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REVIEW ARTICLE

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Trade-offs and synergies of soil carbon sequestration: Addressing knowledge gaps related to soil management strategies

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Abstract

Soil organic carbon (SOC) sequestration in agricultural soils is an important tool for climate change mitigation within the EU soil strategy for 2030 and can be achieved via the adoption of soil management strategies (SMS). These strategies may induce synergistic effects by simultaneously reducing greenhouse gas (GHG) emissions and/or nitrogen (N) leaching. In contrast, other SMS may stimulate emissions of GHG such as nitrous oxide (N_2O) or methane (CH_4), offsetting the climate change mitigation gained via SOC sequestration. Despite the importance of understanding trade-offs and synergies for selecting sustainable SMS for European agriculture, knowledge on these effects remains limited. This review synthesizes existing knowledge, identifies knowledge gaps and provides research recommendations on trade-offs and synergies between SOC sequestration or SOC accrual, non-CO_2 GHG emissions and N leaching related to selected SMS. We investigated 87 peer-reviewed articles that address SMS and categorized them under tillage management, cropping systems, water management and fertilization and organic matter (OM) inputs. SMS, such as conservation tillage, adapted crop rotations, adapted water management, OM inputs by cover crops (CC), organic amendments (OA) and biochar, contribute to increase SOC stocks and reduce N leaching. Adoption of leguminous CC or specific cropping systems and adapted water management tend to create trade-offs by stimulating N_2O emissions, while specific cropping systems or application of biochar can mitigate N_2O emissions. The effect of crop residues on N_2O emissions depends strongly on their C/N ratio. Organic agriculture and agroforestry clearly mitigate CH_4 emissions but the impact of other SMS requires additional study. More experimental research is needed to study the impact of both the pedoclimatic conditions and the long-term dynamics of trade-offs and synergies. Researchers should simultaneously assess the impact of (multiple) agricultural SMS on SOC stocks, GHG emissions and N leaching. This review provides guidance to policymakers as well as a framework to design field experiments and model simulations, which can address knowledge gaps and non-intentional effects of applying agricultural SMS meant to increase SOC sequestration.

KEYWORDS

CH_4, climate change mitigation, conservation agriculture, cropping systems, EJP SOIL, N_2O, nitrogen leaching, organic matter inputs, tillage, water management

1 | INTRODUCTION

In recent decades, soil organic carbon (SOC) sequestration has been suggested as a sustainable and cost-effective strategy for climate change mitigation on agricultural lands (Wijesekara et al., 2021). SOC sequestration refers to the removal of carbon (C) from the atmosphere and storage in the soil through plants or other organisms on the medium- and long term (≥15 years) and results in a global soil C stock increase (Don et al., 2024; Goh, 2011). It has been estimated that the global biophysical potential of SOC sequestration through the adoption of recommended C management practices (RCMPs) ranges between 0.14 and 0.56 gigatons (Gt) of carbon annually (Peralta et al., 2022). Recent emphasis on promoting SOC storage has resulted in the '4 per mille' (4p1000) international initiative launched by France during the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) 21. Increasing global agricultural SOC stocks at an annual rate of 4‰ could result in a C sequestration potential of 2–3 petagrams (Pg) C/year (Minasny et al., 2017). This implies that even very small increases per unit area in the SOC pool can have important implications for the global C balance and climate change as these increases may offset a significant fraction of CO_2 emissions worldwide (Guenet et al., 2021).

SOC content represents a crucial soil quality indicator as it directly affects soil functions and ecosystem services.

Highlights

- This review outlines knowledge (gaps) on carbon sequestration trade-offs related to soil management.
- Specific cover crops, cropping systems and water management tend to stimulate N_2O emissions.
- Research should consider all trade-off components simultaneously in long-term experiments.
- Interaction effects of soil management on trade-offs should be assessed in long-term experiments.

SOC stocks reflect the long-term balance between C inputs (i.e., rhizodeposition, crop residues and exogenous organic products) and C losses through mineralization and leaching. Loss of SOC represents one of the most important soil threats as addressed in the Soil Thematic Strategy (European Commission, 2006). Globally, SOC in agricultural soils is undergoing substantial change due to environmental conditions (e.g., temperature and precipitation patterns), land use/cover changes (LULUCF), and management effects (Hu et al., 2018; Tiefenbacher et al., 2021).

The intensity and type of agricultural soil management strategies (SMS) influence the SOC stocks of agricultural soils (Rumpel et al., 2020). Appropriate soil management may result in improved soil functioning and more productive crops. SMS may also play a role in climate mitigation: they may contribute to a reduction of agricultural greenhouse gas (GHG) emissions by limiting soil C losses (e.g., C mineralization and CO_2 emissions), or increase C inputs, for example, through retention of crop residues in the field, application of external organic matter (OM) inputs into the soils (manure, organic amendments [OA] or biosolids), or a combination of these two factors (Paustian et al., 2016). In addition, conservation agriculture, organic agriculture and agroforestry can favour positive changes in SOC stocks. Applying external OA to agricultural soils can help to improve the soil organic matter (SOM) content and can aid nutrient recycling (e.g., nutrients from straw that would otherwise be burned, compost, manure, etc.; Pezzolla et al., 2012). Similarly, agricultural management practices that contribute to minimal soil disturbance and erosion (e.g., conservation tillage, the use of cover crops [CC]) can maximize the amount of crop residues retained on the soil surface as well as increase the soil water storage and the nutrient use efficiencies of cropping systems (Jarecki & Lal, 2003).

Because the carbon cycle is tightly coupled with the nitrogen (N) cycle, efforts to increase SOC stocks may directly affect the N cycle and associated direct and indirect nitrous oxide (N_2O) emissions (Tiefenbacher et al., 2021) as well as N leaching. Particularly the application of OA can also affect non-CO_2 GHG emissions (such as N_2O) or N leaching (Diacono & Montemurro, 2011; Guenet et al., 2021). Agricultural SMS may also strengthen climate change mitigation when synergistic effects are stimulated, such as a net SOC sequestration or SOC accrual coupled with a reduction in N_2O emissions or N leaching. However, increased N_2O emissions can potentially offset the climate change mitigation gained via SOC storage, creating a trade-off. Guenet et al. (2021) found that when associated N_2O emissions are not taken into account, climate change mitigation by increased SOC stocks can be strongly overestimated. Indeed, soil N_2O emissions are identified as one of the most uncertain components of the global warming potential of agricultural systems (Lugato et al., 2018).

N_2O emissions are largely derived from microbial turnover of N inputs to agricultural land, i.e., chemical fertilizers, manure, urine deposited by grazing animals, and residues of leguminous crops. N inputs may also stimulate nitrate (NO_3^-) leaching. This is an abiotic process where NO_3^- is transported out of the root zone along with the downward water flow (Hansen et al., 2019), which usually occurs during periods of high drainage rates. While N leaching is especially known to result in groundwater contamination (Tiefenbacher et al., 2021), the process is also a source of indirect N_2O emissions (IPCC, 2006) that contribute to global warming. The leaching rate is highly influenced by soil water content, texture and soil structure. It is thus important to evaluate how the supply of C and N inputs addresses NO_3^- leaching as well as the direct and indirect N_2O emissions.

Methane (CH_4) is another non-CO_2 GHG that must be considered when studying the climate mitigation potential of SMS with a focus on carbon sequestration. Generally, agricultural soils are a sink for methane rather than a source. Consumption rates of atmospheric CH_4 in soils are low in European agricultural soils (Guenet et al., 2021; Kim et al., 2016) but they contribute to the GHG balance of agroecosystems. So far, results are inconclusive, showing that specific SMS aiming to increase SOC levels may either increase or decrease CH_4 emissions from agricultural soils (Sykes et al., 2020).

Although the potential trade-offs of carbon sequestration may offset the obtained climate change mitigation, the understanding of the impact of SMS on these trade-offs or synergies remains limited. Diacono and Montemurro (2011) state that the effects of the application of OM inputs on soil quality and fertility should not be restricted to a simple quantification of SOC stock or CO_2 balance, but they must consider all GHG fluxes by trying to include all possible emission sources and sinks within the soil–plant system.

Today only scattered information on this subject is available, characterized by a strong heterogeneity of experimental designs performed under different pedoclimatic conditions. The aim of this review is therefore not only to synthesize existing knowledge but also to identify knowledge gaps about both trade-offs and synergies between soil carbon sequestration or SOC accrual (Don et al., 2024), non-CO_2 GHG emissions and N leaching under selected agricultural SMS. After these knowledge gaps have been identified, dedicated experiments can be set up to elucidate the impact of SMS on observed trade-offs. In this paper, the investigated agricultural SMS are grouped into four categories: (i) tillage management, (ii) cropping systems, (iii) water management and (iv) fertilization and OM inputs, with the latter comprising crop residues, cover crops, livestock manure, slurry, compost, biochar and liming. The aim is to help identify the combinations of agricultural SMS that have yet to be investigated and to recommend future research on possible trade-offs and synergies.

