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SOLO Soil organic carbon stocks

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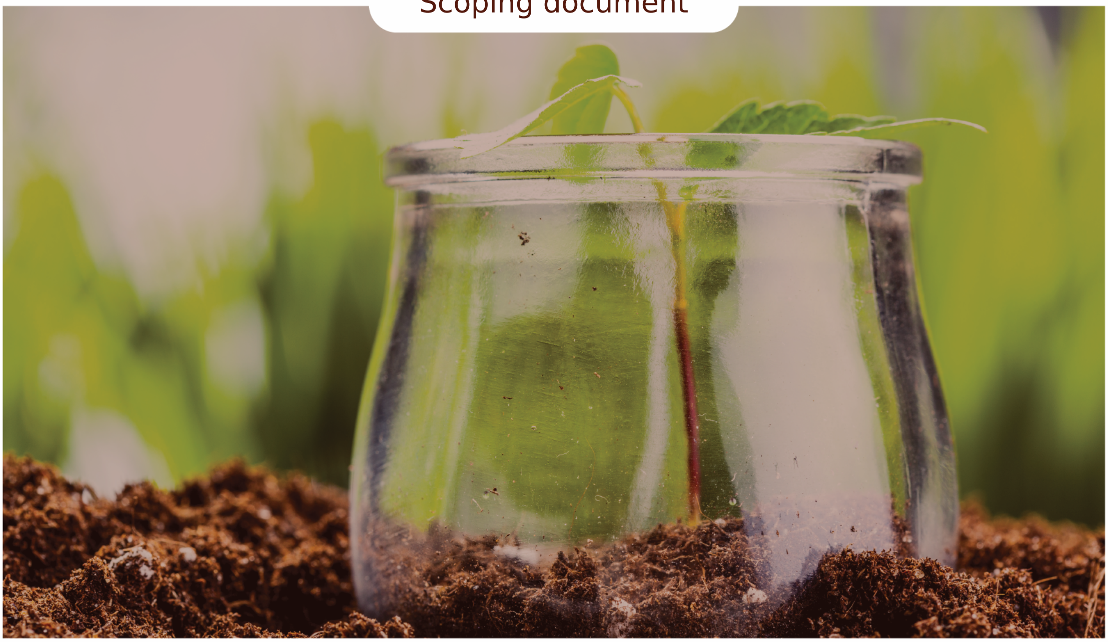

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Scoping Document

# Outlook on the knowledge gaps to conserve and increase soil organic carbon stocks

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## 1. Introduction to the Think Tank conserve and increase soil organic carbon stocks

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 (Fig. 1), and currently represent a net source of greenhouse gas emissions in the EU, European Environmental Agency (EEA 2022). Thus, improved soil management geared at improving soil heath and reducing C losses could substantially contribute to achieving European Union climate targets. 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 contain the highest carbon stocks (Batjes 2002, De Vos et al. 2015) and it is essential to manage the water level of peat wetlands to maintain these stocks (Lloyd 2006). On average, global agricultural topsoil may have lost 2.5 ± 2.3 Mg C $ha^{-1}$ (3.9 ± 5.4%) under constant net primary production (NPP). When accounting for NPP variations influenced by temperature and precipitation, the estimated loss is 1.6 ± 3.4 Mg C $ha^{-1}$ (2.5 ± 5.5%) (Poeplau and Dechow 2023).

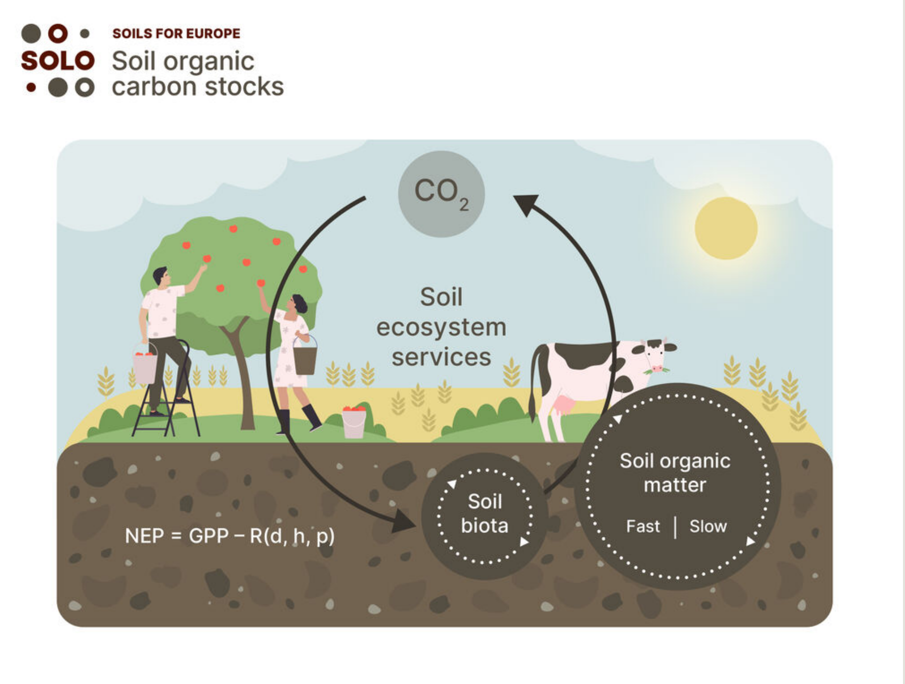


Figure 1. doi

The figure illustrates how soil organic carbon (SOC) is a key component in the global carbon cycle. The flow of carbon (C) in the ecosystem is intricately linked to SOC stocks as fast and slow reacting soil organic matter. The C-flow play a crucial role in providing essential ecosystem services, acting as both a carbon sink and a source, depending on land use and management practices. The net ecosystem production (NEP) is a function of the gross primary production (GPP), respiration (R) by herbivores (h), plants (p), below- and above ground decomposers (d)

It is important to acknowledge that in addition to mineralisation, a significant loss of soil C happens by erosion and leaching (Chenu et al. 2019). Thus, the SOC stocks are a result of the simple balance of input and output with time as outlined in Equation 1:

$$dC/dt = I(t) – k(t)C \quad \text{(eq. 1)}$$

where I is organic C input, k is the rate of C loss in the time-interval t.

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 SOC stocks. As illustrated in figure 1, SOC is the main a major 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 adhering 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 1000” 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 their use and quality in relation to carbon storage e.g (Moinet et al. 2022, Powlson and Galdos 2023, White et al. 2018).There is, however, an overwhelming body of evidence that increasing SOC stock in agricultural soils may can 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 SOC stock is often declining, and vulnerable to further losses due to intensive management and climate change. Emphasizing the entire carbon cycle and the various functions of SOC, not just its stable forms, to better address climate mitigation and ecosystem functions, is essential for creating sustainable and resilient ecosystems (Janzen 2024). Conserving SOC in soils may support climate change adaptation, resistance and resilience to adverse weather conditions (Qiao et al. 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.

This 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.). The SOC Think Tank addresses the importance of maintaining, or in many situations where possible increasing the soil organic carbon SOC stocks by:

- Addressing the impacts of management:
  - Climate change and adaptation technologies
  - Biodiversity and soil health
  - Forestry management
  - Agronomic and land use management
- Finding Technical solutions for monitoring, reporting and verification (MRVs):
  - Soil carbon measurement and monitoring
- Considering the socio-economic context:
  - Policy making and decision support
  - Urbanization and circular economy
  - Education and awareness raising
  - EU-footprints on SOC-stocks outside EU

# 2. State-of-the-Art

## 2.1 Current status of knowledge on conserving and increasing soil organic carbon stocks

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). A review of recent studies by Bai and Cotrufo (2022) highlights 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, and thus mediating the impacts of climate change. The biogeochemistry of SOC is a dynamic continuum, ranging from intact plant residues to highly oxidized carbon in carboxylic acids. Understanding this continuum requires a mechanistic grasp of how SOC interacts with minerals, and how microbial activity mediates the balance between organic matter stocks and flows (Lehmann and Kleber 2015). 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).

The EUSO soil health dashboard reveals that over 60% of EU soils are affected by one or more soil degradation processes or by soil sealing (EU comission 2023b), however gaps remain due to limited data on various soil degradation issues. Soil health is closely linked to SOC, as SOM affects soil structure, soil life and elemental cycles, which together sustain essential ecosystem functions such as erosion protection, soil biodiversity, primary production, climate regulation and water quality (Hoffland et al. 2020). 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 thus been a matter of intense research (Georgiou et al. 2022, Liang et al. 2017).

Increasing SOC stocks for climate change adaptaion in Europe necessitates understanding the trade-offs and synergies of soil management strategies (SMS) and land use change (LUC) in relation to SOC stocks. This is closely linked to the concept of soil as a living ecosystem and the impact of biodiversity on SOC. Many lists of indicators for soil quality and soil health include carbon content and microbial respiration together because they are positively correlated (EU comission 2023a). This complex topic is influenced by various factors, including land use, environmental conditions, and biodiversity (Ratcliffe et al. 2017). 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 exist; see Bongiorno et al. (2019). As microbial activity and nutrient release increase with increasing carbon content, nutrient mining may occur, potentially counteracting efforts to improve soil health Additional biological indicators may also provide insight about C dynamics and microbial activity (Liptzin et al. 2022).

Estimates of SOC stocks in Europe and globally are characterized by significant variability and complexity, influenced by factors such as initial SOC stock, climate, land use, and soil type. The initial SOC stocks are tightly related to SOC loss and initial SOC stocks explain the variability of the loss of SOC stocks globally (Poeplau and Dechow 2023). Soil organic carbon stocks in European agricultural soils are estimated at 17.63 Gt for the 0-30 cm depth, with regional variations due to climate and land use (Lugato et al. 2018). The average SOC stocks in forest floor soils has been estimated at 22.1 t C $ha^{-1}$, 108 t C $ha^{-1}$ in mineral soils, and 578 t C $ha^{-1}$ in peat soils, measured to a depth of 1 meter. In line with global trends observed in forest soils, the vertical distribution of SOC showed that approximately 50% of the carbon was concentrated in the top 20 cm, and about 55–65% was found within the top 30 cm of the soil profile (Vos et al. 2015). Soil organic carbon stocks and their distribution in the landscape are influenced by environmental factors such as climate, soil pH, and land cover type, which vary across Europe (Vos et al. 2015). This spatial variability necessitates region-specific models for accurate SOC estimation. Current estimates and models indicate both challenges and opportunities for SOC management, highlighting the need for further research to refine these estimates to reduce uncertainties, and support effective policymaking for carbon sequestration and soil management in general.

