Canadian Journal of Soil Science 92 (6): 821-833. https://doi.org/10.4141/cjss2012-036
- Bongiorno G, Bünemann EK, Oguejiofor CU, Meier J, Gort G, Comans R, Mäder P, Brussaard L, de Goede R (2019) Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecological Indicators 99: 38-50. https://doi.org/10.1016/j.ecolind.2018.12.008
- Breil NL, Lamaze T, Bustillo V, Coudert B, Queguiner S, Claverie N, Jarosz-Pellé N (2021) How does agroecology practices impact soil carbon stock and fluxes in a maize field? EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-14949, 19-30 April 2021. https://doi.org/10.5194/egusphere-egu21-14949,2021
- Chahal SH, Singh A (2020) Impact of Agricultural Practices and their Management Techniques on Soil Carbon Sequestration: A Review. Agricultural Reviews 42 (1). https://doi.org/10.18805/ag.R-2003
- Chaplot V, Smith P (2023) Cover crops do not increase soil organic carbon stocks as much as has been claimed: What is the way forward? Global Change Biology 29 (22): 6163-6169. https://doi.org/10.1111/gcb.16917
- Chenu C, Angers DA, Barré P, Derrien D, Arrouays D, Balesdent J (2019) Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. Soil & Tillage Research 188: 41-52. https://doi.org/10.1016/j.still.2018.04.011
- Clark M, Tilman D (2017) Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environmental Research Letters 12 (6). https://doi.org/10.1088/1748-9326/aa6cd5
- Clark N (2012) Ecological Consequences of Increased Biomass Removal for Bioenergy from Boreal Forests. Sustainable Forest Management - Current Research https://doi.org/10.5772/30347

- Cremers D, Ebinger M, Breshears D, Unkefer P, Kammerdiener S, Ferris M, Catlett K, Brown J, et al. (2001) Measuring Total Soil Carbon with Laser-Induced Breakdown Spectroscopy (LIBS). Journal of Environmental Quality 30 (6): 2202-2206. https://doi.org/10.2134/jeq2001.2202
- Cui YF, Zhang WW, Zhang Y, Liu XM, Zhang Y, Zheng XY, Luo J, Zou JL (2022) Effects of no-till on upland crop yield and soil organic carbon: a global meta-analysis. Plant and Soil https://doi.org/10.1007/s11104-022-05854-y
- De Vos B, Cools N, Ilvesniemi H, Vesterdal L, Vanguelova E, Camicelli S (2015) Benchmark values for forest soil carbon stocks in Europe: Results from a large scale forest soil survey. Geoderma 251: 33-46. https://doi.org/10.1016/j.geoderma.2015.03.008
- EEA (2022) Soil Carbon. URL: https://www.eea.europa.eu/en
- England J, Viscarra Rossel R (2018) Proximal sensing for soil carbon accounting. SOIL 4 (2): 101-122. https://doi.org/10.5194/soil-4-101-2018
- EU commission (2020) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. EU Biodiversity Strategy for 2030. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380
- EU commission (2021) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU Soil Strategy for 2030 Reaping the benefits of healthy soils for people, food, nature and climate. https://environment.ec.europa.eu/publications/eu-soil-strategy-2030_en
- EU commission (2023) Proposal for aDIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCILon Soil Monitoring and Resilience (Soil Monitoring Law). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0416&%3Bqid=1706624227744
- EU Science hub (2023) A new tool maps the state of soil health across Europe. European Commission[In English]. URL: https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/new-tool-maps-state-soil-health-across-europe-2023-03-13_en
- Fan M, Wang X (2022) Enhancing soil quality makes crop production more resilient to climate change. Nature Climate Change 12 (6): 516-517. https://doi.org/10.1038/s41558-022-01387-5
- Ferrara A, Salvati L, Sabbi A, Colantoni A (2014) Soil resources, land cover changes and rural areas: Towards a spatial mismatch? Science of the Total Environment 478: 116-122. https://doi.org/10.1016/j.scitotenv.2014.01.040
- Fornara D, Higgins A (2022) Tillage and reseeding effects on soil carbon stocks: evidence from 500 agricultural grasslands in the UK. Agronomy for Sustainable Development 42 (4). https://doi.org/10.1007/s13593-022-00804-5
- Francaviglia R, Alvaro-Fuentes J, Di Bene C, Gai LT, Regina K, Turtola E (2019) Diversified Arable Cropping Systems and Management Schemes in Selected European Regions Have Positive Effects on Soil Organic Carbon Content. Agriculture-Basel 9 (12). https://doi.org/10.3390/agriculture9120261
- Frank S, Schmid E, Havlík P, Schneider UA, Böttcher H, Balkovic J, Obersteiner M (2015) The dynamic soil organic carbon mitigation potential of European cropland.