2 | MATERIALS AND METHODS

This narrative review focused on relevant European agricultural SMS grouped into four categories as stated in the introduction (above). Relevant literature published since 2010 was collected from Scopus, Web of Science and Google Scholar. Studies were selected according to the following guidelines: reviews and meta-analyses describing the effect of the selected agricultural SMS on the trade-offs and synergies between carbon sequestration or SOC accrual (Don et al., 2024) and GHG emissions or N leaching; literature that describes the effects on GHG emissions or N leaching or carbon sequestration (or SOC accrual) either individually or as a combination of topics; and original research papers that described either trade-offs or synergies on between carbon sequestration (or SOC accrual), GHG emissions or N leaching. When only a limited number of reviews, meta-analyses and original papers could be identified, we also included original research papers on the effects of an SMS on carbon sequestration (or SOC accrual), GHG emissions or N leaching. This criterion only applied to the SMS 'liming'.

The effects of SMS application in both conventional and organic farming systems were considered in this narrative review. Despite the noted effects of SMS on crop yield, this direct effect fell largely outside the scope of this paper. A variety of land cover types were included: arable land, permanent crops (woody crops), pasture/grassland, permanent fallow ground and heterogeneous agricultural areas (e.g., annual crops associated with permanent crops). Agroforestry was considered as part of the 'cropping systems' SMS category. The number of European studies was often limited, thus global reviews and meta-analyses were also included on the condition that they included at least one European study on the same subject. The focus remained on the European agricultural SMS; any global studies were included in order to confirm or add nuance to the results of the European studies.

All collected literature items were grouped according to the abovementioned SMS categories. In total, 87 unique literature items were included: 29 reviews, 42 meta-analyses and 16 original papers. From these 87 items, information for this qualitative review was expressed using vocabulary based on the FAO, WRB/USDA, Agrovoc and Corine Land Cover standards and was reported in a qualitative database available on Zenodo (https://doi.org/10.5281/zenodo.10959077). Some of the retained literature items describe the effects of several SMS categories, thus the qualitative database comprises 112 unique inputs. A majority of literature considered fertilization and OM input (58 input lines, 51.8%), followed by tillage management (23 input lines, 20.5%) and cropping systems (20 input lines, 17.9%); only 11 studies reported on water management (9.8%). Information extracted from the literature items includes (1) information on the effect of an SMS on a trade-off component (SOC sequestration or SOC accrual, N_2O emissions, CH_4 emission, N leaching) or the trade-offs and (2) knowledge gaps and research recommendations (Table S1).

First, for each relevant literature item (Table S1, List S1), a qualitative expert evaluation was performed to assess the effect of the reported SMS category on SOC change, GHG emission mitigation or N leaching (Tables S2–S9). This expert evaluation was based on the evidence and conclusions described in the literature item. See 'Results and Discussion' section below for a qualitative evaluation and summary of the overall effect of each SMS category from the environmental point of view. The effect of a given soil management practice is defined as positive when it results in increased SOC change while it denotes decreased N_2O and CH_4 emissions and N leaching; negative when the opposite; and neutral when no effect on SOC change, GHG emissions or N leaching are observed. Some literature items reported SMS effects from different pedoclimatic conditions or crops, meaning that one literature item can generate more than one output describing the effect of a particular SMS category on the chosen parameter. Second, all evaluations of the literature items were grouped per SMS category. For the evaluation of the effect of an SMS category on SOC change, GHG emission mitigation or N leaching, all of the included considered literature items (sorted per SMS; Table S1) were attributed equal weight. Reviews and meta-analyses include information on multiple studies, but the original studies included in our review were attributed equal weight as these focus on European regions. In case the expert evaluation of a single literature item (Tables S2–S9) concluded that both positive and/or negative or neutral effects occur, for example, effects that depend on the C/N ratio of OM inputs, these effects were proportionally accounted for in the contribution of this single literature item. Thus, if n effects were concluded for one literature item (Tables S2–S9), the weight of one effect of this literature item was equal to the weight of the literature item divided by n. Detailed information on the literature items included for each SMS can be found in Table S1 and List S1.

Moreover, we also identified knowledge gaps and research recommendations from the relevant literature items (see Table S1) grouped per SMS category and subcategories in the database. The most relevant knowledge gaps and research recommendations are described in 'Results and Discussion' section.

3 | RESULTS AND DISCUSSION

3.1 | Tillage management

Intensive tillage with complete soil inversion (inversion tillage) has been shown to (1) increase soil vulnerability to erosion and compaction and (2) reduce SOC. Further, inversion tillage requires more labour and higher consumption of fossil fuels due to the intensive use of machinery in comparison to other less intensive types of tillage (Sørensen & Nielsen, 2005). To mitigate some of these negative effects and to preserve SOC, less intensive tillage practices (also referred to as reduced, minimum or conservation tillage) and no-till (the absence of mechanical soil disturbance) have been promoted in recent decades. Reduced tillage intensity generally increases topsoil SOC content, but the effect on the total (whole soil profile) SOC storage is being questioned due to insufficient sampling of the complete soil profile and/or lack of accompanying data for carbon stock calculations (Guenet et al., 2021; Haddaway et al., 2017; Meurer et al., 2018; Tiefenbacher et al., 2021).

Under reduced tillage, most studies reported increased SOC stocks in the upper 30 cm of the soil profile (Figure 1a; Aguilera, Lassaletta, Gattinger, & Gimeno, 2013; Autret et al., 2019; Dignac et al., 2017; Guenet et al., 2021; Haddaway et al., 2017; Meurer et al., 2018; Payen et al., 2021; Powlson et al., 2016; Tiefenbacher et al., 2021). Careful investigation is needed to account for actual SOC accrual and not just vertical redistribution.