Integrating soil monitoring frameworks with natural capital accounting can improve assessments of soil conditions and changes, supporting policy and socio-economic decisions. While public awareness of the importance of soil health, soil carbon, and climate change is growing in Europe, significant gaps and challenges remain (Thorsøe et al. 2023). Enhancing knowledge transfer and increasing public engagement are essential. Key recommendations include strengthening knowledge brokers, making research more applicable to practitioners, and providing incentives for sustainable land management.

Changes in soil carbon stocks occur slowly, with management effects varying across climate zones and soil types. Effective implementation of soil carbon management technologies necessitates interaction with all relevant stakeholders, including farmers and landowners, agronomic advisors, agricultural supply companies, policymakers, and those involved in the food supply chain. Practitioners possess essential knowledge and experience about their own land, and mutual knowledge exchange will facilitate the necessary engagement for innovative technology implementation, ultimately improving soil carbon stocks and overall soil health.

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 grass 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 on-farm situations
4. interaction between policy makers and relevant stakeholders

## 2.2 Prioritizations of knowledge gaps

The SOC Think Tank has examined the state of the art and identified knowledge gaps regarding the impact of agricultural and forest land uses on SOC. It also explored how biodiversity, the circular economy, and urbanization interact with SOC stocks. Additionally, the need for further research and implementation in modelling and method standardization was highlighted. The investigation extended to identifying how SOC is affected by EU policies outside the EU and addressing literacy gaps in this context. Numerous knowledge gaps were identified for each topic. Despite this, several gaps can be grouped and prioritized, while still validating the identified research and innovation development and application gaps. The preliminary identification of all knowledge gaps was published in the Almås et al. (2024) scoping document.

Before the stakeholder workshop organized by the SOLO team in Sofia on November 5th and 6th, 2024, the SOC Think Tank key stakeholders identified the most critical knowledge gaps for each of the aforementioned topics affecting SOC stocks. Based on this pre-identification, Think Tank members grouped and reported the ten most essential and comprehensive knowledge gaps for further prioritization at the Sofia workshop. The key knowledge gaps that received the highest scores defined a preliminary ranking. This process was later repeated with a larger group of stakeholders in an online meeting. The cumulative scores resulted in the ranking identified in Table 1 below. The final list was also presented and verified by participants of the “soil pollution and restoration” Think Tank "Soil-week" event held in Hungary on December 4th.

Table 1.

Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is available under Suppl. material 1. *KDG = knowledge development gap, KAG = knowledge application gap*)

| Rank | Knowledge gap | Type of knowledge gap |
|---|---|---|
| 1 | Increasing SOC stocks for climate change adaptation | KDG |
| 2 | Biodiversity; interaction between soil carbon and soil biology | KDG |
| 3 | Policy making and decision support | KAG |
| 4 | Soil carbon monitoring, reporting and verification (MRV) | KDG |
| 5 | SOC and circular economy, LCA | KDG |
| 6 | SOC in agronomic systems | KDG |

| Rank | Knowledge gap | Type of knowledge gap |
|---|---|---|
| 7 | Urbanization and SOC | KAG |
| 8 | Education and awareness raising on SOC | KAG |
| 9 | Management of forests and SOC | KDG |
| 10 | EU footprints of soil carbon outside Europe | KAG |

# 3. Roadmap for the topic “Conserving and increasing soil organic carbon stocks”

## 3.1 Key knowledge gaps

An overview of the prioritized knowledge gaps, their sector impact, bottlenecks and suggested actions are summarised in Table 2 (Suppl. material 1) in the end of Chapter 3.

### Knowledge gap 1: Increase SOC stocks for climate change adaptation

*The investigation has identified the following knowledge development gap:*

*The knowledge gap to increase SOC stocks for climate change adaptation requires 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 policies. This knowledge gap represents several topics requiring knowledge development for further research and innovation actions.*

Many European soils are degraded, necessitating the development of specific indicators that correlate with SOC storage and climate resilience. Monitoring and assessing SOC stocks across diverse landscapes is challenging due to inconsistent data and methodologies. Integrating SOC considerations into agricultural policies and fostering collaboration among policymakers, scientists, and practitioners is crucial. Additionally, understanding the effects of climate adaptation measures and forest management practices on SOC, and providing incentives for farmers and forest owners to adopt sustainable strategies, is important.

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 (Page et al. 2020). Increased SOC stocks generally favor both mitigation and adaptation as higher SOC in top layers in e.g. no tillage systems, provide resilience to extreme weather conditions (Haddaway et al. 2017).

Climate change adaptation includes soil and crop management practices for soil water retention and effective water infiltration strategies, which both are closely linked to maintaining or increasing SOC stocks. Practices such as organic amendments and maintaining continuous living cover improve soil structure, by improving soil aggregation and enhancing bio-porosity. Bio-porosity refers to the presence of pores in the soil that are created or enhanced by biological activity, such as the action of soil organisms like earthworms. This enhances water infiltration and reduces surface runoff, although bypass flow through biopores may increase nutrient losses (Sims et al. 1998). However, these can also reduce soil water storage and groundwater recharge, particularly in dry climates: In Mediterranean rainfed agroecosystems, techniques like no or minimum tillage, and direct drilling improve soil water retention and potentially carbon storage in top mineral soils (Blanchy et al. 2023). But the potential in climate change mitigation is limited considering the whole soil profile (Cai et al. 2022), acting as both adaptation and mitigation strategies, and results from cool and humid climate are not so promising (Honkanen et al. 2024). The choice of tillage and residue management significantly affects SOC dynamics. Retaining crop residues can mitigate SOC losses, while residue harvesting leads to substantial declines (Herzfeld et al. 2021).

Soil organic carbon stocks are influenced by climate and land use changes, and in Mediterranean areas, conversion from natural vegetation to agriculture significantly reduces SOC stocks (Lozano-García et al. 2017). Other studies have shown the same, and generally the loss of SOC is strongest when turning grassland and forest into cropland (De Rosa et al. 2024, Poeplau and Don 2013). According to the study by Poeplau and Don (2013) the land use change from cropland to forest increased SOC by 21 Mg $ha^{-1}$, while grassland to cropland decreased SOC by 19 Mg $ha^{-1}$. Across Europe, SOC stocks may increase by 2050 under various climate and land cover scenarios, although the extent varies (Yigini and Panagos 2016). The effectiveness of these strategies can vary based on local conditions and requires careful consideration of trade-offs.

Farming systems with focus on soil management, e.g. practicing reduced or no tillage to achieve minimal soil disturbance, as well as crop rotation, cover crops, and plant residue or manure return. Such practices will have impacts on SOC storage, thus contributing to climate change mitigation and adaptation.

Organic farming has the potential to increase SOC stocks and sequestration rates (Clark and Tilman 2017), and can offer larger environmental benefits in comparison to conventional agricultural systems (Gattinger et al. 2012). However, organic farming generally produce slightly less biomass, and the effect on soil carbon stock from organic farming is complex and content performance dependent (e.g. climate, soil characteristics etc, Seufert and Ramankutty (2017)). Organic farming is, in principle, based on fertile soil that must be maintained through regular application of organic material as fertiliser. Over time, this has the potential to also increase SOC. Organic farming may in some cases also involve reduced tillage, although soil tillage is often used for weed control. Reduced tillage has the 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 increase in top 10-15 cm, slight decrease in intermediate dept (down to 50 cm), followed by a slight increase again in 70-100 cm depth. The investigation reported in Gaudaré et al. (2023) indicates, 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 uncertain consequences for the environment.

Regenerative agriculture (RA) may be defined as “an approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production” (Schreefel et al. 2020). As such, it consists of a range of different practices that vary varies between regions, farmers and farming systems. It often includes focus on reduced tillage, crop retention, cover crops crop residue management. These practices in combination have shown to increase SOC (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 regenerative practices, particularly reduced or no-tillage and cover crops, have the potential to increase SOC content (Breil et al. 2021). Regenerative agricultural practices are not only likely to enhance carbon storage (Breil et al. 2021) but reports also indicate improved general soil fertility and crop yields in many situations (Rhodes 2017).

Conservation agriculture (CA) is based on many of the abovementioned principles and focuses on 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 metastudy 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.

Results of the impacts of agroforestry on soil C stocs from the boreal zone are scarce, but some studies show that agroforestry and intercropping can significantly impact soil organic carbon stocks in Europe Heimsch et al. (2023). Trees increased C accumulation of the ecosystem, and thus, the net emissions were estimated to be smaller than without the tree row, but soil SOC stocks were not measured. Mayer et al. (2020) conducted a meta study on temperate climate zones worldwide and found that agroforestry systems sequester significant amounts of SOC in topsoil 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. Further, Kay et al. (2019) emphasized the potential of agroforestry in sequestering carbon and mitigating environmental pressures in European farmland. Positive effects of diversified arable cropping systems on SOC content in European agroecosystems have generally been reported (Francaviglia et al. 2019).

Forest management must incorporate adaptive strategies to address climate change impacts, such as altering tree species composition, adjusting rotation periods, and modifying stand structures to maintain forest productivity and resilience (Jandl et al. 2019). Maintaining genetic diversity and resilience of forest ecosystems is crucial. This includes selecting tree species and genotypes that are better adapted to future climatic conditions, such as increased drought risks (Keenan 2015).

Effective climate change adaptation in marginal and alpine systems requires managing the impacts of shifting conditions on these fragile ecosystems. Adaptation strategies are essential for preserving biodiversity, ecosystem functions, and agricultural productivity. In alpine grasslands, climate change may alter plant species composition, potentially stabilizing primary production despite warming. However, these changes often lead to deeper root systems, which can influence soil carbon storage dynamics (Liu et al. 2018). Marginal populations of plants, such as those in alpine environments, may exhibit strong local adaptations to environmental stressors like frost. These adaptations are crucial for survival but may be limited by genetic diversity (Kreyling et al. 2014).

*The investigation has identified following bottleneck*

*Complexity and unclear mechanisms of SOC dynamics hinder understanding and application in climate adaptation strategies*.

*Suggested actions include*:

*(i) More experimental research is needed to study the long-term dynamics of trade-offs and synergies in SOC sequestration under various soil management strategies*;

*(ii) There is also need to developing models and monitoring programs to better understand soil carbon stocks and degradation is crucial*;

*(iii) Research should provide further knowledge on how soil structure, management practices and extreme weather events impact organic carbon stocks, and how this interacts with functional biodiversity. To assess these effects, research on harmonizing measuring, accounting, monitoring and model development across Europe is required*

*(iv) It's also essential to provide regional-specific long-term knowledge for tailoring adaptation strategies*;

*(v) There is also a need to increase the understanding on the indirect effects of adaptation practices on soil functions and biodiversity*.