Global Environmental Change-Human and Policy Dimensions 35: 269-278. https://doi.org/10.1016/j.gloenvcha.2015.08.004

- Furey GN, Tilman D (2021) Plant biodiversity and the regeneration of soil fertility. Proceedings of the National Academy of Sciences of the United States of America 118 (49). https://doi.org/10.1073/pnas.2111321118
- Gattinger A, Muller A, Haeni M, Skinner C, Fliessbach A, Buchmann N, Mäder P, Stolze M, Smith P, Scialabba NE, Niggli U (2012) Enhanced top soil carbon stocks under organic farming. Proceedings of the National Academy of Sciences 109 (44): 18226-18231. https://doi.org/10.1073/pnas.1209429109
- Gaudaré U, Kuhnert M, Smith P, Martin M, Barbieri P, Pellerin S, Nesme T (2023) Soil organic carbon stocks potentially at risk of decline with organic farming expansion. Nature Climate Change 13 (7): 719-725. https://doi.org/10.1038/s41558-023-01721-5
- Georgiou K, Jackson RB, Vindusková O, Abramoff RZ, Ahlström A, Feng WT, Harden JW, Pellegrini AFA, Polley HW, Soong JL, Riley WJ, Torn MS (2022) Global stocks and capacity of mineral-associated soil organic carbon. Nature Communications 13 (1). https://doi.org/10.1038/s41467-022-31540-9
- Giuntoli J, Searle S, Jonsson R, Agostini A, Robert N, Amaducci S, Marelli L, Camia A (2020) Carbon accounting of bioenergy and forest management nexus. A reality-check of modeling assumptions and expectations. Renewable & Sustainable Energy Reviews 134 https://doi.org/10.1016/j.rser.2020.110368
- Guenet B, Gabrielle B, Chenu C, Arrouays D, Balesdent JM, Bernoux M, Bruni E, Caliman JP, Cardinael R, Chen SC, Ciais P, Desbois D, Fouche J, Frank S, Henault C, Lugato E, Naipal V, Nesme T, Obersteiner M, Pellerin S, Powlson DS, Rasse DP, Rees F, Soussana JF, Su Y, Tian HQ, Valin H, Zhou F (2021) Can N_2O emissions offset the benefits from soil organic carbon storage? Global Change Biology 27 (2): 237-256. https://doi.org/10.1111/gcb.15342
- Haddaway NR, Hedlund K, Jackson LE, Kätterer T, Lugato E, Thomsen IK, Jorgensen HB, Isberg PE (2017) How does tillage intensity affect soil organic carbon? A systematic review. Environmental Evidence 6 (1). https://doi.org/10.1186/s13750-017-0108-9
- Hellsmark H, Mossberg J, Söderholm P, Frishammar J (2016) Innovation system strengths and weaknesses in progressing sustainable technology: the case of Swedish biorefinery development. Journal of Cleaner Production 131: 702-715. https://doi.org/10.1016/j.jclepro.2016.04.109
- Hoffland E, Kuyper T, Comans RJ, Creamer R (2020) Eco-functionality of organic matter in soils. Plant and Soil 455: 1-22. https://doi.org/10.1007/s11104-020-04651-9
- Jandl R, Ledermann T, Kindermann G, Weiss P (2021) Soil Organic Carbon Stocks in Mixed-Deciduous and Coniferous Forests in Austria. Frontiers in Forests and Global Change 4 https://doi.org/10.3389/ffgc.2021.688851
- Janzen HH (2006) The soil carbon dilemma: Shall we hoard it or use it? Soil Biology & Biochemistry 38 (3): 419-424. https://doi.org/10.1016/j.soilbio.2005.10.008
- Kallenbach C, Frey S, Grandy AS (2016) Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nature Communications 7 (1). https://doi.org/10.1038/ncomms13630
- Kätterer T, Bolinder MA, Andrén O, Kirchmann H, Menichetti L (2011) Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. Agriculture Ecosystems & Environment 141 (1-2): 184-192. https://doi.org/10.1016/j.agee.2011.02.029