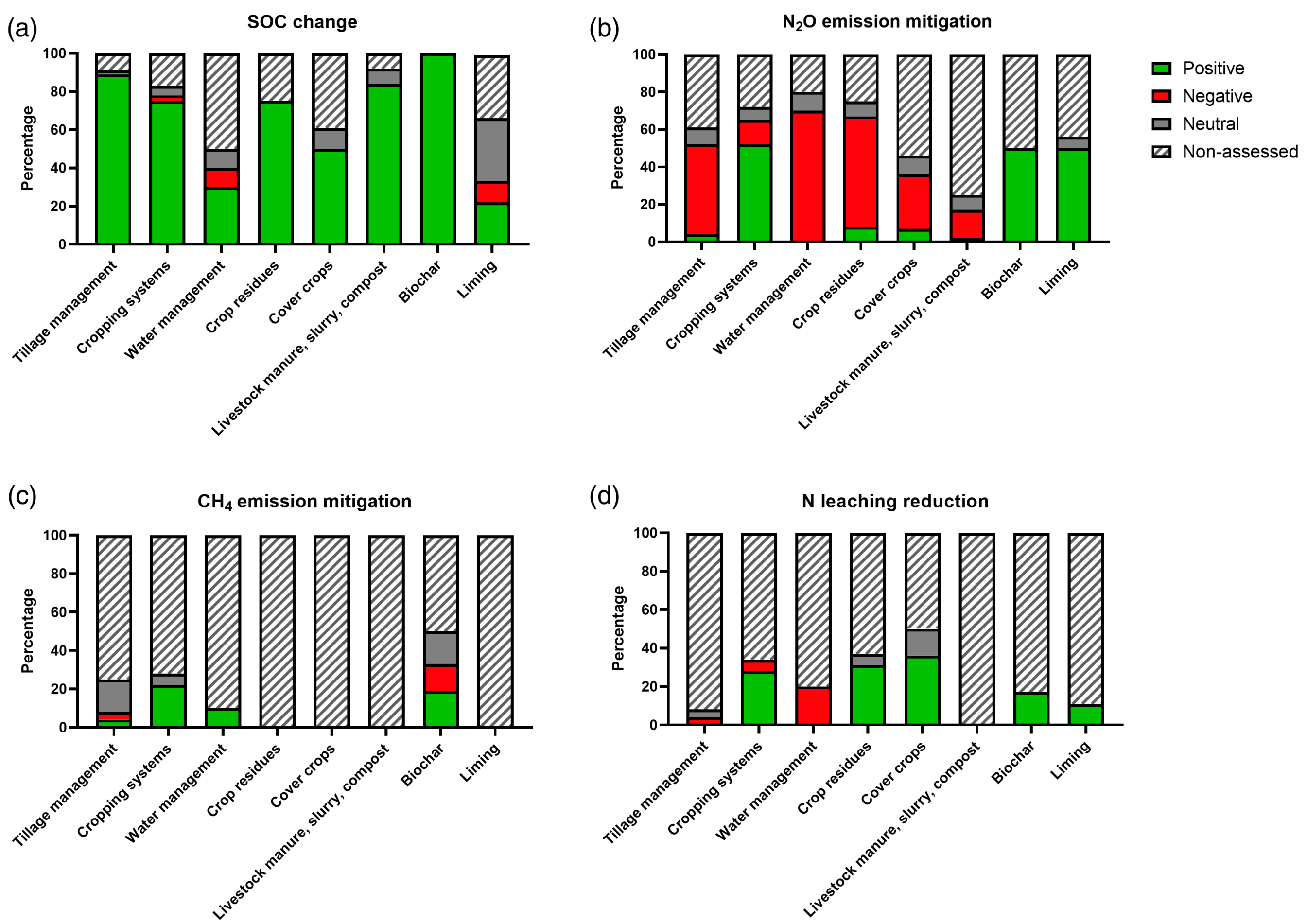

FIGURE 1 The percentage of literature items that report positive (green colour), negative (red colour) and neutral (grey colour) effects of soil management strategies on soil organic carbon (SOC) change (a), N_2O emission mitigation (b), CH_4 emission mitigation (c) and N leaching reduction (d). The shaded area indicates the percentage of literature items in which the effect was not assessed. These effects were evaluated for tillage management ($n = 23$); cropping systems ($n = 18$); water management ($n = 10$); crop residues ($n = 8$); cover crops ($n = 14$); livestock manure, slurry and compost ($n = 12$); biochar ($n = 6$) and liming ($n = 9$). In case a single literature item reported both positive and/or negative or neutral effects, these effects were assigned a proportional weight in the contribution of this single literature item. Detailed information on the literature items included for each soil management strategy can be found in Table S1 and List S1. The results of the qualitative expert evaluations executed on the effect of the reported SMS category on SOC change, GHG emission mitigation or N leaching reduction are shown in Tables S2–S9.

The few studies that included deeper sampling depths (down to 60 cm: 45 cm in Jacobs et al. (2015); 50 cm in Krauss et al. (2017); 40 cm in Murugan et al. (2014) and 60 cm in Zikeli et al. (2013)) report conflicting results. The effect throughout the entire soil profile needs further examination (Haddaway et al., 2017). Further, the 'equivalent soil mass' approach is not commonly used, which further hinders comparison in case the soil bulk density is significantly altered due to management. For more reliable estimates of SOC accrual or carbon sequestration, additional research is needed to investigate the underlying mechanisms of SOC stabilization and turnover within the soil profile on a longer temporal scale.

Less intensive tillage resulted in either constant or increased N_2O emissions as compared to conventional tillage practices (Figure 1b; Guenet et al., 2021; Krauss et al., 2017; Mangalassery et al., 2014; Tellez-Rio, García-Marco, Navas, López-Solanilla, Rees, et al., 2015; Tellez-Rio, García-Marco, Navas, López-Solanilla, Tenorio, & Vallejo, 2015). Because N_2O emissions are a product of a microbially guided process, this effect is influenced by several soil properties that can be altered by (inversion) tillage, such as SOC and nutrient contents, water holding capacity, porosity, soil structure and soil air–water conditions. Heterotrophic denitrification, the main source of soil-borne N_2O emissions, is influenced by available soil carbon and anoxic conditions. Under reduced tillage, both parameters usually increase due to SOC accumulation. In practice, the impact of tillage management on N_2O emissions may vary among different soil management systems (e.g., fertilization, crop rotation, etc.). This has sparked an ongoing debate about how different tillage systems influence N_2O emissions. Soils with improved water-holding capacity, porosity and hydrophilicity tend to have better nitrogen and water retention (Guenet et al., 2021). In the short term, no-till can lead to higher soil density; the resulting lower porosity and higher water content thus creates favourable conditions for denitrification.

Under reduced tillage or no-till, reductions in CO_2 have been observed (Abdalla et al., 2016; Aguilera, Lassaletta, Gattinger, & Gimeno, 2013; Huang et al., 2018). Most authors report no significant effect of tillage on CH_4 emissions (Figure 1c; Krauss et al., 2017; Sanaullah et al., 2020; Tellez-Rio, García-Marco, Navas, López-Solanilla, Rees, et al., 2015; Tellez-Rio, García-Marco, Navas, López-Solanilla, Tenorio, & Vallejo, 2015) while others note a decrease (Huang et al., 2018).

In general, the degree of evidence in literature is too low to draw conclusions about the effect of tillage management on GHG fluxes. Most studies confirm a complex interplay between tillage and soil bio-chemical–physical properties, pedoclimatic conditions and other agricultural management practices (crop rotation, CC, fertilization, irrigation, etc.) that impede the ability to draw general conclusions. Further, the duration of the experiment plays a role (Six et al., 2004) as the processes involved have different temporal dynamics. Future studies are needed with different (longer) experimental duration under different cropping conditions that consider both SOC accrual or SOC sequestration and GHG emissions to get more insight into potential trade-offs. Another problem is the lack of consistency in reporting the soil depth considered. Last, too few experiments have been performed that test the impact of different combinations of tillage and fertilization as applied in real agricultural practice.

Few studies have simultaneously estimated N leaching and SOC stocks and/or GHG emissions under different tillage systems. The results of Daryanto et al. (2017) suggest that changes in water flux between tillage systems affect N leaching, with a potentially higher loss of N to groundwater in the no-till system (Figure 1d). Only one study from the present literature analysis simultaneously estimated SOC stock changes, GHG emissions and NO_3^- leaching under different tillage practices at field level (Autret et al., 2019). When reduced tillage was applied, the authors observed a reduction in the potential to mitigate climate change, owing to high N_2O emissions that partially offset the high carbon sequestration rate. No effect on nitrate leaching was observed in that study. Recently, Taghizadeh-Toosi et al. (2022) simultaneously studied the effect of no-tillage, CC and straw retention on N_2O emissions and N leaching. They found that no-tillage reduced N_2O emissions by 46% compared to ploughing, while the effect of no-tillage on N leaching reduction was non-significant. The three SMS resulted in a positive effect on N retention and the GHG balance.

3.2 | Cropping systems

Diversification of crops and well-designed cropping systems are important strategies to improve soil properties and promote soil fertility such as nutrient cycling and biological activity. Cropping systems that strive for agro-environmental protection and socio-economic sustainability can be considered as a well-developed form of sustainable farming.

Cropping systems and SOC dynamics are strictly linked. Cropping systems based on crop rotation with legumes (Guenet et al., 2021), perennials (Morugán-Coronado et al., 2020) and agroforestry (Kim et al., 2016), combined with conservation or organic agriculture (Autret et al., 2019; Tiefenbacher et al., 2021) induce a positive SOC stock change (Figure 1a). Likewise, crop diversification, permanent crops and CC can enhance SOC storage. Further, recycling of crop biomass (e.g., catch crops, agroforestry or deep rooting crops) can prevent C losses from soils (Tiefenbacher et al., 2021). Nevertheless, Sandén et al. (2018) found that in crop rotations mainly based on cereals such as maize, wheat or barley, where grain legumes (e.g., faba bean, pea), forage legumes (e.g., lucerne, clover, vetch), grass, root and tuber crops (e.g., potato, sugar beet) are less frequently present, SOC content remained unchanged in the long term. Interestingly, Gattinger et al. (2012) found that SOC increases under organic agriculture are mainly due to differences observed in crop rotations and total C inputs (i.e., the sum of external C inputs and crop residues). This is because organic cropping systems are more often mixed systems (e.g., livestock and arable crops) that are characterized by diversified rotations with higher percentage of legumes (grain or forage) in the crop rotation. However, Leifeld and Fuhrer (2010) concluded that the higher SOC stock change under organic agriculture compared to conventional agriculture was mainly due to the higher application of organic fertilizer in organic systems. Although agroforestry systems may play a crucial role in increasing SOC stock and reducing net GHG emissions (Debaeke et al., 2017; Kim et al., 2016), the climate change mitigation potential of these systems is not conclusive due to insufficient evidence. A complete understanding of above- and below-ground biomass C storage in trees and/or shrubs is required based on long-term data. A better understanding of the C translocation and its contribution to C inputs and retention in soils is needed.