*(Vi) Research should focus on practices that promote SOC accumulation while balancing trade-offs between climate adaptation, food security, and ecosystem services*;

*(Vii) Transfer of existing research to practical applications remains insufficient*

## Knowledge gap 2: Biodiversity - interaction between soil carbon and soil biology

*The investigation has identified the following knowledge development gap*:

*There is limited understanding of how soil biodiversity influences carbon cycling processes and the lack of comprehensive data on soil biodiversity across different regions and scales. While there is growing evidence linking plant diversity to soil carbon cycling, there is limited information on how soil biodiversity itself influences these processes*.

The "Convention on Biological Diversity (CBD)" (www.cbd.int) 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 below ground, including microorganisms, microfauna, mesofauna, and macro/megafauna. Soil biodiversity blends four complementary dimensions of soil systems: soil physics, soil chemistry, soil biology, and soil ecosystem functions. It relates to specific ecological indicators and includes a wide variety of soil-related Essential Biodiversity Variables (EBVs) to track the state and dynamics of global soil biodiversity and ecosystem functioning over time (Guerra et al. 2021).

Soil biodiversity plays a 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 (Chen et al. 2020, Chen et al. 2018). 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, biodiversity does 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 global soils.

High soil biodiversity supports various soil ecosystem functions and increases the system's ability to withstand and recover from environmental changes (Delgado-Baquerizo et al. 2025), and diverse plant species and soil organisms improve nutrient cycling and soil fertility (Furey and Tilman 2021). This is achieved through interactions among soil organisms, which enhance nutrient availability and storage, leading to increased soil fertility and reduced fertilizer needs (Delgado-Baquerizo et al. 2020). There is evidence that that high soil biodiversity increases ecosystem stability, resistance to environmental changes, and protection against diseases (Wang et al. 2025). These functions collectively contribute to a more robust and sustainable soil ecosystem, capable of adapting to and recovering from various environmental challenges (Bender et al. 2016, Brussaard et al. 2007), and soil health, high biodiversity and conservation of soil organic carbon are strongly connected (Chen et al. 2020, Lal 2016). It is important to note, however, that in some terrestrial ecosystems, the functional biodiversity is naturally low, particularly in marginal and extreme environments. This low biodiversity is characteristic for such systems, but this results in limited functional redundancy, making these ecosystems particularly susceptible to disturbances (Wall and Virginia 1999).

High plant biodiversity boosts plant productivity and root biomass, enhancing microbial growth and activity (Prommer et al. 2020). This leads to greater carbon inputs into the soil and improved carbon sequestration. Maintaining high levels of plant and soil organism diversity is essential for improving soil carbon storage and mitigating climate change impacts. Land-use practices that promote biodiversity, such as organic farming and diverse plantings, are beneficial for SOC conservation (Maron et al. 2018). However, the complexity of mechanisms at play is not yet well understood. For example, mixed species stands with low diversity in root architecture have recently been found to contribute to soil C storage more than those displaying contrasting root-system architecture (Yin et al. 2025). These insights underscore the importance of integrating biodiversity considerations into land management and policy decisions to enhance soil carbon sequestration.

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. 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 a grassland clay rich soils, where essential nutrients 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, plant species can 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). Higher plant diversity can enhance soil multifunctionality and increase SOC stocks by promoting below-ground organism diversity, which in turn supports carbon sequestration (Schittko et al. 2022, Steinbeiss et al. 2008,Yin et al. 2025). The study by Steinbeiss et al. (2008), showed that higher species richness significantly increased carbon storage and reduced carbon losses across all soil depths. Species diversity was found to be more important than biomass production for soil carbon changes. Finally, they report that tall herbs seem to aid in reducing carbon losses below 20 cm depth early on. An important observation is that this effect may be consistent across different land-use types, including forests, grasslands, and croplands (Chen et al. 2020). In contrast, intensifying land use leads to a reduction in the number of soil biota functional groups, with fewer species that are more closely related taxonomically (Tsiafouli et al. 2015).

Biodiversity, both above- and belowground, is integral to maintaining and enhancing SOC in Europe. Diverse plant species and soil organisms contribute to carbon sequestration and overall ecosystem functionality. Land use changes and agricultural practices significantly influence these dynamics, with more diverse systems generally supporting higher SOC levels. Conservation efforts should focus on maintaining biodiversity to ensure the sustainability of soil carbon stocks. Li and colleagues (Li et al. 2024) examined croplands with varying SOC levels to explore the relationship between SOC decomposition and the diversity, composition, and networks of belowground communities, including archaea, bacteria, fungi, protists, and invertebrates. They reported that SOC is crucial for the structure and metabolic activities of belowground biota. Thus understanding the evolution of belowground communities and their feedback on SOC dynamics seems important for carbon cycling, biodiversity conservation, and carbon management.

Biodiversity in urban ecosystems remains a largely unexplored field. However, even in these environments, biodiversity appears to enhance ecosystem functions and services, particularly through soil carbon sequestration. Schittko et al. (2022) conducted a study in Berlin, Germany, and they found that plant diversity positively influences soil multifunctionality and organic carbon stocks by increasing the diversity of below-ground organisms. These benefits are seen in both native and non-native plant species, though they are more pronounced in native species. Therefore, increasing the diversity of plants and soil fauna in urban grasslands can improve soil multifunctionality and help mitigate climate change.

A study from South Africa addressed that although no clear global relationship exists, positive local and regional relationships highlight the potential value of biodiversity in enhancing carbon management, but that knowledge gaps still hinder effective policy development for co-managing biodiversity and carbon (Midgley et al. 2010). This is also acknowledged in the study by Chenu et al. (2019), reporting that while existing knowledge and tools address many questions, further research is needed, especially on practices and the role of soil microorganisms in stabilizing soil organic matter. Protecting natural areas helps safeguard biota and reduce atmospheric carbon emissions, and including the interaction between soil biodiversity and soil carbon content, could increase funding opportunities for conservation (Sheil et al. 2016).

Evidence points to the need for further research to understand the role of biodiversity in SOC dynamics, the impact of land use management practices, and how to integrate soil biodiversity into policy and conservation efforts. Additionally, it is crucial to investigate how climate change and environmental conditions interact with biodiversity and to better understand belowground biological processes.

*The investigation has identified the following bottlenecks:*

*(i) The lack of understanding of the mechanisms driving the observed congruence between biodiversity and carbon stocks limits the ability to predict and manage ecosystem services effectively.*

*(ii) Limited knowledge about how belowground communities—particularly microbes and invertebrates—regulate SOC turnover and ecosystem functioning constrains the development of holistic soil management strategies.*

*(iii) The unclear influence of biodiversity on SOC dynamics in novel ecosystems, such as those with high non-native species presence or urban disturbances, hampers the formulation of adaptive conservation and restoration practices.*

*(iv) The poorly understood interplay between plant litter inputs and microbial respiration across ecosystems creates a bottleneck in determining how plant diversity influences SOC accumulation and stability.*

*(v) The lack of clarity on how different biodiversity measures—such as species richness and functional traits—affect carbon stocks, especially in forest ecosystems, impedes the integration of biodiversity into carbon management frameworks*.

*(vi) Current policy frameworks are not fully equipped to address the intricate and dynamic interactions between biodiversity and SOC, creating a bottleneck in implementing effective climate and conservation strategies*.

*(vii) The lack of integration of recent scientific insights—particularly regarding the role of soil microorganisms and biodiversity in stabilizing soil organic matter—into agricultural and forest management practices hinders efforts to enhance SOC storage at scale*.

*(viii) Uncertainty about how soils should be used for carbon storage hinders climate mitigation planning*.

*(ix) Limited research and political sensitivity around carbon sequestration techniques hinder policy support and long-term adoption*.

*Suggested actions include*:

*(i) Integrate belowground biological processes into SOC models to improve carbon management strategies.*

*(ii) Developing high-resolution maps and models to predict soil biodiversity and SOC is crucial. This includes using digital soil mapping and regression analysis to link soil attributes with biodiversity .*

*(iii) An integrative approach that includes setting baselines, monitoring threats, and establishing soil indicators is recommended*.

*(iv) Encouraging sustainable land-use practices and reducing agricultural intensification can help preserve soil biodiversity. Providing incentives for sustainable practices and improving knowledge access are also suggested*.

*(v) Providing incentives for sustainable practices and improving knowledge access are also suggested*.

*(vi) Strengthen the role of knowledge brokers and improve the relevance of research activities for land users through targeted advice and information dissemination.*

*(vii) Encourage research that integrates social and ecological systems to develop comprehensive soil carbon management strategies*.

## Knowledge gap 3: Policy making and decision support

*The investigation has identified the following knowledge application gap:*

*The gap between existing scientific knowledge and its practical implementation in policy and land management creates a bottleneck in efforts to conserve and enhance SOC stocks. Without effective knowledge exchange and decision support, proven strategies remain underutilized, slowing progress in SOC restoration and climate resilience*.

European soil carbon management is supported by various policy frameworks and social strategies, including the European Green Deal, Common Agricultural Policy (CAP), and carbon credit systems. The European Green Deal aims to make the EU climate-neutral by 2050, incorporating soil protection measures such as reducing chemical pesticide use and increasing organic farming. The European Climate Law also addresses SOC enhancement and wetland maintenance (Montanarella and Panagos 2021). The CAP supports soil carbon management through incentives for sustainable practices and the integration of soil carbon sequestration into climate-smart agriculture. However, current policies are deemed insufficient for large-scale adoption, suggesting a need for more focused regulatory frameworks (Verschuuren 2018). Carbon farming practices incentivized through carbon credit systems reward increased soil carbon stocks (Criscuoli et al. 2024). The credit system risks masking harmful practices, especially outside the EU, through offsetting, while also creating dependency on external, non-productive funding, echoing inefficiencies seen in parts of the CAP. Recommendations include expanding eligible practices and setting regulatory baselines to ensure effective implementation. The EU Soil Observatory collects data and develops indicators to assess progress towards soil management targets, supporting policy development and implementation (Montanarella and Panagos 2021).

Despite these initiatives, challenges persist in policy adequacy and knowledge dissemination. To ensure effective soil carbon management and climate change mitigation, it is essential to address these issues through targeted interventions and local adaptation strategies. Increasing SOC stocks is crucial for enhancing soil fertility, food security, and climate change mitigation, but significant knowledge and application gaps remain in policymaking and decision support.