- Kay S, Rega C, Moreno G, den Herder M, Palma JHN, Borek R, Crous-Duran J, Freese D, Giannitsopoulos M, Graves A, Jäger M, Lamersdorf N, Memedemin D, Mosquera-Losada R, Pantera A, Paracchini ML, Pari P, Roces-Diaz JV, Rolo V, Rosati A, Sandor M, Smith J, Szerencsits E, Varga A, Viaud V, Wawer R, Burgess PJ, Herzog F (2019) Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. Land Use Policy 83: 581-593. https://doi.org/10.1016/j.landusepol.2019.02.025
- Krauss M, Wiesmeier M, Don A, Cuperus F, Gattinger A, Gruber S, Haagsma WK, Peigné J, Palazzoli MC, Schulz F, van der Heijden MG, Vincent-Caboud L, Wittwer RA, Zikeli S, Steffens M (2022) Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe. Soil and Tillage Research 216 https://doi.org/10.1016/j.still.2021.105262
- Kraychenko AN, Guber AK, Razavi BS, Koestel J, Quigley MY, Robertson GP, Kuzyakov Y (2019) Microbial spatial footprint as a driver of soil carbon stabilization. Nature Communications 10 https://doi.org/10.1038/s41467-019-11057-4
- Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304 (5677): 1623-1627. https://doi.org/10.1126/science.1097396
- Land M, Haddaway NR, Hedlund K, Jørgensen HB, Kätterer T, Isberg P (2017) How do selected crop rotations affect soil organic carbon in boreo-temperate systems? A systematic review protocol. Environmental Evidence 6 (1). https://doi.org/10.1186/s13750-017-0086-y
- Lange M, Eisenhauer N, Sierra CA, Bessler H, Engels C, Griffiths RI, Mellado-Vázquez PG, Malik AA, Roy J, Scheu S, Steinbeiss S, Thomson BC, Trumbore SE, Gleixner G (2015) Plant diversity increases soil microbial activity and soil carbon storage. Nature Communications 6 https://doi.org/10.1038/ncomms7707
- Lange M, Roth VN, Eisenhauer N, Roscher C, Dittmar T, Fischer-Bedtke C, Macé OG, Hildebrandt A, Milcu A, Mommer L, Oram NJ, Ravenek J, Scheu S, Schmid B, Strecker T, Wagg C, Weigelt A, Gleixner G (2021) Plant diversity enhances production and downward transport of biodegradable dissolved organic matter. Journal of Ecology 109 (3): 1284-1297. https://doi.org/10.1111/1365-2745.13556
- Lehmann J, Kleber M (2015) The contentious nature of soil organic matter. Nature 528 (7580): 60-68. https://doi.org/10.1038/nature16069
- Liang C, Schimel JP, Jastrow JD (2017) The importance of anabolism in microbial control over soil carbon storage. Nature Microbiology 2 (8). https://doi.org/10.1038/nmicrobiol.2017.105
- Liptzin D, Norris C, Cappellazzi S, Bean GM, Cope M, Greub KH, Rieke E, Tracy P, Aberle E, Ashworth A, Bañuelos Tavarez O, Bary A, Baumhardt RL, Borbón Gracia A, Brainard D, Brennan J, Briones Reyes D, Bruhjell D, Carlyle C, Crawford JW, Creech C, Culman S, Deen B, Dell C, Derner J, Ducey T, Duiker S, Dyck M, Ellert B, Entz M, Espinosa Solorio A, Fonte S, Fonteyne S, Fortuna A, Foster J, Fultz L, Gamble A, Geddes C, Griffin-LaHue D, Grove J, Hamilton S, Hao X, Hayden Z, Honsdorf N, Howe J, Ippolito J, Johnson G, Kautz M, Kitchen N, Kumar S, Kurtz KM, Larney F, Lewis K, Liebman M, Lopez Ramirez A, Machado S, Maharjan B, Martinez Gamiño MA, May W, McClaran M, McDaniel M, Millar N, Mitchell J, Moore A, Moore P, Mora Gutiérrez M, Nelson K, Omondi E, Osborne S, Osorio Alcalá L, Owens P, Pena-Yewtukhiw E, Poffenbarger H, Ponce Lira B, Reeve J, Reinbott T, Reiter M, Ritchey E, Roozeboom K, Rui Y, Sadeghpour A, Sainju U, Sanford G, Schillinger W, Schindelbeck R, Schipanski