Recently, minor differences in N_2O emissions in agroforestry systems compared to adjacent non-agroforestry farmland were found (Figure 1b; Guenet et al., 2021; Kim et al., 2016). However, no clear trend of change could be identified. Enhanced N_2O emissions can be due to the greater N supply through N_2-fixing trees, the introduction of leguminous CC, land use change from forestry or grassland to cropland or the incorporation of crop residues (Doltra et al., 2019; Guenet et al., 2021; Kim & Kirschbaum, 2015). In temperate regions where agroforestry systems are generally planted with non-leguminous trees, N_2O emissions are often reduced due to the presence of deep-rooted trees. These trees can reduce the amount of N available for nitrification and denitrification because they require more water than croplands, resulting in decreased soil moisture content (Guenet et al., 2021; Kim et al., 2016). Permanent cropping systems (e.g., willow short rotation crop, grass, miscanthus) in conservation and organic agriculture have been shown to reduce N_2O emissions (Figure 1b) compared to annual cropping systems (e.g., winter-oat, fodder maize and annual bioenergy crops; Oertel et al., 2016). Intercropping and crop rotation seem to have mainly beneficial effects on GHG emission mitigation. During the growth of unfertilized legumes (grain legumes, grass–clover leys, green manure or CC), low N_2O emissions were observed, particularly when grown in mixtures with non-legumes, because low soil mineral N concentration is associated with legume–rhizobium symbioses (Figure 1b; Hansen et al., 2019). The impact of cropping systems on N_2O emission mitigation thus depends on the specific cropping system. CH_4 emissions were also reduced when using crop rotations and an organic agricultural system (Figure 1c; Oertel et al., 2016).

Nitrate leaching was usually reduced when CC and especially legumes were introduced into the crop rotation (Figure 1d; Debaeke et al., 2017; Guenet et al., 2021), although the number of studies available is low. Permanent cropping reduces soil NO_3^- leaching compared to arable crops (Don et al., 2012; Novak & Fiorelli, 2010). Similarly, NO_3^- leaching was reduced in organic agricultural systems (Autret et al., 2019). However, the study of De Notaris et al. (2018) demonstrates that the selection of the crop rotation can strongly impact the risk of N leaching and result in higher N leaching losses in organic compared to conventional agricultural systems.

3.3 | Water management

Irrigation and water management practices are important to ensure an adequate water supply for crops under climate change scenarios that include the lack of reliable rainfall (Trost et al., 2013). Irrigation increases plant-available water in soils and helps to increase net primary production and C inputs into the soil under dry environmental conditions. Irrigation itself might thus affect climate change by altering the capacity of soils to act as a C sink or source, as well as affecting GHG emissions (Lal, 2004).

Irrigation can increase CO_2 emissions due to a stimulation of the soil microbial activity (Sapkota et al., 2020) but this effect is usually outweighed by SOC inputs via plant growth (Emde et al., 2021), resulting in net SOC accumulation (Figure 1a). This was mainly observed in arid and semi-arid regions (Emde et al., 2021; Trost et al., 2013). At the global level, no SOC stock increase was observed in flood- or furrow-irrigated soils (Emde et al., 2021). When combined with N fertilization, irrigation stimulates SOC accumulation, especially in sandy soils and soils low in SOC content (Trost et al., 2013; Trost et al., 2016). Furthermore, reduced tillage strengthens the SOC accumulation obtained via irrigation (Trost et al., 2013).

To fully understand the effects of irrigation on SOC stock, the impact of pedoclimatic conditions and initial SOC stocks needs to be assessed. Researchers should take the SOC storage in deeper soil layers into account to more accurately estimate the effects of irrigation on SOC. Insights into fundamental mechanisms are required. The impact of irrigation on changes in soil texture and translocation of clay particles needs to be assessed to achieve an in-depth understanding of the impact on SOC accumulation. Moreover, future research should also focus on the impact of water table changes on SOC stocks. Last, the formation of secondary carbonates, which may lead to inorganic C accrual, has been seldom investigated and thus requires attention.

Irrigation can stimulate both direct and indirect N_2O emissions (Aguilera, Lassaletta, Sanz-Cobena, et al., 2013; Cayuela et al., 2017), with reported increases ranging from 50% to 140% (Trost et al., 2013) depending on the availability of reactive N (Kuang et al., 2021; Trost et al., 2013), soil type (Kuang et al., 2021; Trost et al., 2016) and cropping systems (Figure 1b). However, as irrigation can enhance agronomic yields it can result in lower yield-scaled N_2O emissions (Trost et al., 2016). Water-saving irrigation techniques seem to have a positive impact on mitigation of N_2O emissions. Drip irrigation was found to cause less N_2O emissions than sprinkler (Cayuela et al., 2017; Kuang et al., 2021) or other conventional (furrow) irrigation techniques (Aguilera, Lassaletta, Sanz-Cobena, et al., 2013; Kuang et al., 2021). Deficit irrigation applied via drip irrigation was also found to decrease N_2O emissions (Zornoza et al., 2018). CH_4 emission may be stimulated by flood irrigation as this creates anaerobic conditions in soil, while reduced irrigation (volume or frequency) may favour a reduction of CH_4 emissions or even a CH_4 uptake (Figure 1c; Sapkota et al., 2020). The effects of irrigation practices on CH_4 emissions require more attention, especially in upland soil systems.

Inappropriate irrigation practices can stimulate nitrate leaching (Figure 1d; Quemada et al., 2013; Tiefenbacher et al., 2021) and reduce nitrogen use efficiency (Quemada et al., 2013). In general, irrigation has a negative impact on N leaching when compared to rainfed systems. In contrast, optimal management practices can considerably reduce nitrate leaching. Adapting the amount of water to the crop's needs may reduce nitrate leaching by 80% (Quemada et al., 2013), especially in furrow and flood irrigation systems. Deficit irrigation helps to reduce nitrate leaching but has a negative impact on yield (Quemada et al., 2013). Improved irrigation management may reduce nitrate leaching while increasing yields. In future research, nitrate leaching should be monitored within long-term field trials.

To properly assess the sustainability of irrigation strategies, water-saving irrigation strategies (i.e., deficit irrigation, subsoil irrigation) should be investigated, including non-irrigated and full irrigation controls. Interaction effects of water management with fertilization (organic and synthetic) and the diversity of crops (including woody perennials) in both conventional and organic farming systems require more research. Furthermore, the impact of soil type (including acid soil types) and climate requires more attention. In general, an important limitation in current research is the lack of long-term experiments. Field studies that investigate the effect of irrigation on both SOC accrual and GHG emissions are scarce (Trost et al., 2016; Zornoza et al., 2018). Such studies are highly relevant and could provide better insights into the trade-offs between GHG emission/N leaching and SOC accrual or C sequestration. Furthermore, the information on how water quality may affect SOC stocks and N_2O fluxes in the long term is still limited. Zhang et al. (2016) found that increased salinity of irrigation water increased N_2O emissions. At the same time, long-term irrigation with saline water has been found to decrease soil organic and inorganic C storage (Dong et al., 2022). In related findings, constructed water bodies used for irrigation may also act as a source of indirect N_2O emissions (Cayuela et al., 2017; Webb et al., 2021) but this effect is currently underinvestigated (Webb et al., 2021).

3.4 | Fertilization and OM inputs

3.4.1 | Cover crops

Cover crops are sown in order to cover soil with vegetation before sowing a subsequent crop, in order to reduce the risk of soil loss through erosion. Furthermore, CC increase the amount of crop residues incorporated into the soil upon termination of the CC.

Mediterranean (Aguilera, Lassaletta, Gattinger, & Gimeno, 2013; Shackelford et al., 2019) and global meta-analyses (Jian et al., 2020) show that both non-legume and legume CCs resulted in increased SOC stocks in the topsoil compared to leaving the soil bare between crops or fallow in winter (Figure 1a). The soil carbon stock had significant and positive correlations with the annual temperature and the duration of CC cultivation (Jian et al., 2020). CC species composition may influence the change in SOC stock, with mixtures and legumes usually showing higher SOC accrual rates than mono-species or grasses (Jian et al., 2020). However, a recent review on Mediterranean viticulture showed larger increases in SOC under the growth of spontaneous grass species compared to the use of legumes (Abad et al., 2021).