There is a need to clearly differentiate between SOC storage and sequestration and to develop methods for accurately estimating potential SOC gains from various agricultural practices. Chenu et al. (2019) elaborate on how implementing management strategies to boost SOC stocks addresses several key questions and considerations, including methods to increase SOC stocks, the rate and duration of these increases, prioritizing storage areas, estimating potential carbon gains, and selecting suitable agricultural practices. According to Maenhout et al. (2024), soil management strategies (SMS) can enhance SOC stocks, reduce greenhouse gas (GHG) emissions, and decrease nitrogen

(N) leaching. However, some SMS may increase emissions of GHGs like nitrous oxide ($N_2O$) or methane ($CH_4$), offsetting the benefits of SOC sequestration. Understanding these trade-offs and synergies is essential for selecting sustainable SMS for European agriculture, but knowledge remains limited.

The effect of policymaking and support on the long-term dynamics of SOC stocks under different management practices and climatic conditions is also underexplored (Maenhout et al. 2024, Wang et al. 2022). Globally, much research predominantly focuses on ecological aspects, with a lack of integration of social components, such as farmer perspectives, which are essential for the sustainability of carbon-building practices (Amin et al. 2020). The study by Thorsøe et al. (2023) highlights that stakeholders emphasize the need for better knowledge transfer to practitioners and recommend raising awareness, improving research relevance, and providing incentives. Moreover, tailoring soil management techniques to local conditions, such as climate and farming systems seems essential to enhance SOC (Mäkipää et al. 2024). Common barriers seem to include biophysical conditions, financial support, and advisory service quality. Opportunities lie in economic incentives, regulatory harmonization, and fostering long-term planning and resilience (Mills et al. 2020).

*The investigation has identified the following bottlenecks:*

*(i) Uncertainty about how soils should be used for carbon storage hinders climate mitigation planning*.

*(ii) Limited research and political sensitivity around carbon sequestration techniques hinder policy support and long-term adoption*.

*Suggested actions include*:

*(i) Strengthen the role of knowledge brokers and improve the relevance of research activities for land users through targeted advice and information dissemination*.

*(ii) Encourage research that integrates social and ecological systems to develop comprehensive soil carbon management strategies*.

*(iii) Promote studies in underrepresented regions to ensure a more global understanding of SOC dynamics*.

*(iv) Invest in monitoring and modelling frameworks to provide robust data for decision-making and policy development.*

## 3.2 Prioritized knowledge gaps

### Knowledge gap 4: Soil carbon monitoring, reporting and verification (MRV)

*The investigation has identified following knowledge development gap:*

*There is a significant lack of understanding and infrastructure for monitoring, reporting, and verifying SOC across Europe.*

Limited data, inconsistent methods, and lack of localized models hinder accurate monitoring and verification of SOC across Europe. This includes insufficient long-term datasets, non-standardized sampling methods, and a shortage of localized models that reflect environmental variables like climate, soil pH, and land cover, limiting the accuracy and effectiveness of SOC assessments for policy and land management. To effectively address content and quality of SOC stock, several methods exist ranging from laboratory measurements to remote sensing modelling. In short, the determination of SOC stocks requires measurements of bulk density, gravel content and SOC concentration in different depths. Careful, repeated field sampling followed by laboratory analysis following standardized and procedural guidelines are, however, necessary for accurate reporting and verification. Traditional analysis methods are often time consuming, so more recent methods, such as Visible–Near-Infrared (vis–NIR) Spectroscopy for SOC determination and Active Gamma-Ray Attenuation for bulk density can be relevant for some studies. However, gravel content may still require (wet) sieving (England and Viscarra Rossel 2018). For remote sensing eddy covariance is a costy application useful for measuring respiration and carbon fluxes, providing insights into regional SOC sequestration when used in combination with simulation modelling (Zeng et al. 2020). There is a challenge in developing cost effective methods for detecting changes in SOC resulting from changes in management etc., but several 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).

Existing soil monitoring networks in Europe are inadequate for comprehensive SOC accounting. They often lack biological and physical parameters, focusing predominantly on chemical attributes, which limits their ability to assess soil functions comprehensively (van Leeuwen et al. 2017). There is a lack of standardized methods and comprehensive datasets, particularly for agricultural soils. This results in inconsistent data across different regions and countries, (Rodrigues et al. 2021), making it difficult to compare and integrate findings at a European scale (Lugato et al. 2014). Efforts to model SOC stocks are ongoing, but these models often require improvements to account for regional environmental factors and land-use changes accurately (Rial et al. 2017). The impact of environmental factors such as climate, soil pH, and land cover on SOC storage is not fully understood, necessitating more localized and specific models (*Prechtel et al. 2009, Rial et al. 2017*).

<u>*The investigation has identified following bottlenecks*</u>

*(i) Lack of long-term datasets, standardized sampling protocols, and harmonized data across regions, prevents accurate, comparable SOC assessments across Europe, limiting the reliability of MRV systems.*

*(ii) Traditional SOC measurement methods are time-consuming, and newer technologies (e.g., vis–NIR, LIBS, neutron scattering) are underutilized or costly and this slows down large-scale, cost-effective SOC monitoring and reduces the feasibility of frequent updates* .

*(iii) SOC models often fail to account for key environmental variables like climate, soil pH, and land cover, reducing the accuracy of SOC predictions and limits the ability to tailor management strategies to local conditions*.

*(iv) Existing monitoring networks focus mainly on chemical properties and lack biological and physical indicators, limiting comprehensive understanding of soil functions and their role in SOC dynamics, weakening the foundation for effective MRV and land-use policy*.

*Suggested actions include*

*(i) Develop unified protocols and long-term monitoring programs across Europe*.

*(ii) Create open-access databases to integrate data across regions and land uses*.

*(iii) Support the development and field use of rapid SOC assessment tools*.

*(iv) Provide technical training for researchers and land managers in modern SOC methods*.

*(v) Refine models to include climate, soil pH, and land cover for better regional accuracy*.

*(vi) Integrate biological and physical indicators into existing networks for holistic SOC assessment*.

## Knowledge gap 5: SOC in circular bioeconomy, LCA

*The investigation has identified following knowledge development gap*

*The effects of organic residues on soil carbon processes and ecosystem services are not fully understood, while potential risks from pollutants, microplastics, and unregulated toxic compounds raise concerns about soil health and safety*.

In a sustainable bioeconomy, recycling of nutrients from organic residues is imperative (Hellsmark et al. 2016, Sawatdeenarunat et al. 2016). The circular economy emphasizes maximizing resource reuse and minimizing waste, which directly influences soil management. Efficient soil and land management are essential for the circular economy to function effectively, as soils play a critical role in food production, water filtration, and carbon storage (Breure et al. 2018). There is a huge diversity in organic residues depending on their origin and the type of process involved in their production. Hence, it is essential to distinguish between organic wastes, residues, and processed products like compost and digestate. Certified compost and digestate, produced through regulated biological processes, are no longer considered waste but valuable soil amendments under EU law, provided they meet strict quality and safety standards (Regulation (EU)

2019/1009 2019). Application of organic residues as soil amendment and fertilizer to agricultural land gives the opportunity of recovering the nutrients, primarily N and P, and of potentially improving soil quality by adding organic matter. The European Union's new Soil Strategy for 2030 aligns with the circular economy by setting a framework for protecting and restoring soils, however, only materials that comply with legal thresholds can and should be used in agriculture; those exceeding limits remain classified as waste. Harmonized quality standards and proper life cycle assessments are crucial to ensure their safe and effective use. This strategy also covers sustainable waste management (Panagiotakis and Dermatas 2022). The circular economy principles are integrated into broader environmental strategies, such as the European Green Deal. The European Union promotes the use of organic inputs on arable land to maintain or increase SOM, particularly in carbon-depleted soils. This is part of broader strategies to offset greenhouse gas emissions and ensure soil protection across member states (Marmo 2008).

Long-term application of organic amendments, such as compost and sludge, can significantly increase SOC contents. Studies also show that the repeated application of organic residues enhances soil biological functions, including microbial biomass carbon and enzymatic activity, which are crucial for maintaining healthy soil ecosystems (e.g. Diacono and Montemurro 2010). Regular addition of composted organic residues, for instance, improves soil physical properties, such as aggregate stability and bulk density, and enhances soil fertility, increased crop yields and improved crop quality without reducing yield quality (Agegnehu et al. 2016).

However, organic residues may also increase greenhouse gas production through the input of microbial substrates and increased mineralization of N. Pyrolyzing residual biomass for biochar application to soil is the main method for C sequestration in soils, that also has clear positive effects on reducing $N_2O$ emissions form soils (Guenet et al. 2021) . 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 organic residues in soil, and its impact on SOC stocks and soil health.

Policies often prioritize meeting crop N and P demands. Strict environmental regulations govern the use of organic residues in agriculture, with a particular focus on the treatment of animal manure and the management of farm nutrient balances. These regulations are designed to prevent environmental contamination and promote sustainable waste management practices (Lourenzi et al. 2021, Westerman and Bicudo 2005). Mixed municipal solid waste compost is no longer going to be representative for compost and digestate practices in the EU due to the obligation to separately collect bio-waste. However, persistent contaminants such as PFAS, and biochar containing heavy metals (Sørmo et al. 2024) can still be introduced, highlighting the need for careful monitoring, regulation, and ongoing research to safeguard soil health and food safety. Finally, composts and sewage sludge may contain significat amounts of microplastic fragments, depending on the origin of the material (Boctor et al. 2025). Hence, the use of organic residues for nutrient recycling and C addition is challenging, as we should not make use of organic residues if they transfer contaminants, pathogenic organisms, and unwanted plant species such as weeds to healthy soils. While circular economy principles emphasize resource efficiency, their direct influence on SOC stocks remains an area of study.

It would therefore be important that organic amendments, such as compost and digestate, intended for agricultural use, are consistently produced through improved and traceable waste management practices, ensuring compliance with the criteria set out in the EU Fertilizing Products Regulation (Regulation (EU) 2019/1009 2019). At the same time, it would be advisable to further harmonize at the European level the minimum quality requirements for compost and digestate to facilitate their safe use in agriculture and to ensure a level playing field across Member States. In order to correctly assess the intrinsic value of organic amendments such as compost and digestate, as well as their long-term effects, it is necessary to carry out a proper evaluation of the various ecosystem services provided by soil. Similarly, to perform a life cycle assessment (LCA) of organic amendments, the benefits of these products must be correctly estimated and evaluated. This is particularly true as not all LCA methodologies include emissions from reference scenario in which no composting takes place.