M, Schlegel A, Scow K, Sherrod L, Shober A, Sidhu S, Solís Moya E, St Luce M, Strock J, Suyker A, Sykes V, Tao H, Trujillo Campos A, Van Eerd L, van Es H, Verhulst N, Vyn T, Wang Y, Watts D, Wright D, Zhang T, Morgan CS, Honeycutt CW (2022) An evaluation of carbon indicators of soil health in long-term agricultural experiments. Soil Biology and Biochemistry 172 https://doi.org/10.1016/j.soilbio.2022.108708

- Lloyd CR (2006) Annual carbon balance of a managed wetland meadow in the Somerset Levels, UK. Agricultural and Forest Meteorology 138 (1-4): 168-179. https://doi.org/10.1016/j.agrformet.2006.04.005
- Lorenz K, Lal R, Ehlers K (2019) Soil organic carbon stock as an indicator for monitoring land and soil degradation in relation to United Nations' Sustainable Development Goals. Land Degradation & Development 30 (7): 824-838. https://doi.org/10.1002/ldr.3270
- Lugato E, Panagos P, Bampa F, Jones A, Montanarella L (2014) A new baseline of organic carbon stock in European agricultural soils using a modelling approach. Global Change Biology 20 (1): 313-326. https://doi.org/10.1111/gcb.12292
- Lugato E, Leip A, Jones A (2018) Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions. Nature Climate Change 8 (3). https://doi.org/10.1038/s41558-018-0087-z
- Mäkipää R, Abramoff R, Adamczyk B, Baldy V, Biryol C, Bosela M, Casals P, Yuste JC, Dondini M, Filipek S, Garcia-Pausas J, Gros R, Gömöryová E, Hashimoto S, Hassegawa M, Immonen P, Laiho R, Li HH, Li Q, Luyssaert S, Menival C, Mori T, Naudts K, Santonja M, Smolander A, Toriyama J, Tupek B, Ubeda X, Verkerk PJ, Lehtonen A (2023) How does management affect soil C sequestration and greenhouse gas fluxes in boreal and temperate forests? - A review. Forest Ecology and Management 529 https://doi.org/10.1016/j.foreco.2022.120637
- Matyssek R, Wieser G, Calfapietra C, de Vries W, Dizengremel P, Ernst D, Jolivet Y, Mikkelsen TN, Mohren GMJ, Le Thiec D, Tuovinen JP, Weatherall A, Paoletti E (2012) Forests under climate change and air pollution: Gaps in understanding and future directions for research. Environmental Pollution 160: 57-65. https://doi.org/10.1016/j.envpol.2011.07.007
- Mayer M, Prescott CE, Abaker WEA, Augusto L, Cécillon L, Ferreira GWD, James J, Jandl R, Katzensteiner K, Laclau JP, Laganière J, Nouvellon Y, Paré D, Stanturf JA, Vanguelova EI, Vesterdal L (2020) Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. Forest Ecology and Management 466 https://doi.org/10.1016/j.foreco.2020.118127
- Mayer S, Wiesmeier M, Sakamoto E, Hübner R, Cardinael R, Kühnel A, Kögel-Knabner I (2022) Soil organic carbon sequestration in temperate agroforestry systems - A meta-analysis. Agriculture Ecosystems & Environment 323 https://doi.org/10.1016/j.agee.2021.107689
- McCarty GW, Reeves JB, Reeves VB, Follett RF, Kimble JM (2002) Mid-Infrared and Near-Infrared Diffuse Reflectance Spectroscopy for Soil Carbon Measurement. Soil Science Society of America Journal 66 (2): 640-646. https://doi.org/10.2136/sssaj2002.6400a
- Means M, Crews T, Souza L (2022) Annual and perennial crop composition impacts on soil carbon and nitrogen dynamics at two different depths. Renewable Agriculture and Food Systems 37 (5): 437-444. https://doi.org/10.1017/s1742170522000084

- Mikutta R, Mikutta C, Kalbitz K, Scheel T, Kaiser K, Jahn R (2007) Biodegradation of forest floor organic matter bound to minerals via different binding mechanisms. Geochimica et Cosmochimica Acta 71 (10): 2569-2590. https://doi.org/10.1016/j.gca.2007.03.002