An analysis of European long-term experiments showed that N_2O emissions increased by 65% due to CCs and green manures, but the response was insignificant after random effects were taken into account (Sandén et al., 2018). Typically, legumes result in higher N_2O emissions, while non-legume and mixed CC have either a neutral effect or lower N_2O emissions (Figure 1b; Abdalla et al., 2019; Basche et al., 2014; Muhammad et al., 2019), probably because of the legumes' ability to fix atmospheric N and increase soil N levels. One of the key points to controlling the CC effect on N_2O emissions is the frequency of integration of legume crops in the crop rotation (Guenet et al., 2021), along with the C/N ratio of CC residues and their rate of decomposition and whether the residues are ploughed under or left to decay on the soil surface (Guenet et al., 2021). Incorporation of CC may actually stimulate N_2O emissions, in contrast to leaving them on the soil surface (Basche et al., 2014; Muhammad et al., 2019), through a variety of mechanisms, such as increasing N mineralization rates of both SOM and CC residues, increasing soil temperature and the ensuing potential for denitrification (Basche et al., 2014). The use of legume CC can indirectly impact N_2O emissions originating from mineral fertilizer application if biologically fixated N is taken into account in fertilization schemes. Knowledge gaps should be addressed regarding the following: the influence of CC residue quality and quantity on CO_2 and N_2O emissions (Muhammad et al., 2019), the impact of weather conditions on N_2O dynamics (Basche et al., 2014) and specific climate conditions such as dry cool and dry warm zones with annual precipitation ≤500 mm (Abdalla et al., 2019; Quemada et al., 2013). Measurements of N_2O emissions over the entire year are required to determine the net effect of CC on N_2O (Basche et al., 2014). Existing monitoring measurement systems and available datasets do not allow for robust estimations of N_2O emissions and conclusions on the possible trade-off between N_2O emissions and management practices that stimulate C sequestration or SOC accrual (Lugato et al., 2018).

Several European studies show that replacing a fallow field with a non-legume CC reduced N leaching by about 50% via N uptake and less nitrate provision to the soil in autumn (Valkama et al., 2015), while the use of legumes had no effect (Quemada et al., 2013; Shackelford et al., 2019; Thapa et al., 2018). A European review on organic arable crop rotations (Hansen et al., 2019) stressed that continued use of CC, even with mixtures of legumes and non-legumes, had the proven ability to reduce NO_3-N leaching and had a better impact on soil fertility than using non-legumes as CC (Figure 1d). However, more research is needed on N_2O emissions and NO_3-N leaching within organic arable crop rotations (Hansen et al., 2019) as well as accounting for spatial variability of nitrate fluxes (Thapa et al., 2018). Furthermore, there is no meta-analysis that summarizes studies on the effects of CC on SOC, N_2O emissions and N leaching across Europe.

3.4.2 | Crop residues

Incorporation of crop residues has been shown to result in 3%–18% higher SOC stocks compared to crop residue removal in a synthesis of meta-analyses (Bolinder et al., 2020) and about 6%–7% in a European meta-analysis and long-term experiment (Figure 1a; Lehtinen et al., 2014; Sandén et al., 2018). SOC content increased significantly with an increasing straw addition rate and straw C input rate (Xia et al., 2018). The impact on SOC stocks is expected to be greater for grain maize because the potential aboveground crop residues represent approximately twice the amount of small grain cereals (Bolinder et al., 2020). The impact is greater with a C/N ratio of residues larger than 30 (e.g., cereal straw), compared to C/N ratio <30 (e.g., legume straw; Xia et al., 2018). The effect of straw application on SOC content was similar for different mineral N fertilization rates and application methods (surface application vs. incorporated), but a long-term (≥4 year) straw addition resulted in significantly higher relative SOC increase (27.7%) than a short-term addition (13.4%; Xia et al., 2018). Furthermore, the increase in nutrient availability following straw addition was also associated with an increase in microbial biomass (Siedt et al., 2021; Wang et al., 2018; Xia et al., 2018).

Temporal dynamics of SOC changes following straw addition are still unclear due to the different durations of the experiments (Bolinder et al., 2020). Xia et al. (2018) concluded that experiments with an intermediate duration (>4 years) resulted in a significantly higher C increase than short-term experiments, while other authors (Lehtinen et al., 2014) stressed that long-term experiments (>20 years) yielded larger SOC increases than short-term experiments. Meta-analyses also showed a lack of agreement for relationships between the changes in SOC due to residue incorporation and soil texture or climate (Bolinder et al., 2020).

Straw C/N ratio was the main factor determining the variability of the N_2O emission response after residue addition, as indicated by two global meta-analyses (Chen et al., 2013; Xia et al., 2018). Crop residue amendment stimulated soil N_2O emissions when C/N ratios were <45, with the effect attenuated for C/N ratios of 45–100, and induced a reduction of N_2O fluxes for C/N ratios

>100 (Figure 1b; Chen et al., 2013). Different thresholds of C/N ratio may be set for evaluation of their impact on N_2O emissions. Xia et al. (2018) observed enhanced N_2O emissions when applying straw with a C/N ratio <30 (e.g., legume straws), no effect for C/N ratio between 30 and 60 (e.g., cereal straws) and N_2O flux reductions for C/N ratio >60 (Figure 1b). As suggested by Olesen et al. (2023), both meta-analyses agreed that wheat straw reduced N_2O emissions, while maize, bean and particularly green manure and vegetables increased N_2O emissions. Studies that did not take straw C/N ratios into account reported an increase in soil N_2O emissions following the incorporation of residues (Lehtinen et al., 2014; Sandén et al., 2018; Wang et al., 2018). Incorporation of residue into the soil through tillage increases aeration and microbial activity by exposing more residue surface to microorganisms, thereby stimulating residue mineralization and N_2O emissions (Alluvione et al., 2010; Baggs et al., 2000); see 'Tillage' section above. This stimulated microbial activity is favoured by a high content of easily degradable carbon in crop residues and may result in lower oxygen concentrations, which in turn may stimulate denitrification (Olesen et al., 2023). More long-term field studies are needed to better assess the N_2O emissions following crop residue incorporation, specifically from the same studies in which SOC is measured (Lehtinen et al., 2014).

Global meta-analyses showed that crop residue return (incorporation and mulching) resulted in a decrease in N leaching by about 9% in upland soils (Wang et al., 2018; Xia et al., 2018). The meta-analysis by Xia et al. (2018) stressed that the response of N leaching depended on N fertilization rates, C/N ratio of crop straw, straw application method and climate. No European synthesis on the topic of NO_3^- leaching and straw application was found.

3.4.3 | Livestock manure, slurry and compost

The application of farmyard manure, slurry and compost (OA) was examined in relation to SOC change, GHG emissions and N leaching. Farmyard manure consists of faeces, urine and bedding (usually cereal straw or sawdust). Slurry (also called liquid manure) contains urine and faeces without the inclusion of bedding and is sometimes diluted with water. Both farmyard and liquid manure may contain fodder residues. Compost is aerobically treated biogenic waste, such as source-separated municipal waste, farmyard manure or green waste (grass, shrub and yard clippings). Literature widely agrees that the application of these OA results in increased SOC content compared to inorganic fertilizers or no fertilization (Figure 1a; Maillard & Angers, 2014; Morugán-Coronado et al., 2020; Shakoor et al., 2021). The majority of the studies focus on SOC contents and not SOC stocks, however. The question remains what the SOC saturation level would be after OA application under different pedoclimatic conditions (Zhou et al., 2017). Increases in SOC content in the range of 20%–35% have been found after manure application (Gross & Glaser, 2021; Sandén et al., 2018). Relative SOC increase tends to be higher with compost amendment than with raw manure due to the presence of more stable forms of carbon, which are not easily mineralized and released back to the atmosphere (Aguilera, Lassaletta, Gattinger, & Gimeno, 2013; Luo et al., 2018; Sandén et al., 2018; Siedt et al., 2021). However, composts vary in feedstock and degree of decomposition, which results in variable SOC change potentials (Siedt et al., 2021). The average C sequestration potential of compost was estimated to be 714 ± 404 kg C ha^{-1} $year^{-1}$ compared to 292 ± 132 kg C ha^{-1} $year^{-1}$ for farmyard manure (Tiefenbacher et al., 2021). Liquid materials (e.g., slurry, digestate) can be mineralized rapidly and have the lowest impact on SOC compared to other organic materials (Aguilera, Lassaletta, Gattinger, & Gimeno, 2013). Nevertheless, the impact of slurry on SOC stock has not been thoroughly studied (Maillard & Angers, 2014).