*The investigation has identified following bottlenecks:*

*(i) Limited understanding of SOC and eosystem impacts, limits accurate prediction of carbon sequestration potential and informed decision-making on residue use in sustainable land management.*

*(ii) Risk of soil contamination from organic residues limits safe application of organic residues and public trust in recycling practices within the circular economy.*

*(iii) Lack of harmonized quality standards and traceability limits safe, widespread adoption of organic amendments and a level playing field for sustainable agriculture.*

*(iv) Incomplete life cycle assessments (ICA) limits accurate environmental impact assessments and policy development for circular bioeconomy strategies.*

*(v) Regulatory prioritize nitrogen and phosphorus management, often overlooking broader soil health indicators and contaminant risks, hinders comprehensive soil protection and the integration of organic residue use into long-term soil carbon strategies.*

*Suggested actions include*:

*(i) Enhance research on microbial interactions and nutrient cycling in soils with organic amendments to improve carbon sequestration models and nutrient management strategies*

*(ii) Conduct more detailed studies on the effects of organic waste on various soil organisms to better understand and mitigate potential toxic impacts*

*(iii) Develop more precise and comprehensive methods for monitoring soil structure changes and pollutant levels, including advanced imaging and chemical analysis techniques.*

*(iv) Implement better waste management practices that consider the complex interactions of different waste types and their potential environmental impacts*

*(v) Increase data collection on soil physical, chemical and biological properties and promote sharing of findings to build a more comprehensive understanding of the effects of organic residue applications*

*(vi) Revising policies to account for the complex interactions of organic waste components and their long-term effects on soil health and ecosystem stability is c rucial.*

## Knowledge gap 6: SOC and Agronomic system approach

*The investigation has identified following knowledge development gaps*

*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)*

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. Adopting regenarative agricultural practices, such as reduced tillage, crop rotation, cover crops, and intercropping, can enhance SOC storage and restore soil quality, thereby strengthening long-term food security. However, the production benefits may not be apparent in the short or medium term.

Growing cover crops where soil would otherwise be bare has many benefits, including decreased $NO_3$- leaching over winter and reduced soil erosion. However, their role in increasing SOC may have limitations in many European situations. Where cover crops can be grown, they may lead to some increase in SOC, though the magnitude may 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). Additionally, cover crops may contribute to increased nitrous oxide emissions due to the accumulation of organic nitrogen 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 the top layer in no tillage systems, however, 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 in the top-soil (0-30 cm) (Taylor et al. 2024). The increased SOC stabilization in topsoil was connected to better plant growth at no-tillage in Mediterranean (rather dry) climates. A study by Fornara and Higgins (2022) of 500 grassland fields in Northern Ireland, UK, showed that C and N stocks (mg/ha) in the top 30 cm were not affected by frequency of tillage + reseeding, as differences in bulk density levels out the stock variation. Additionally, the risk of dissolved reactive phosphorus losses increases in no-till fields. The overall impact on water quality depends on the extent to which particulate phosphorus losses are reduced, and the proportion of that particle-bound phosphorus that becomes bioavailable once it enters surface waters (Daryanto et al. 2017, Iho et al. 2023)

Crop rotation is an important aspect of farming systems, but according to Land et al. (2017) there are not many comprehensive studies designed to unravel the effect of crop rotation on SOC stocks. Calculations 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. 2012, Bolinder et al. 2007, Land et al. 2017). Perennial crop seems to increase the C storage and flux, more strongly in shallow soil (0-15 cm) compared to deeper soil layers (15-30 cm) (Means et al. 2022) in comparison to annual monoculture crop.

*The investigation has identified following bottlenecks:*

*(i) Insufficient knowledge of how different soil management strategies affect SOC sequestration, greenhouse gas emissions, and nutrient leaching, hinders development of integrated practices that balance productivity with environmental sustainability*.

*(ii) Lack of comprehensive and harmonized data on soil carbon stocks, degradation, and fertility across regions, hinders accurate assessment of soil conditions and targeted improvement strategies*.

*(iii) Limited empirical evidence on how specific agronomic practices influence SOC levels over time, limits effective evidence-based recommendations for sustainable farming systems*.

*(iv) Weak communication channels and limited collaboration between researchers, policymakers, and land managers, limits adoption and scaling of effective soil carbon management practices*.

*(v) Absence of consistent methods for measuring and comparing SOC outcomes across studies and regions, hinders cross-comparison, policy alignment, and coordinated action at national and EU levels*.

*<u>Suggested actions include</u>:*

*(i) More experimental research is needed to study the impact of pedoclimatic conditions and long-term dynamics of SMS on SOC and emissions*

*(ii) Developing models and monitoring programs to better understand soil processes is crucial*

*(iii) Increase awareness among stakeholders about the importance of SOC and sustainable soil management practices*

*(iv) Enhance the role of intermediaries who can effectively communicate research findings to practitioners and policymakers*

*(v) Align research activities with the needs of land users and ensure that findings are accessible and applicable*

*(vi) Introduce financial incentives, such as subsidies and payments for ecosystem services, to encourage the adoption of sustainable practices, and probably very important*

*(vii) encourage direct communication among farmers and stakeholders to share experiences and best practices.*

## Knowledge gap 7: Urbanisation and SOC

*<u>The investigation has identified following knowledge development gaps</u>*

*There are limited data on SOC storage in urban areas, with high variability across land uses and regions. The effects of different urbanization pathways on SOC are poorly understood, and accurate SOC stock estimations and integrations into regional and national carbon budgets remain challenging*

Urbanization is the process of transforming rural areas into urban areas, which can have various effects on food production and SOC stocks. 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, 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, integrating soil health and carbon sequestration goals into urban planning and policies will be challenging. 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 centimetres 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 comission 2020), to protect and restore soils, and ensure that they are used sustainably and finally the "science for Environment Policy: No net land take " future brief, to outline what measures can avoid, reduce or compensate for land take (EU comission 2016).

*The investigation has identified following bottlenecks*

*(i) SOC stocks vary widely across urban land uses, and the effects of urbanization pathways on SOC, are poorly understood. This limits accurate assessment and integration of urban SOC into carbon budgets and climate strategies.*

*(ii) Urbanization often targets fertile agricultural land, leading to irreversible soil loss and reduced capacity for food production and carbon storage. This undermines long-term food security, ecosystem service provision, and sustainable land use planning.*

*(iii) Soil health and carbon sequestration goals are not systematically incorporated into urban development policies. This restricts multifunctional land use strategies that balance housing, food production, and environmental sustainability*.

*(iv) Urban soils face unique challenges such as compaction, pollution, and limited space, which affect their ability to store carbon and support ecosystem functions. This limits effective use of urban green spaces for climate mitigation and biodiversity enhancement*.

*Suggested actions include*:

*(i) Implement soil and land-use management practices that enhance SOC stocks and support ecosystem services in urban areas*

*(ii) Increase efforts to collect and analyse SOC data across various urban land uses and regions to improve accuracy in SOC stock estimations*

*(iii) Encourage the development of urban green spaces, such as parks and gardens, which have been shown to retain higher SOC stocks compared to other urban land uses*

*(iv) Adopt strategies to control urban sprawl and promote resource-efficient land use, which can help mitigate the negative impacts on SOC stocks*

## Knowledge gap 8: Education and awareness raising on SOC

*The investigation has identified following knowledge application gap:*

*The main knowledge gap in Europe concerning the importance of SOC, particularly in education and awareness, lies in the effective communication and application of existing research to practitioners and the public. This disconnect limits the adoption of sustainable soil management practices essential for climate change mitigation and soil health*.

Awareness of soil health's importance has grown in recent years. Initiatives like the PREPSOIL project contribute to the Soil Mission by enhancing knowledge and awareness of soil needs among stakeholders across Europe. Such projects address the critical need to educate diverse audiences on the role of soil organic carbon conservation in sustaining life and natural resources, from individuals to society as a whole. Despite its significance, soil remains widely under-communicated, including within educational institutions at all levels. This highlights the clear connection to the eighth mission objective on soil literacy, which emphasizes both general soil health and the importance of its carbon stocks.

Soil C storage refers to an increase of soil C stocks, while soil C sequestration implies a net removal of atmospheric $CO_2$. However, these terms are often used interchangeably or ambiguously, which can cause confusion and misunderstanding among different stakeholders and audiences. Recently, Janzen (2024) published an important adjustment in how we should appreciate SOC, which is easily under communicated in the discussion about conserving and increasing SOC: Rather than using the term 'sequestration,' we might instead speak of SOC 'stewardship,' which captures the full range of SOC rather than just a narrowly defined 'stable' or 'persistent' fraction. This shift in perspective could reshape research questions, for example, is long-term stability necessary for SOC to effectively store excess atmospheric $CO_2$? 'Stewardship' recognizes the continuous cycling of SOC, emphasizing the need to manage both stored carbon and the ongoing flows that sustain ecosystem functions.

Therefore, it is crucial to promote education and awareness not only about soil quality and health but also about the global benefits of effective SOC management, particularly in climate change adaptation and sustainable food security. There is a need to improve fellow citizens, land managers, politicians and policymakers common understanding of SOC dynamics and its central role. Communicating this has been challenging, partly due to the complexity of organic C composition and its dynamic behaviour in soil, as well as its connections to key soil functions such as structure, biodiversity, and elemental cycles (Chenu et al. 2019).

The knowledge gaps on communicating the role and importance of SOC to society and its role in providing and sustaining a number of the soil ecosystems, seems to be mostly related to communication and suitability of soil data management. There is a lack of comprehensive models and monitoring programs to address the loss of SOC in various systems, and its importance for water infiltration and reducing soil compaction for instance (Thorsøe et al. 2023). Moreover, there is a need to clearly differentiate between SOC storage and sequestration, as they have different implications for climate change adaptation and mitigation (Chenu et al. 2019, Janzen 2024), and stakeholders have varying perceptions of soil quality and functions, indicating a need for regionally relevant advice and credible information on sustainable management practices (Bampa et al. 2019).

*The investigation has identified following bottlenecks*

*(i) Existing SOC knowledge is not effectively communicated or applied by practitioners and the public. This limits the adoption of sustainable soil management practices and climate mitigation strategies*.

*(ii) SOC and soil health are underrepresented in education and public discourse. This weakens societal understanding of soil's role in climate adaptation, food security, and ecosystem services*.

*(iii) Terms like "SOC storage" and "sequestration" are often used interchangeably, leading to misunderstanding. This creates confusion in communication, policy development, and alignment of research and management goals*.