- Minasny B, Malone B, McBratney A, Angers D, Arrouays D, Chambers A, Chaplot V, Chen Z, Cheng K, Das B, Field D, Gimona A, Hedley C, Hong SY, Mandal B, Marchant B, Martin M, McConkey B, Mulder VL, O'Rourke S, Richer-de-Forges A, Odeh I, Padarian J, Paustian K, Pan G, Poggio L, Savin I, Stolbovoy V, Stockmann U, Sulaeman Y, Tsui C, Vågen T, van Wesemael B, Winowiecki L (2017) Soil carbon 4 per mille. Geoderma 292: 59-86. https://doi.org/10.1016/j.geoderma.2017.01.002
- Moinet GYK, Hijbeek R, van Vuuren DP, Giller KE (2022) Carbon for soils, not soils for carbon. Global Change Biology https://doi.org/10.1111/gcb.16570
- Ontl TA, Janowiak MK, Swanston CW, Daley J, Handler S, Cornett M, Hagenbuch S, Handrick C, McCarthy L, Patch N (2020) Forest Management for Carbon Sequestration and Climate Adaptation. Journal of Forestry 118 (1): 86-101. https://doi.org/10.1093/jofore/fvz062
- Page KL, Dang YP, Dalal RC (2020) The Ability of Conservation Agriculture to Conserve Soil Organic Carbon and the Subsequent Impact on Soil Physical, Chemical, and Biological Properties and Yield. Frontiers in Sustainable Food Systems 4 https://doi.org/10.3389/fsufs.2020.00031
- Perry S, Falvo G, Mosier S, Robertson GP (2023) Long-term changes in soil carbon and nitrogen fractions in switchgrass, native grasses, and no-till corn bioenergy production systems. Soil Science Society of America Journal https://doi.org/10.1002/saj2.20575
- Powlson DS, Brookes PC, Christensen BT (1987) MEASUREMENT OF SOIL MICROBIAL BIOMASS PROVIDES AN EARLY INDICATION OF CHANGES IN TOTAL SOIL ORGANIC-MATTER DUE TO STRAW INCORPORATION. Soil Biology & Biochemistry 19 (2): 159-164. https://doi.org/10.1016/0038-0717(87)90076-9
- Powlson DS, Galdos MV (2023) Challenging claimed benefits of soil carbon sequestration for mitigating climate change and increasing crop yields: Heresy or sober realism? Global Change Biology https://doi.org/10.1111/gcb.16640
- Qiao Y, Wang J, Liang GP, Du ZG, Zhou J, Zhu C, Huang K, Zhou XH, Luo YQ, Yan LM, Xia JY (2019) Global variation of soil microbial carbon-use efficiency in relation to growth temperature and substrate supply. Scientific Reports 9 https://doi.org/10.1038/s41598-019-42145-6
- Rhodes CJ (2017) The imperative for regenerative agriculture. Science Progress 100 (1): 80-129. https://doi.org/10.3184/003685017x14876775256165
- Sawatdeenarunat C, Nguyen D, Surendra C, Shrestha S, Rajendran K, Oechsner H, Xie L, Khanal SK (2016) Anaerobic biorefinery: Current status, challenges, and opportunities. Bioresource Technology 215: 304-313. https://doi.org/10.1016/j.biortech.2016.03.074
- Schmidt MI, Torn M, Abiven S, Dittmar T, Guggenberger G, Janssens I, Kleber M, Kögel-Knabner I, Lehmann J, Manning DC, Nannipieri P, Rasse D, Weiner S, Trumbore S (2011) Persistence of soil organic matter as an ecosystem property. Nature 478 (7367): 49-56. https://doi.org/10.1038/nature10386
- Science for Environment Policy (2016) No net land take by 2050? Future Brief 14. Produced for the European Commission DG Environment by the Science

Communication Unit, UWE, Bristol. https://catalogue.unccd.int/650_no_net_land_take_by_2050.pdf

- Seufert V, Ramankutty N (2017) Many shades of gray—The context-dependent performance of organic agriculture. Science Advances 3 (3). https://doi.org/10.1126/sciadv.1602638