In addition, a limited number of studies adequately address the effects of OA to estimate impacts on SOC stock changes. This is due to a lack of essential information on C concentration, application rate, dry matter content and animal species (Maillard & Angers, 2014; Shakoor et al., 2021; Tiefenbacher et al., 2021). Better parameterization of organic fertilizers is needed to improve existing dynamic biogeochemical SOC models used to study the interactions between the C and N cycles. These models could be used to re-evaluate the impacts of organic fertilizers on SOC pools (Zhou et al., 2017).

All types of manure (liquid and solid; raw but also composted or digested) increase soil N_2O emissions by an average of 33% compared to mineral N fertilizer alone (Figure 1b; Zhou et al., 2017). However, data on N_2O emissions associated with the addition of OA are limited (Guenet et al., 2021) and only a few articles compared the application of manure from different animal species (Maillard & Angers, 2014). In particular, subsurface application of manure (recommended to reduce NH_3 volatilization) increased N_2O emissions by an average of 75% compared (Zhou et al., 2017) to mineral N fertilizers. This is in contrast with the findings of Velthof et al. (2003). Surface application of pretreated manure (e.g., compost) resulted in similar N_2O fluxes to mineral N fertilization, whereas raw manure significantly increased (46.9%) emissions compared with mineral N fertilizer (Figure 1b; Zhou et al., 2017). This difference was attributed to the contrasting contents of easily degradable C and N compounds (Zhou et al., 2017).

The nitrogen replacement value of OA tends to increase with the level of the total nitrogen applied via OA (Hijbeek et al., 2018). This indicates a high immediate nitrogen availability and a high mineralization rate and thus a significant risk of GHG emissions and NO_3^- leaching if there is no simultaneous, consistent use of mineral N in the soil by plants. Recently, Valkama et al. (2024) found that for OM inputs such as livestock manure and slurry, a slight N_2O emission reduction can be obtained when no mineral fertilizer was applied. Combined application with mineral fertilizer seemed to stimulate N_2O emissions. Organic fertilizers have a slow but effective nitrogen release (Lehtinen et al., 2017), and the nitrogen balance should therefore be considered to avoid NO_3^- leaching and stimulation of GHG emissions (Sandén et al., 2018). On the other hand, a more stable compost with an annual N mineralization rate of 3%–8% from the second year after application, that is, the amount that can replace mineral fertilizer N, does not pose a risk for increased N_2O emissions (Diacono & Montemurro, 2011). Siedt et al. (2021) indicated that because of the lower availability of N forms in compost, nitrate leaching to groundwater after compost application may be lower than mineral fertilizer application.

The results of a recent meta-analysis show the use of compost was found to reduce N_2O emissions by 25%. This effect depends on the pedoclimatic conditions, however (Valkama et al., 2024). Zhu et al. (2023) suggested that the soil N_2O emissions are controlled by the ratios of dissolved organic C, easily oxidizable C, particulate organic C and light fraction of organic C-to-total N. Furthermore, higher particulate organic C and hydrolysable ammonium-N increase soil N_2O emissions (Zhu et al., 2023). Compost with an average C/N ratio of approximately 15 and a dissolved organic C/NO_3 ratio of approximately 1000 characterizes the nitrification–denitrification activities in soils and is thus one way to reduce N_2O emissions. C/NO_3 ratios between 84 and 130 showed that after NO_3^- is largely consumed, N_2O is reduced to N_2. A dissolved organic $C_{(H2O)}$/NO_3 ratio that balances towards an excess of electron donors under anaerobic denitrification conditions forces denitrifying bacteria, archaea and fungi to use the electron acceptors NO_3^-, NO_2^-, NO and N_2O sparingly by reducing them predominantly to N_2 (Benckiser et al., 2015). Mitigation strategies to minimize GHG and especially N_2O emissions while still achieving high crop yields should therefore be based on tailored nutrient management approaches that account for the nature of the organic carbon and nitrogen forms in the organic fertilizers/soil amendment used and keep the N balance within safe limits.

More research is required to elucidate the effects of livestock manure, slurry and compost on N_2O emission mitigation. Pretreatment of manure could offer potential for reducing N_2O emissions in agricultural systems. Future research should focus on investigating the effect of duration and methods of composting or other pretreatments for the N_2O fluxes (Graham et al., 2017). Furthermore, different OM inputs with similar C/N ratios should be compared with constant total N rates, as C/N ratios lower than 20 tended to reduce emissions (Graham et al., 2017). More research on the effects of livestock manure, slurry and compost on N leaching is required (Figure 1d).

3.4.4 | Biochar

Biochar is the solid product remaining after biomass undergoes pyrolysis under low-oxygen conditions. It is intended for use in soil or other environmental applications (Lehmann & Joseph, 2015). Biochar has received immense research attention in the last 10 years to investigate its potential efficacy for climate change mitigation (Smith, 2016; Woolf et al., 2010), soil and water pollution remediation (Ahmad et al., 2014) and improving agronomic soils (Jeffery et al., 2016).

Biochar is a promising organic C amendment, characterized by different fractions of C (easily mineralizable and more recalcitrant C; Borchard et al., 2019). Its unique feature in the context of climate mitigation is that biochar is more resistant to microbial decomposition compared to the biomass feedstock it was made from and thus persists longer in the soil as a carbon store (Lehmann et al., 2015). Conversion of biomass to biochar and its deposition in soil can sequester ∼50% of the biomass-C (Figure 1a). The soil C sequestration potential of biochar is widely acknowledged in literature, but more research is still required. More certainty is needed to document biochar's net climate change mitigation effect, using studies that also account for indirect emissions occurring in the production of biochar and its associated value chain (Tisserant & Cherubini, 2019).

Literature summarized in recent meta-analyses shows that biochar addition to soils leads to a 10%–50% reduction in N_2O emissions (Figure 1b; Borchard et al., 2019; Cayuela et al., 2014; Verhoeven et al., 2017). Mechanisms explaining this effect include abiotic reduction of N_2O on organo-mineral biochar surfaces (Quin et al., 2015); microbial reduction of N_2O to N_2 mediated by a pH increase (Weldon et al., 2019); and abiotic/biotic synergies where N_2O is held in biochar pores (Cornelissen et al., 2013), which gives denitrifiers more time to reduce

N_2O to N_2 (Harter et al., 2016). Even though the mitigation effect is often reported, more mechanistic studies are needed to unravel the effects of feedstock, pyrolysis process conditions and the optimal physio-chemical properties of biochar to mitigate N_2O (Cayuela et al., 2014). Furthermore, there is a lack of knowledge about the duration of the mitigation effect as well as which biochars mitigate N_2O in different soils and climatic conditions. Borchard et al. (2019) found a reduction in the N_2O mitigation strength from biochar addition in studies that were conducted >120 days. Further, short-term incubations had a larger mitigation (54%; Cayuela et al., 2014) than field studies (approximately 10%; Verhoeven et al., 2017). Higher dose rates (2–10% w/w) used in incubation experiments compared with field trials dose rates (usually <2%) explain much of the difference in the N_2O mitigation effect, with N_2O decreasing by half when biochar dose was doubled (Cayuela et al., 2014). The heterogeneous spread of biochar particles in field soil (as compared to in controlled incubations) can also explain some of the differences (Kammann et al., 2017). More studies that evaluate the long-term effect of biochar addition should be performed, including tests to determine whether N_2O mitigation effects endure over time and how biochar interacts with soil minerals and OM in the long term. The long-term effect on native SOC levels and N cycling requires a more in-depth understanding as well, for example, to seek agreement on the effect of biochar on nitrification rates or nitrification-mediated N_2O emissions (Verhoeven et al., 2017; Wells & Baggs, 2014). The body of knowledge of biochar-induced effects on soil N_2O emissions in grassland and perennial crops is also incomplete.

Several meta-analyses (Cong et al., 2018; Jeffery et al., 2016; Ji et al., 2018) dealt with the effect of biochar on CH_4 emissions and uptake in soil. In Jeffery et al. (2016), biochar was found to significantly increase CH_4 sink strength (Figure 1c), and a decrease in source strength was noted in acidic soil but an increase was noted in soils with neutral pH range (i.e., pH 6–8). The same study found that biochar was also more likely to reduce CH_4 emissions in studies where N application was <120 kg ha^{-1}, which is related to the well-known inhibition effect of N fertilization on methanotrophic bacteria population (Chen et al., 2021). Emission reductions were also observed when biochar was made at temperatures >600°C, which creates biochar with a greater surface area and minimal labile carbon. However, Cong et al. (2018), who assessed studies conducted up to 2016 and applied a stricter criterion to the influence of multiple treatments within studies, found no effect of biochar on CH_4 emissions or uptake in upland soils (Figure 1c). In contrast, the meta-analysis of Ji et al. (2018) found a 84% reduction in CH_4 uptake in upland soils. Given the predominance of upland soils in Europe, the potential reduction in CH_4 uptake due to biochar requires more research (Ji et al., 2018). Furthermore, more knowledge is needed on the interactions of soil properties when assessing the biochar impacts on CH_4, for example, different moisture conditions and tillage practices combined with biochar application (Cong et al., 2018). According to Jeffery et al. (2016), more knowledge is needed to discern under which environmental conditions biochar decreases CH_4 uptake. Van Zwieten et al. (2015) outlined the need for more research on how CH_4 uptake in soils may be affected via biochar-mediated changes in soil gas diffusivity. They also recommended more research on how aged biochar interacts with NH_4^+ adsorption and how this affects methanotrophic bacterial communities.