*(iv) Stakeholders have diverse perceptions of soil quality, and there is limited access to tailored, trustworthy information. This reduces the effectiveness decision-making and adoption of context-specific sustainable practices*.

*(v) There is a lack of comprehensive models and monitoring systems to track SOC loss and its impact on soil functions. This undermines evidence-based policy, long-term planning, and evaluation of soil management outcomes*

*Suggested actions include*:

*(i) Enhancing the role of intermediaries who can translate scientific findings into practical advice for land users*,

*(ii) Encouraging communication among farmers and stakeholders to share best practices and experiences*,

*(iii) Providing tailored advice and information that considers local environmental and socio-economic conditions*,

*(iv) Raising awareness about the importance of SOC and strengthening educational programs are essential. This includes providing credible information and locally relevant advice to stakeholders*,

*(v) Funding for applied research, and support for training programs can encourage the adoption of sustainable practice*.

## Knowledge gap 9: Forest management and SOC

*The investigation has identified following knowledge development gap:*

*The main research gap in forest SOC management is understanding how different practices impact SOC stocks and interact with environmental factors like climate change. Addressing this requires site-specific studies, large dataset integration, and comprehensive management frameworks.*

Forest soils store almost half of the total organic C in terrestrial ecosystems, and forest management practices can influence the rates of input or release of C 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, C 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 C. 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). Boosting SOC stocks addresses several key questions and considerations. Clear-cutting in Nordic and Canadian forests leads to a significant, decadal decline in forest floor SOC (Johannesson et al. 2025). This decline persists for many years after harvesting, highlighting a long-term impact of clear-cutting on forest soil carbon storage. The decline is most pronounced in the organic layer (forest floor), while the mineral soil shows little to no significant change in SOC stocks. The loss of SOC is attributed to increased decomposition rates and reduced litter input following the removal of trees. SOC in the forest floor may begin to recover several decades after clear-cutting, but full recovery to pre-harvest levels can take 30–50 years or more (Clarke et al. 2021).

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 C 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 C 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).

There is a need for advanced modelling techniques like boosted regression trees (BRT) and other machine learning models can improve SOC stock estimates by identifying key predictors such as groundwater level, clay fraction, and tree genus (Ottoy et al. 2017). In addition geostatistical models, using climate and land cover data, that can predict current and future SOC stocks, providing insights into how SOC might change under different climate scenarios (Yigini and Panagos 2016). And simulation models which are used to simulate SOC stocks and changes, offering a way to assess the impact of land use and climate change on SOC (Hernández et al. 2017). Complementary to this, future climate scenarios suggest varying impacts on SOC stocks, with potential increases or decreases depending on the region and forest type. Models should be developed to predict an overall increase in SOC stocks in Europe by 2050 under various climate scenarios (Yigini and Panagos 2016). Advancing SOC research and management through modelling, forest practice analysis, and climate adaptation can improve implementation, leading to better predictions and conservation strategies in European forests.

*The investigation has identified following bottlenecks*

*(i) Forest management often prioritizes biodiversity, timber, or recreation over soil carbon storage, and SOC is frequently treated as a secondary consideration. This limits the integration of SOC conservation into forest policy and practice, reducing the potential for forests to contribute to climate mitigation*.

*(ii) Practices like clear-cutting and residue removal for bioenergy can lead to long-term SOC losses, especially in the forest floor layer. This limits the long-term stability of forest soil carbon stocks and the sustainability of bioenergy strategies*.

*(iii) Despite the availability of advanced modelling tools (e.g., machine learning, geostatistics, simulation models), they are underutilized in forest SOC assessments. This limits accurate prediction of SOC changes under different management and climate scenarios, hindering informed decision-making and adaptive forest planning*.

*Suggested actions include*:

*(i) Utilize large observational databases and meta-analyses can help synthesize existing data and provide a clearer picture of SOC dynamics across different regions and management practices*.

*(ii) Creating comprehensive classifications and thesauri, like DATA4C+, can help standardize the description of management practices and improve the quality of meta-analyses, aiding in the identification of effective SOC management strategies*.

*(iii) Research should prioritize understanding how climate change scenarios affect SOC, as these changes pose significant risks to SOC stocks, particularly in temperate forests*.

## Knowledge gap 10: EU footprints of soil carbon outside Europe

*The investigation has identified following knowledge development gap:*

*The main gap in understanding European impacts on global SOC stocks is the lack of comprehensive monitoring of how European consumption and land use affect SOC worldwide. This is compounded by insufficient data on environmental factors influencing SOC storage and the effects of trade and consumption patterns outside Europe*.

The import of food and fiber into Europe has a complex and varied impact on SOC stocks 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 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 of 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. 2018, Wiesmeier et al. 2012).

There is a need for improved methodologies to monitor and identify environmental factors that control SOC storage, as current models often rely on geographically non-stationary processes that vary by location (Rial et al. 2017). And the role of European consumption in driving SOC changes outside Europe is not well understood, particularly how trade and consumption patterns contribute to SOC losses in other regions (Wilting et al. 2021). Addressing knowledge gaps on European impacts on global SOC stocks requires improved monitoring, policy integration, and data standardization to better understand SOC dynamics and reduce the effects of European consumption on global soil C.

*The investigation has identified following bottlenecks*

(i) Prioritizing carbon sequestration in Europe may lead to increased food and fiber imports from regions where land is cleared for agriculture, causing SOC loss and $CO_2$ emissions abroad. As a result, the global climate benefits of European SOC strategies may be undermined, shifting environmental burdens to other regions.

(ii) There is a shortage of standardized methods, comprehensive datasets, and accurate mapping techniques for assessing SOC stocks outside Europe. This gap hampers reliable global assessments of SOC dynamics and weakens the ability to track the external impacts of European consumption.

(iii) The role of European trade and consumption in driving SOC changes in other regions is not well understood. This lack of insight constrains informed policymaking and the integration of global SOC considerations into European sustainability and trade strategies.

*The actions include*:

*(i) Enhance the integration of research findings into policymaking to address the impacts of European consumption on global SOC stocks. This includes considering trade impacts in national and regional policies*

*(ii) Promote standardization in SOC measurement and data sharing across countries to improve the accuracy of SOC assessments and facilitate better policy decisions*

*(iii) Implement incentives for sustainable soil management practices that enhance SOC sequestration, such as carbon credits and other financial mechanisms*

### Summarisation of prioritized knowledge gaps

An overview table of the prioritized knowledge gaps, their sector impact, bottlenecks and suggested actions can be found under Suppl. material 1

## References


- Agegnehu G, Bass AM, Nelson PN, Bird MI (2016) Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. Science of The Total Environment 543 (Part A): 295-306. https://doi.org/10.1016/j.scitotenv.2015.11.054
- 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
- Almås ÅR, Eich-Greatorex S, Sogn T, Mulder J, Pandey MK, Dauby V, Powlson DS, Farina R, Watte J, Rasse D (2024) Preliminary assessment of the knowledge gaps to conserve and increase soil organic carbon stocks. Soils for Europe https://doi.org/10.3897/soils4europe.e118635
- Amin MN, Hossain MS, de Bruyn LL, Wilson B (2020) A systematic review of soil carbon management in Australia and the need for a social-ecological systems framework. Science of the Total Environment 719 https://doi.org/10.1016/j.scitotenv.2019.135182
- 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
- Bampa F, O'Sullivan L, Madena K, Sandén T, Spiegel H, Henriksen CB, Ghaley BB, Jones A, Staes J, Sturel S, Trajanov A, Creamer R, Debeljak M (2019) Harvesting

European knowledge on soil functions and land management using multi-criteria decision analysis. Soil Use and Management 35 (1): 6-20. https://doi.org/10.1111/sum.12506
- 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
- Bender SF, Wagg C, van der Heijden MGA (2016) An Underground Revolution: Biodiversity and Soil Ecological Engineering for Agricultural Sustainability. Trends in Ecology & Evolution 31 (6): 440-452. https://doi.org/10.1016/j.tree.2016.02.016
- Blanchy G, Bragato G, Di Bene C, Jarvis N, Larsbo M, Meurer K, Garré S (2023) Soil and crop management practices and the water regulation functions of soils: a qualitative synthesis of meta-analyses relevant to European agriculture. Soil 9 (1). https://doi.org/10.5194/soil-9-1-2023
- Boctor J, Hoyle FC, Farag MA, Ebaid M, Walsh T, Whitney AS, Murphy DV (2025) Microplastics and nanoplastics: fate, transport, and governance from agricultural soil to food webs and humans. Environmental Sciences Europe https://doi.org/10.1186/s12302-025-01104-x
- 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
- Breure AM, Lijzen JPA, Maring L (2018) Soil and land management in a circular economy. Science of the Total Environment 624: 1125-1130. https://doi.org/10.1016/j.scitotenv.2017.12.137
- Brussaard L, de Ruiter PC, Brown GG (2007) Soil biodiversity for agricultural sustainability. Agriculture Ecosystems & Environment 121 (3): 233-244. https://doi.org/10.1016/j.agee.2006.12.013
- Cai AD, Han TF, Ren TJ, Sanderman J, Rui YC, Wang B, Smith P, Xu MG, Li YE (2022) Declines in soil carbon storage under no tillage can be alleviated in the long run. Geoderma 425 https://doi.org/10.1016/j.geoderma.2022.116028