- Skog KL, Steinnes M (2016) How do centrality, population growth and urban sprawl impact farmland conversion in Norway? Land Use Policy 59: 185-196. https://doi.org/10.1016/j.landusepol.2016.08.035
- Spohn M, Bagchi S, Biederman LA, Borer ET, Bråthen KA, Bugalho MN, Caldeira MC, Catford JA, Collins SL, Eisenhauer N, Hagenah N, Haider S, Hautier Y, Knops JMH, Koerner SE, Laanisto L, Lekberg Y, Martina JP, Martinson H, McCulley RL, Peri PL, Macek P, Power SA, Risch AC, Roscher C, Seabloom EW, Stevens C, (Ciska)Veen GF, Virtanen R, Yahdjian L (2023) The positive effect of plant diversity on soil carbon depends on climate. Nature Communications 14 (1). https://doi.org/10.1038/s41467-023-42340-0
- Tan R, Beckmann V, van den Berg L, Qu F (2009) Governing farmland conversion: Comparing China with the Netherlands and Germany. Land Use Policy 26 (4): 961-974. https://doi.org/10.1016/j.landusepol.2008.11.009
- Tao F, Huang YY, Hungate BA, Manzoni S, Frey SD, Schmidt MWI, Reichstein M, Carvalhais N, Ciais P, Jiang LF, Lehmann J, Wang YP, Houlton BZ, Ahrens B, Mishra U, Hugelius G, Hocking TD, Lu XJ, Shi Z, Viatkin K, Vargas R, Yigini Y, Omuto C, Malik AA, Peralta G, Cuevas-Corona R, Di Paolo LE, Luotto I, Liao CJ, Liang YS, Saynes VS, Huang XM, Luo YQ (2023) Microbial carbon use efficiency promotes global soil carbon storage. Nature 618 (7967). https://doi.org/10.1038/s41586-023-06042-3
- Taylor K, Nelsen T, Scow K, Lundy M (2024) No-till annual wheat increases plant productivity, soil microbial biomass, and soil carbon stabilization relative to intermediate wheatgrass in a Mediterranean climate. Soil and Tillage Research 235 https://doi.org/10.1016/j.still.2023.105874
- Tilman D, Downing JA (1994) Biodiversity and stability in grasslands. Nature 367 (6461): 363-365. https://doi.org/10.1038/367363a0
- Tisserant A, Morales M, Cavalett O, O'Toole A, Weldon S, Rasse D, Cherubini F (2022) Life-cycle assessment to unravel co-benefits and trade-offs of large-scale biochar deployment in Norwegian agriculture. Resources, Conservation and Recycling 179 https://doi.org/10.1016/j.resconrec.2021.106030
- White R, Davidson B, Lam SK, Chen D (2018) A critique of the paper ‘Soil carbon 4 per mille’ by Minasny et al. (2017). Geoderma 309: 115-117. https://doi.org/10.1016/j.geoderma.2017.05.025
- Wielopolski L, Orion I, Hendrey G, Roger H, et al. (2000) Soil carbon measurements using inelastic neutron scattering. IEEE Transactions on Nuclear Science 47 (3): 914-917. https://doi.org/10.1109/23.856717
- Wiesmeier M, Spörlein P, Geuss U, Hangen E, Haug S, Reischl A, Schilling B, von Lützow M, Kögel-Knabner I (2012) Soil organic carbon stocks in southeast Germany (Bavaria) as affected by land use, soil type and sampling depth. Global Change Biology 18 (7): 2233-2245. https://doi.org/10.1111/j.1365-2486.2012.02699.x
- Yang Y, Tilman D, Furey G, Lehman C (2019) Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nature Communications 10 https://doi.org/10.1038/s41467-019-08636-w

- Zeng J, Matsunaga T, Tan Z, Saigusa N, Shirai T, Tang Y, Peng S, Fukuda Y, et al. (2020) Global terrestrial carbon fluxes of 1999–2019 estimated by upscaling eddy covariance data with a random forest. Scientific Data 7 (1). https://doi.org/10.1038/s41597-020-00653-5
- Zuazo VHD, Pleguezuelo CRR, Tavira SC, Martínez JRF (2014) Linking Soil Organic Carbon Stocks to Land-use Types in a Mediterranean Agroforestry Landscape. Journal of Agricultural Science and Technology 16 (3): 667-679. URL: ://WOS:000335980300017