Biochar can both increase and decrease NO_3^- leaching in soil depending on the type of biochar, its particle size, soil type and how long biochar has been in the soil (Laird & Rogovska, 2015). Borchard et al. (2019) did a global meta-analysis with 88 lab and field studies and found a −26% to −32% reduction in NO_3^- across studies with experiments that lasted >30 days (Figure 1d), but a ∼20% increase in NO_3^- leaching was noted for experiments <30 days. This may imply that soil structure disturbance due to biochar addition may be a relevant factor when assessing the influence of biochar on NO_3^- leaching. In general, biochar is known to help retain NO_3^- in coarse soils due to greater water retention but the reverse effect was observed in clay soils where it may increase hydraulic conductivity (Laird & Rogovska, 2015). Given the variability in biochar impact on NO_3^- leaching, research is needed to develop a functional classification system that can be used to predict NO_3^- leaching effects based on soil type, biochar type and climate interactions (Laird & Rogovska, 2015).

3.4.5 | Liming

The aim of applying calcium- and magnesium-rich materials (liming) is to reduce soil acidity in order to improve plant nutrient uptake. Liming with lime (Eze et al., 2018) and dolomite (Shaaban et al., 2019) can stimulate SOC stocks (Figure 1a), which seems to be mediated by increased crop biomass productivity. Some studies found a neutral effect (Figure 1a) on SOC by adding lime (Paradelo et al., 2015), sugar beet lime with red gypsum (Vázquez et al., 2020) and dolomite (Abalos et al., 2020). However, liming could be an effective strategy to mitigate climate change (Fornara et al., 2011). A 129-year experiment showed that net C increase measured in the 0–23 cm layer in limed soils was 2–20 times higher than in non-limed soils. The greater biological activity in limed soils resulted in plant C inputs being more effectively processed and incorporated into resistant soil organo-mineral pools, despite increasing soil respiration rates (Goulding, 2016). Neutralization of pH likely favours microbial activity, therefore increasing CO_2 effluxes (Abalos et al., 2020; Lochon et al., 2018) but the overall effect of liming on SOC is usually either positive or neutral (Figure 1a). In some cases, even reductions in CO_2 emissions with lime amendment have been observed (Egan et al., 2018).

Silicate weathering consumes CO_2 and therefore has the potential to mitigate CO_2 emissions (Dietzen et al., 2018). By applying finely ground silicate minerals to soils, silicate weathering increases the rate of SOC accrual. The weathering of olivine by carbonic acid, which consumes twice as much CO_2 as the dissolution of lime, results in a stronger positive SOC change (Dietzen et al., 2018). However, the weathering effect of strong acids must also be considered when evaluating the SOC accrual potential of silicate minerals, especially when soil pH is below 5 (Dietzen et al., 2018) and acid neutralization occurs in the soil (Goulding, 2016; Paradelo et al., 2015). The specific effects of liming on the soil C input due to enhanced plant performance and C outputs due to stimulated microbial activity, along with the role of silicate weathering to remove atmospheric CO_2, still need further investigation.

The addition of different liming amendments usually led to a reduction of N_2O emissions (Figure 1b) (Abalos et al., 2020; Khaliq et al., 2019; Shaaban et al., 2019; Vázquez et al., 2020; Zaman & Nguyen, 2010), which is linked to the stimulation of N_2O reduction to N_2. It is also associated with stimulated plant growth and thus plant N uptake, which also reduces nitrate leaching (Bergholm et al., 2015). Vázquez et al. (2020) demonstrated that sugar beet lime application and red gypsum could reduce the cumulative N_2O emissions by more than 70% and 65% after the soil was rewetted to 50% and 100% of field capacity, respectively. Application of dolomite ($CaMg(CO_3)_2$) significantly reduced N_2O emissions by 40%–50% (Khaliq et al., 2019) or even 82% (Abalos et al., 2020). Lime ($CaCO_3$) amendment reduced N_2O emissions by 37%–44% (Khaliq et al., 2019). In contrast, Zaman and Nguyen (2010) found no effect of lime on N_2O emissions, but did note a N_2O emission reduction after application of zeolite. The soil N_2O emission reduction potential of different liming materials needs further evaluation (Shaaban et al., 2019; Zaman & Nguyen, 2010).

More studies are needed that investigate the effects of liming on N leaching (Figure 1d). The latter was studied by Bergholm et al. (2015) over 4 years (1992–1995) in a newly clear-cut field. N leaching at 50 cm depth was dominated by NO_3–N; it peaked during the second year in the lime-amended treatment and during the third year in the control treatment. Cumulative N leaching for the 4-year period was lower for a treatment with lime (31 kg N ha^{-1}) than for the control (53 kg N ha^{-1}) and was inversely correlated with plant N uptake.

4 | FUTURE PERSPECTIVES

4.1 | The impact of pedoclimatic conditions

The literature review on the four agricultural SMS categories identified a lack of information about the impact of pedoclimatic conditions on the trade-offs and synergies (Guenet et al., 2021; Hu et al., 2018; Lochon et al., 2018) on a global and especially European level (Hansen et al., 2019; Lugato et al., 2018; Poeplau & Don, 2015). Currently, the lack of sufficiently robust field data hinders accurate estimations and conclusions on the possible trade-offs among SOC sequestration, GHG emissions and NO_3^- leaching. It is crucial to obtain datasets in the different European agro-environmental zones (Gross & Glaser, 2021; Guenet et al., 2021; Maillard & Angers, 2014; Payen et al., 2021) as pedoclimatic conditions strongly influence the soil C and N dynamics (Eze et al., 2018).

In the literature reviewed here, climate change is usually not considered, although it is known that this will have an important impact on SOC stock change, GHG emissions and NO_3^- leaching. To better assess the effects in terms of potential trade-offs, literature suggests investigating the impacts of climatic factors on N_2O and NO_3^- leaching (Wang et al., 2018), especially in dry cool temperate (Xia et al., 2018) and dry warm climatic zones (Abdalla et al., 2019; Basche et al., 2014; Quemada et al., 2013). In general, GHG emissions and SOC accrual and thus also SOC sequestration are affected by soil type, local climate and weather conditions. Therefore, additional field experiments with different agricultural practices in different geographic locations across the climatic gradient will yield data to account for the above factors. Likewise, the global meta-analysis of Eze et al. (2018) highlighted that more site-specific field experiments focusing on the interactive effects of climate change and agricultural soil management practices are required. Study of the impact of projected changes in climatic conditions (i.e., warmer temperatures, periods of drought, wetter conditions) is also recommended.

4.2 | Subsoil is overlooked

The effects of soil management practices on the subsoil represent a knowledge gap, as only few studies investigated the subsoil below the level of tillage (Aguilera, Lassaletta, Gattinger, & Gimeno, 2013; Emde et al., 2021; Poeplau & Don, 2015). The effects of tillage strategies on SOC stocks in the deeper soil layers are largely unknown. This results in a misrepresentation of the effects of tillage systems, water management and CC (types and termination strategies) on SOC stock, as only shallow layers are considered (Poeplau & Don, 2015). Moreover, the lack of a full estimation of organic C inputs and the lack of examination of the coarse fraction are important sources of errors in SOC stock estimation. This is reported to be a crucial knowledge gap (Aguilera, Lassaletta, Gattinger, & Gimeno, 2013; Muhammad et al., 2019; Payen et al., 2021).

4.3 | Combined and synergetic effects of agricultural SMS

In the context of the impact of pedoclimatic conditions, many studies point out that a better understanding of the interaction effects of agricultural SMS and soil properties (e.g., pH, texture, nutrient status or other physico-chemical properties) is crucial and should be better investigated (Chen et al., 2013; Guenet et al., 2021; Shakoor et al., 2021; Wang et al., 2018), as interaction effects can considerably influence SOC stocks, GHG emissions and N leaching.