- 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
- Chen S, Wang W, Xu W, Wang Y, Wan H, Chen D, Tang Z, Tang X, Zhou G, Xie Z, Zhou D, Shangguan Z, Huang J, He J, Wang Y, Sheng J, Tang L, Li X, Dong M, Wu Y, Wang Q, Wang Z, Wu J, Chapin FS, Bai Y (2018) Plant diversity enhances productivity and soil carbon storage. Proceedings of the National Academy of Sciences of the United States of America 115 (16): 4027-4032. https://doi.org/10.1073/pnas.1700298114
- 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
- Chen XL, Chen HYH, Chen C, Ma ZL, Searle EB, Yu ZP, Huang ZQ (2020) Effects of plant diversity on soil carbon in diverse ecosystems: a global meta-analysis. Biological Reviews 95 (1): 167-183. https://doi.org/10.1111/brv.12554
- Clarke N, Kiær LP, Kjonaas JO, Barcena TG, Vesterdal L, Stupak S, Finer L, Jacobson S, Armolatis K, Lazdina D, Stafansdottir HM, Sigurdsson BD (2021) Effects of intensive biomass harvesting on forest soils in the Nordic countries and the UK: A meta-analysis. Forest Ecology and Management 482 https://doi.org/10.1016/j.foreco.2020.118877
- 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 DA, Ebinger MH, Breshears DD, Unkefer PJ, Kammerdiener SA, Ferris MJ, Catlett KM, Brown JR (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
- Criscuoli I, Martelli A, Falconi I, Galioto F, Lasorella MV, Maurino S, Phillips A, Bonati G, Guccione GD (2024) Lessons learned from existing carbon removal methodologies for agricultural soils to drive European Union policies. European Journal of Soil Science 75 (5). https://doi.org/10.1111/ejss.13577
- 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
- Daryanto S, Wang L, Jacinthe PA (2017) Meta-Analysis of Phosphorus Loss from No-Till Soils. Journal of environmental quality 46 (5): 1028-1037. https://doi.org/10.2134/jeq2017.03.0121
- Delgado-Baquerizo M, Reich PB, Trivedi C, Eldridge DJ, Abades S, Alfaro FD, Bastida F, Berhe AA, Cutler NA, Gallardo A, García-Velázquez L, Hart SC, Hayes PE, He JZ, Hseu ZY, Hu HW, Kirchmair M, Neuhauser S, Pérez CA, Reed SC, Santos F, Sullivan BW, Trivedi P, Wang JT, Weber-Grullon L, Williams MA, Singh BK (2020) Multiple elements of soil biodiversity drive ecosystem functions across biomes. Nature Ecology & Evolution 4 (2): 210-220. https://doi.org/10.1038/s41559-019-1084-y

- Delgado-Baquerizo M, Eldridge DJ, Liu Y, Liu Z, Coleine C, Trivedi P (2025) Soil biodiversity and function under global change. PLoS biology 23 (3): e3003093. https://doi.org/10.1371/journal.pbio.3003093
- De Rosa D, Ballabio C, Lugato E, Fasiolo M, Jones A, Panagos P (2024) Soil organic carbon stocks in European croplands and grasslands: How much have we lost in the past decade? Global Change Biology 30 (1). https://doi.org/10.1111/gcb.16992
- 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
- Diacono M, Montemurro F (2010) Long-term effects of organic amendments on soil fertility. A review. Agronomy for Sustainable Development 30 (2): 401-422. https://doi.org/10.1051/agro/2009040
- 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 comission (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 Bringing nature back into our lives. EU unioin. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380
- EU comission (2016) Science for Environment Policy. FUTURE BRIEF: No net land take by 2050? URL: https://catalogue.unccd.int/650_no_net_land_take_by_2050.pdf
- EU comission (2023a) Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (soil monitoring law). European Union. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0416&%3Bqid=1706624227744
- EU comission (2023b) A new tool maps the state of soil health across Europe. European Commission. URL: https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/new-tool-maps-state-soil-health-across-europe-2023-03-13_en
- 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 NEH, Niggli U (2012) Enhanced top soil carbon stocks under organic farming. Proceedings of the National Academy of Sciences of the United States of America 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
- Guerra CA, Bardgett RD, Caon L, Crowther TW, Delgado-Baquerizo M, Montanarella L, Navarro LM, Orgiazzi A, Singh BK, Tedersoo L, Vargas-Rojas R, Briones MJI, Buscot F, Cameron EK, Cesarz S, Chatzinotas A, Cowan DA, Djukic I, van den Hoogen J, Lehmann A, Maestre FT, Marin C, Reitz T, Rillig MC, Smith LC, de Vries FT, Weigelt A, Wall DH, Eisenhauer N (2021) Tracking, targeting, and conserving soil biodiversity. Science 371 (6526): 239-241. https://doi.org/10.1126/science.abd7926
- 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
- Heimsch L, Huusko K, Karhu K, Mganga KZ, Kalu S, Kumala L (2023) Effects of a tree row on greenhouse gas fluxes, growing conditions and soil microbial communities on an oat field in Southern Finland. Agriculture, Ecosystems & Environment 352 https://doi.org/10.1016/j.agee.2023.108525
- 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
- Hernández L, Jandl R, Blujdea VNB, Lehtonen A, Kriiska K, Alberdi I, Adermann V, Cañellas I, Marin G, Moreno-Fernández D, Ostonen I, Varik M, Didion M (2017) Towards complete and harmonized assessment of soil carbon stocks and balance in forests: The ability of the Yasso07 model across a wide gradient of climatic and forest conditions in Europe. Science of the Total Environment 599: 1171-1180. https://doi.org/10.1016/j.scitotenv.2017.03.298
- Herzfeld T, Heinke J, Rolinski S, Müller C (2021) Soil organic carbon dynamics from agricultural management practices under climate change. Earth System Dynamics 12 (4): 1037-1055. https://doi.org/10.5194/esd-12-1037-2021

- Hoffland E, Kuyper TW, Comans RNJ, Creamer RE (2020) Eco-functionality of organic matter in soils. Plant and Soil 455 (1-2): 1-22. https://doi.org/10.1007/s11104-020-04651-9
- Honkanen H, Kekkonen H, Heikkinen J, Kaseva J, Lång K (2024) Minor efects of no-till treatment on GHG emissions of boreal cultivated peat soil. Biogeochemistry 167: 499-522. https://doi.org/10.1007/s10533-023-01097-w
- Iho A, Valve H, Ekholm P, Uusitalo R, Lehtoranta J, Soinne H, Salminen J (2023) Efficient protection of the Baltic Sea needs a revision of phosphorus metric. Ambio 52 (8): 1389-1399. https://doi.org/10.1007/s13280-023-01851-2
- Jandl R, Spathelf P, Bolte A, Prescott CE (2019) Forest adaptation to climate changeis non-management an option? Annals of Forest Science 76 (2). https://doi.org/10.1007/s13595-019-0827-x
- 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
- Janzen HH (2024) RUSSELL REVIEW Soil carbon stewardship: Thinking in circles. European Journal of Soil Science 75 (5). https://doi.org/10.1111/ejss.13536
- Johannesson CF, Ilvesniemi H, Kjønaas OJ, Larsen KS, Lehtonen A, Nordén J, Paré D, Silvennoinen H, Stendahl J, Stupak I, Vesterdal L (2025) Decadal decline in forest floor soil organic carbon after clear-cutting in Nordic and Canadian forests. Forest Ecology and Management 586 https://doi.org/10.1016/j.foreco.2025.122668
- Kallenbach CM, Frey SD, Grandy AS (2016) Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nature Communications 7 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
- Keenan RJ (2015) Climate change impacts and adaptation in forest management: a review. Annals of Forest Science 72 (2): 145-167. https://doi.org/10.1007/s13595-014-0446-5
- 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

- Kreyling J, Buhk C, Backhaus S, Hallinger M, Huber G, Huber L, Jentsch A, Konnert M, Thiel D, Wilmking M, Beierkuhnlein C (2014) Local adaptations to frost in marginal and central populations of the dominant forest tree *Fagus sylvatica* L. as affected by temperature and extreme drought in common garden experiments. Ecology and Evolution 4 (5): 594-605. https://doi.org/10.1002/ece3.971
- 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
- Lal R (2016) Soil health and carbon management. Food and Energy Security 5 (4): 212-222. https://doi.org/10.1002/fes3.96
- 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
- Liu HY, Mi ZR, Lin L, Wang YH, Zhang ZH, Zhang FW, Wang H, Liu LL, Zhu BA, Cao GM, Zhao XQ, Sanders NJ, Classen AT, Reich PB, He JS (2018) Shifting plant species composition in response to climate change stabilizes grassland primary production.

Proceedings of the National Academy of Sciences of the United States of America 115 (16): 4051-4056. https://doi.org/10.1073/pnas.1700299114

- Li Y, Chen ZM, Wagg C, Castellano MJ, Zhang N, Ding WX (2024) Soil organic carbon loss decreases biodiversity but stimulates multitrophic interactions that promote belowground metabolism. Global Change Biology 30 (1). https://doi.org/10.1111/gcb.17101
- 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
- Lourenzi CR, Ceretta CA, Ciancio NHR, Tiecher TL, da Silva LOS, De Conti L, Girotto E, Ferreira PAA, Vidal RF, Scopel G, Marchezan C, Brunetto G (2021) Forms of nitrogen and phosphorus transfer by runoff in soil under no-tillage with successive organic waste and mineral fertilizers applications. Agricultural Water Management 248 https://doi.org/10.1016/j.agwat.2021.106779
- Lozano-García B, Muñoz-Rojas M, Parras-Alcántara L (2017) Climate and land use changes effects on soil organic carbon stocks in a Mediterranean semi-natural area. Science of the Total Environment 579: 1249-1259. https://doi.org/10.1016/j.scitotenv.2016.11.111
- 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
- Maenhout P, Di Bene C, Cayuela ML, Diaz-Pines E, Govednik A, Keuper F, Mavsar S, Mihelic R, O'Toole A, Schwarzmann A, Suhadolc M, Syp A, Valkama E (2024) Trade-offs and synergies of soil carbon sequestration: Addressing knowledge gaps related to soil management strategies. European Journal of Soil Science 75 (3). https://doi.org/10.1111/ejss.13515
- 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
- Mäkipää R, Bruun O, Lehtonen A, Peltoniemi M, Kulovesi K (2024) We need targeted policy interventions in the EU to save soil carbon. Frontiers in Environmental Science 12 https://doi.org/10.3389/fenvs.2024.1354695
- Marmo L (2008) EU strategies and policies on soil and waste management to offset greenhouse gas emissions. Waste Management 28 (4): 685-689. https://doi.org/10.1016/j.wasman.2007.09.030
- Maron PA, Sarr A, Kaisermann A, Lévêque J, Mathieu O, Guigue J, Karimi B, Bernard L, Dequiedt S, Terrat S, Chabbi A, Ranjard L (2018) High Microbial Diversity Promotes Soil

Ecosystem Functioning. Applied and Environmental Microbiology 84 (9). https://doi.org/10.1128/aem.02738-17
- 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
- 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
- Midgley GF, Bond WJ, Kapos V, Ravilious C, Scharlemann JPW, Woodward FI (2010) Terrestrial carbon stocks and biodiversity: key knowledge gaps and some policy implications. Current Opinion in Environmental Sustainability 2 (4): 264-270. https://doi.org/10.1016/j.cosust.2010.06.001
- 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
- Mills J, Ingram J, Dibari C, Merante P, Karaczun Z, Molnar A, Sánchez B, Iglesias A, Ghaley BB (2020) Barriers to and opportunities for the uptake of soil carbon management practices in European sustainable agricultural production. Agroecology and Sustainable Food Systems 44 (9): 1185-1211. https://doi.org/10.1080/21683565.2019.1680476
- 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
- Montanarella L, Panagos P (2021) The relevance of sustainable soil management within the European Green Deal. Land Use Policy 100 https://doi.org/10.1016/j.landusepol.2020.104950
- 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

- Ottoy S, De Vos B, Sindayihebura A, Hermy M, Van Orshoven J (2017) Assessing soil organic carbon stocks under current and potential forest cover using digital soil mapping and spatial generalisation. Ecological Indicators 77: 139-150. https://doi.org/10.1016/j.ecolind.2017.02.010
- 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
- Panagiotakis I, Dermatas D (2022) New European Union soil strategy: A potential worldwide tool for sustainable waste management and circular economy. Waste Management & Research 40 (3): 245-247. https://doi.org/10.1177/0734242x221079114
- 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
- Poeplau C, Don A (2013) Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. Geoderma 192: 189-201. https://doi.org/10.1016/j.geoderma.2012.08.003
- Poeplau C, Dechow R (2023) The legacy of one hundred years of climate change for organic carbon stocks in global agricultural topsoils. Scientific Reports 13 (1). https://doi.org/10.1038/s41598-023-34753-0
- 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
- Prechtel A, von Lützow M, Schneider BU, Bens O, Bannick CG, Kögel-Knabner I, Hüttl RF (2009) Organic carbon in soils of Germany: *Status quo* and the need for new data to evaluate potentials and trends of soil carbon sequestration. Journal of Plant Nutrition and Soil Science 172 (5): 601-614. https://doi.org/10.1002/jpln.200900034
- Prommer J, Walker TWN, Wanek W, Braun J, Zezula D, Hu Y, Hofhansl F, Richter A (2020) Increased microbial growth, biomass, and turnover drive soil organic carbon accumulation at higher plant diversity. Global change biology 26 (2): 669-681. https://doi.org/10.1111/gcb.14777
- Qiao L, Wang XH, Smith P, Fan JL, Lu YL, Emmett B, Li R, Dorling S, Chen HQ, Liu SG, Benton TG, Wang YJ, Ma YQ, Jiang RF, Zhang FS, Piao SL, Müller C, Yang HQ, Hao YN, Li WM, Fan MS (2022) Soil quality both increases crop production and improves resilience to climate change. Nature Climate Change 12 (6). https://doi.org/10.1038/s41558-022-01376-8
- 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
- Ratcliffe S, Wirth C, Jucker T, van der Plas F, Scherer-Lorenzen M, Verheyen K, Allan E, Benavides R, Bruelheide H, Ohse B, Paquette A, Ampoorter E, Bastias CC, Bauhus J, Bonal D, Bouriaud O, Bussotti F, Carnol M, Castagneyrol B, Checko E, Dawud SM, De

Wandeler H, Domisch T, Finér L, Fischer M, Fotelli M, Gessler A, Granier A, Grossiord C, Guyot V, Haase J, Hättenschwiler S, Jactel H, Jaroszewicz B, Joly FX, Kambach S, Kolb S, Koricheva J, Liebersgesell M, Milligan H, Müller S, Muys B, Nguyen D, Nock C, Pollastrini M, Purschke O, Radoglou K, Raulund-Rasmussen K, Roger F, Ruiz-Benito P, Seidl R, Selvi F, Seiferling I, Stenlid J, Valladares F, Vesterdal L, Baeten L (2017) Biodiversity and ecosystem functioning relations in European forests depend on environmental context. Ecology Letters 20 (11): 1414-1426. https://doi.org/10.1111/ele.12849

- Regulation (EU) 2019/1009 (2019) Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. EU comission. URL: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32019R1009
- Rhodes CJ (2017) The imperative for regenerative agriculture. Science Progress 100 (1): 80-129. https://doi.org/10.3184/003685017x14876775256165
- Rial M, Cortizas AM, Rodríguez-Lado L (2017) Understanding the spatial distribution of factors controlling topsoil organic carbon content in European soils. Science of the Total Environment 609: 1411-1422. https://doi.org/10.1016/j.scitotenv.2017.08.012
- Rodrigues L, Hardy B, Huyghebeart B, Fohrafellner J, Fornara D, Barancíková G, Bárcena TG, De Boever M, Di Bene C, Feiziene D, Käetterer T, Laszlo P, O'Sullivan L, Seitz D, Leifeld J (2021) Achievable agricultural soil carbon sequestration across Europe from country-specific estimates. Global Change Biology 27 (24): 6363-6380. https://doi.org/10.1111/gcb.15897
- 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
- Schittko C, Onandia G, Bernard-Verdier M, Heger T, Jeschke JM, Kowarik I, Maass S, Joshi J (2022) Biodiversity maintains soil multifunctionality and soil organic carbon in novel urban ecosystems. Journal of Ecology 110 (4): 916-934. https://doi.org/10.1111/1365-2745.13852
- 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
- Schreefel L, Schulte RP, De Boer IJ, Schrijver AP (2020) Regenerative agriculture – the soil is the base. Global Food Security 26 https://doi.org/10.1016/j.gfs.2020.100404
- 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
- Sheil D, Ladd B, Silva LCR, Laffan SW, Van Heist M (2016) How are soil carbon and tropical biodiversity related? Environmental Conservation 43 (3): 231-241. https://doi.org/10.1017/s0376892916000011
- Sims JT, Simard RR, Joern BC (1998) Phosphorus Loss in Agricultural Drainage: Historical Perspective and Current Research. Journal of Environmental Quality 27: 277-293. https://doi.org/10.2134/jeq1998.00472425002700020006x

- 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
- Sørmo E, Dublet-Adli G, Menlah G, Flatabø GØ, Zivanovic V, Carlsson P, Almås Å, Cornelissen G (2024) Heavy Metals in Pyrolysis of Contaminated Wastes: Phase Distribution and Leaching Behaviour. Environments 11 (6). https://doi.org/10.3390/environments11060130
- 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
- Steinbeiss S, Bessler H, Engels C, Temperton VM, Buchmann N, Roscher C, Kreutziger Y, Baade J, Habekost M, Gleixner G (2008) Plant diversity positively affects short-term soil carbon storage in experimental grasslands. Global Change Biology 14 (12): 2937-2949. https://doi.org/10.1111/j.1365-2486.2008.01697.x
- 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
- Thorsøe MH, Keesstra S, De Boever M, Buchová K, Boe F, Castanheira NL, Chenu C, Cornu S, Don A, Fohrafellner J, Farina R, Fornara D, Goncalves MD, Graversgaard M, Heller O, Inselsbacher E, Jacobs A, Mavsar S, Meurer KHE, Mihelic R, O'Sullivan L, Pulido-Moncada M, Ruysschaert G, Svicek M, Tähtikarhu M, Vanino S, Vervuurt W, Zechmeister-Boltenstern S, Munkholm LJ (2023) Sustainable soil management: Soil knowledge use and gaps in Europe. European Journal of Soil Science 74 (6). https://doi.org/10.1111/ejss.13439
- 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 SP, Rasse DP, 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
- Tsiafouli MA, Thébault E, Sgardelis SP, de Ruiter PC, van der Putten WH, Birkhofer K, Hemerik L, de Vries FT, Bardgett RD, Brady MV, Bjornlund L, Jorgensen HB, Christensen S, D' Hertefeldt T, Hotes S, Hol WHG, Frouz J, Liiri M, Mortimer SR, Setälä H, Tzanopoulos J, Uteseny K, Pizl V, Stary J, Wolters V, Hedlund K (2015) Intensive

agriculture reduces soil biodiversity across Europe. Global Change Biology 21 (2): 973-985. https://doi.org/10.1111/gcb.12752
- van Leeuwen JP, Saby NPA, Jones A, Louwagie G, Micheli E, Rutgers M, Schulte RPO, Spiegel H, Toth G, Creamer RE (2017) Gap assessment in current soil monitoring networks across Europe for measuring soil functions. Environmental Research Letters 12 (12). https://doi.org/10.1088/1748-9326/aa9c5c
- Verschuuren J (2018) Towards an EU Regulatory Framework for Climate-Smart Agriculture: The Example of Soil Carbon Sequestration. Transnational Environmental Law 7 (2): 301-322. https://doi.org/10.1017/s2047102517000395
- Vos B, Cools N, Ilvesniemi H, Vesterdal L, Vanguelova E, Carnicelli 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
- Wall DH, Virginia RA (1999) Controls on soil biodiversity: insights from extreme environments. Applied Soil Ecology 13 (2): 137-150. https://doi.org/10.1016/s0929-1393(99)00029-3
- Wang B, Gray JM, Waters CM, Anwar MR, Orgill SE, Cowie AL, Feng PY, Liu DL (2022) Modelling and mapping soil organic carbon stocks under future climate change in south-eastern Australia. Geoderma 405 https://doi.org/10.1016/j.geoderma.2021.115442
- Wang B, Meng YH, Deng SW, Zhou X, Wang SF, Wu Y, Wu LJ, Bai YF, Chen DM (2025) Biodiversity of soil biota and plants stabilises ecosystem multifunctionality with increasing number of global change factors. Journal of Ecology https://doi.org/10.1111/1365-2745.70054
- Westerman PW, Bicudo JR (2005) Management considerations for organic waste use in agriculture. Bioresource Technology 96 (2): 215-221. https://doi.org/10.1016/j.biortech.2004.05.011
- White RE, Davidson B, Lam SK, Chen DL (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
- Wilting HC, Schipper AM, Ivanova O, Ivanova D, Huijbregts MAJ (2021) Subnational greenhouse gas and land-based biodiversity footprints in the European Union. Journal of Industrial Ecology 25 (1): 79-94. https://doi.org/10.1111/jiec.13042
- 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
- Yigini Y, Panagos P (2016) Assessment of soil organic carbon stocks under future climate and land cover changes in Europe. Science of the Total Environment 557: 838-850. https://doi.org/10.1016/j.scitotenv.2016.03.085
- Yin S, Chen XL, Piton G, Terrer C, Zhou ZH, De Deyn GB, Bertrand I, Rasse D, Chen J, Navarro-Cano JA, Abalos D (2025) The complementarity hypothesis reversed: Root trait

similarity in species mixtures promotes soil organic carbon in agroecosystems. Soil Biology & Biochemistry 203 https://doi.org/10.1016/j.soilbio.2025.109736
- Zeng JY, Matsunaga T, Tan ZH, Saigusa N, Shirai T, Tang YH, Peng SS, Fukuda Y (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: <Go to ISI>://WOS:000335980300017

## Supplementary material

### Suppl. material 1: Prioritized knowledge gaps, their sector impact, bottlenecks and suggested actions doi

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