Furthermore, many of the reviewed studies describe that a major cause of current knowledge gaps is the lack of research that assesses the combined and synergetic interaction effects of agricultural SMS (e.g., tillage management, cropping systems, irrigation management and fertilization and OM inputs) on SOC storage, GHG emissions and nitrogen leaching (Abdalla et al., 2019; Chen et al., 2013; Guenet et al., 2021; Shackelford et al., 2019; Shakoor et al., 2021; Valkama et al., 2015; Wang et al., 2018). Better insights will enhance the efficacy of global efforts aimed at offsetting GHG emissions and N leaching via SOC sequestration (Chen et al., 2013; Quemada et al., 2013). Many of the current studies focus on the effect of a single management practice as a standalone practice; this is far from representative as all agricultural systems apply a combination of management practices. These oversimplified analyses may reflect the difficulty of studying interactive effects, as such studies require a complex experimental design over large experimental areas coupled with intensive monitoring of GHG emissions. Automated GHG emission monitoring systems are costly while non-automated measurements are labour intensive and have a limited temporal resolution. Either way, this type of research carries a high price tag. A complex statistical model is also required to disentangle main and interaction effects.

Too little is currently known about how the management measures adopted in systems such as organic agriculture contribute to C inputs and C retention in soils. Research is needed on the amount of crop residue that can be removed, as this is dependent on soil types, climate conditions and management systems (Blanco-Canqui & Lal, 2008). There is a general lack of understanding of the impact of SMS and a concurrent potential for optimization. Experiments should therefore focus on the optimization of SMS to help farmers apply them in an efficient and effective way. McDaniel et al. (2014) suggested that data from long-term field experiments with different crop management and cropping systems may provide valuable insights on C inputs and SOC changes. Similarly, further investigations on combined effects of tillage, fertilizer and OM input on SOC are required to determine under what conditions manure application can increase soil C storage and crop productivity without increasing N_2O emissions (Guenet et al., 2021; Haddaway et al., 2017; Kuang et al., 2021). However, essential insights from long-term experiments studying both SOC concentrations and GHG emissions are lacking. Xia et al. (2018) stressed the importance of investigating the fraction of N lost as N_2O or NO_3^- leaching in different soils that receive either mineral nitrogen or straw with different C/N ratios to better understand the interaction between C and N cycles. Furthermore, experiments should also consider constraints associated with phosphorus, potassium and other nutrients that influence the effects of OM on SOC accrual, C sequestration, GHG emissions or nutrient losses (Dignac et al., 2017; Guenet et al., 2021).

4.4 | Long-term experiments are needed

Lugato et al. (2018) state that existing monitoring measurement systems and available datasets do not allow for robust estimations of N_2O emissions and conclusions about the possible trade-off between N_2O emissions and management practices meant to stimulate SOC accrual and C sequestration. Furthermore, quantitative data on gaseous N losses (NO, N_2O and N_2) are scarce (Bergholm et al., 2015), and the effects of long-term manipulations of soil properties on N_2O emissions need to be studied under field conditions (Khaliq et al., 2019). To address these knowledge gaps, long-term field experiments that combine different agricultural SMS are needed: they should consider both carbon sequestration and N losses via N_2O emissions and leaching as well as monitor the relationships between biological soil quality indicators and GHG emissions (Sandén et al., 2018). Many aspects related to the establishment of experiments such as the selection of a more appropriate experimental duration, site selection, type of measurements, experimental scale (field/pot/laboratory incubation) and data availability can strongly contribute to the improvement of the insights on trade-offs and synergies (Haddaway et al., 2017). The impact of SMS on crop yield is a fundamental service of agricultural land. This was largely outside the scope of this paper, but it is important to consider as primary production may be a driver of SOC stock dynamics as well. Knowledge about crop yield is also essential to get better insights in yield-scaled N_2O emissions, which may be a better way to assess the impact of SMS on environmental efficiency (Yao et al., 2024).

The duration of experiments and monitoring is generally short (usually less than 12 months) or medium term as revealed by an analysis of literature focused on tillage management (Dignac et al., 2017), cropping systems (Autret et al., 2019), irrigation management (Aguilera, Lassaletta, Sanz-Cobena, et al., 2013; Cayuela et al., 2017) and fertilization and OM input (Lehtinen et al., 2014). This can result in irregular conclusions for the effect of time and management on SOC changes (Bolinder et al., 2020) and GHG emissions, which in turn can contribute to the underestimation of N_2O emission factors (EF). For instance, Emde et al. (2021) reported that information regarding monitoring of irrigation management over the long term (>15 years) is remarkably limited. Monitoring of long-term experimental sites (Morugán-Coronado et al., 2020; Zhou et al., 2017; Zornoza et al., 2018) is required to better assess the effects of tillage systems (Payen et al., 2021), crop diversification (Autret et al., 2019), irrigation methods (Emde et al., 2021) and OA (Gross & Glaser, 2021) on SOC stock change and GHG emissions (Hénault et al., 2012; Lehtinen et al., 2014). Moreover, for modelling purposes, measurements of N_2O emissions and N loss by NO_3^- leaching should be conducted for at least a full year (Basche et al., 2014; Quemada et al., 2013) to allow more reliable modelling and prediction of the effects of agricultural SMS on the trade-offs and synergies between SOC stock changes and these parameters (Dignac et al., 2017).

5 | CONCLUSION

This review shows that an increase in SOC stock change and a reduction in N leaching are positively affected by conservation tillage, crop rotation, permanent cropping, more efficient water management and the use of fertilization and OM inputs (e.g., cover crops, organic amendments, biochar). The effects on the N_2O and CH_4 emission mitigation are dependent on the specific agricultural SMS (e.g., water management, fertilization and OM inputs) and will require more research before generalized conclusions can be reached.

Additional dedicated research is needed to examine the impact of agricultural SMS on the combination of SOC stocks, GHG emissions and N leaching in long-term experiments. The combination of multiple agricultural SMS in practice may lead to interaction effects that may in turn affect the trade-offs and synergies. The impact of different soil management practices should therefore be assessed simultaneously. Our study also revealed a lack of information about how pedoclimatic conditions, specifically on the longer term, may affect trade-offs and synergies. A more concerted use and installation of new long-term field experiments in different pedoclimatic European regions seems to be an essential next step for a comprehensive understanding of the impact of agricultural SMS at the European level. These experiments can contribute to the further development of models to improve the quality of predictions of the impact of different SMS on trade-offs and synergies. Overall, this review provides a unique framework to aid the design of dedicated field experiments and targeted measurements as well as simulations to improve our understanding of the identified knowledge gaps.

AUTHOR CONTRIBUTIONS

Peter Maenhout: Conceptualization; methodology; formal analysis; investigation; validation; data curation; supervision; funding acquisition; visualization; writing – original draft; writing – review and editing; project administration. **Claudia Di Bene:** Conceptualization; methodology; investigation; validation; formal analysis; supervision; funding acquisition; writing – original draft; writing – review and editing; project administration. **Maria Luz Cayuela:** Investigation; funding acquisition; writing – review and editing. **Eugenio Diaz-Pines:** Funding acquisition; writing – review and editing. **Anton Govednik:** Investigation; formal analysis; writing – original draft; writing – review and editing. **Frida Keuper:** Investigation; funding acquisition; writing – review and editing. **Sara Mavsar:** Investigation; formal analysis; writing – original draft; writing – review and editing. **Rok Mihelic:** Investigation; formal analysis; funding acquisition; writing – original draft; writing – review and editing. **Adam O'Toole:** Investigation; formal analysis; funding acquisition; writing – original draft; writing – review and editing. **Ana Schwarzmann:** Investigation; formal analysis; writing – original draft; writing – review and editing. **Marjetka Suhadolc:** Investigation; formal analysis; funding acquisition; writing – original draft; writing – review and editing. **Alina Syp:** Investigation; formal analysis; funding acquisition; writing – original draft; writing – review and editing. **Elena Valkama:** Conceptualization; methodology; investigation; formal analysis; supervision; funding acquisition; writing – original draft; writing – review and editing; project administration.

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CONFLICT OF INTEREST STATEMENT

None of the authors have a conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

The database that supports the findings of this study is free to download in Zenodo (https://doi.org/10.5281/zenodo.10959077). The database should be cited as: Maenhout, P., Di Bene, C., Cayuela, M. L., Govednik, A., Keuper, F., Mavsar, S., Mihelic, R., O'Toole, A., Schwarzmann, A., Suhadolc, M., Syp, A., & Valkama, E. (2024). Knowledge gaps on trade-offs of soil carbon sequestration related to soil management strategies (Version 1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10959077.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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