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Understanding and fostering soil carbon sequestration

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Benefits and trade-offs of soil organic carbon sequestration

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1 Introduction

Soil organic carbon (SOC) sequestration has received increasing attention due to its numerous co-benefits, particularly its crucial role in enhancing important soil functions and ecosystem services (Lal, 2004). SOC is stored in the soil as organic compounds in the form of soil organic matter (SOM), which influences plant growth and soil (micro-)biological activity in numerous ways related to its positive impacts on biological, chemical and physical soil functions. In this context, SOC concentrations rather than stock is a critical soil quality variable positively correlated with most soil functions sustaining supporting, regulating and provisioning ecosystem services (Rumpel and Chabbi, 2021). As a result, SOC sequestration, which mostly implies increases in its concentration, has been indicated as important for soil fertility and agricultural yields (Lal, 2016). Following

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the identification of its potential role in climate change mitigation (Balesdent and Arrouays, 1999), SOC sequestration received policy attention. Indeed, removal of atmospheric CO_2 through carbon storage in soils is attractive relative to other negative emissions technologies because the technology is available, readily accessible, and because the concomitant SOC concentration increases are often associated with co-benefits for enhanced food security (Paustian et al., 2016; Frank et al., 2017) and ecosystem services (Bossio et al., 2020). Recent estimates showed that SOC could make up 9%, 72% and 47% of the mitigation potential of forest, wetland, agriculture and grassland biomes, equivalent to protection or sequestration of 1.2 Gt CO_2e year^{-1}, 2.0 Gt CO_2e year^{-1} and 2.3 Gt CO_2e year^{-1}, respectively, for these biome soils (Bossio et al., 2020).

Due to potential co-benefits, it has been proposed that SOC sequestration may be a win-win-win strategy (Lal, 2008) to be implemented with 'no regrets' (Bossio et al., 2020). However, in order to fulfill these expectations, trade-offs in terms of other greenhouse gas (GHG) emissions, water and nutrient requirements and other potential drawbacks of this nature-based solution (Fig. 1) must be taken into account and addressed by applying sustainable management practices that also restore and protect ecosystems. These trade-offs can be either a consequence of the increased SOM content or consequences of the practices implemented to increase SOC. The former include potential increased nitrogen (N) leaching from SOM-rich soils. The latter are related to environmental and economic resources needed to sequester SOC and also to changes in the energy balance of the system. Without rigorous quantification of these trade-offs, the levels of climate change mitigation that

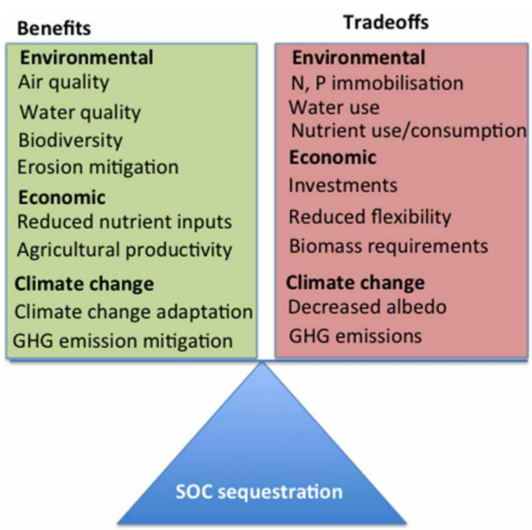

Figure 1 Potential benefits and trade-offs of SOC sequestering practices.

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can be achieved from the implementation of SOC sequestering practices are uncertain. Accounting for changes in carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) emissions is essential to estimate net abatement due to SOC sequestration at field or project scale. Moreover, this estimation is necessary to ensure consistency with IPCC guidelines (IPCC, 2019) and reporting obligations under the UNFCCC (see Chapter 10 of this book). For example, a modeling study of soil and livestock emissions and removals for cropping and grazing management options in Australia showed that N_2O emissions have the potential to partially or fully offset SOC sequestration benefits in cropping and permanent pasture systems (Meier et al., 2020). The study also indicated significant variation in outcomes depending on site and management factors because both influence the impact of the practices on the soil-plant system.

While it is important to consider the potential trade-offs of SOC sequestration, it is also necessary to carefully evaluate and quantify the benefits. The general paradigm is that increasing SOC has positive effects on soil water (quality and quantity), soil physical properties, i.e. bulk density and aggregation, nutrient storage, biological activity and biodiversity. Together these benefits enhance soil functioning and the ecosystem services derived from the soil. While SOC sequestration trade-offs other than GHG emissions received little attention, its benefits are widely accepted. This is probably mainly related to the fact that soils rich in organic matter are highly fertile. However, quantitative assessments of the relationship between SOC increase and its benefits for physical, chemical and biological functions are scarce. The reason may be that benefits and trade-offs are both variable and difficult to quantify. The effects depend on location factors, such as soil and climate characteristics and the form of sequestered SOC, and they also depend on whether SOC is reported as the carbon (C) concentration of soil (expressed as percentage C in dry matter) or as the stock (mass) of C in a given volume of soil.

In this chapter, we will identify and discuss the benefits and trade-offs of sequestering SOC related to soil processes and ecosystem functions and the factors influencing them. We present literature evidence for SOC sequestration benefits and trade-offs and discuss the role of specific carbon forms. Moreover, we collated published data on changes in CO_2, N_2O and CH_4 emissions (or removals) as the main trade-offs for several land management options that are widely seen as prospective for increasing C storage in soils.

2 Should soil organic carbon concentrations or stocks be considered to evaluate the benefits and trade-offs of soil organic carbon sequestration?

SOC sequestration, i.e. the transfer of atmospheric CO_2 into terrestrial reservoirs, implies that this process needs to consider changes in the amount

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of stored SOC, i.e. its stock. Assessing SOC stock changes is thus particularly important for evaluating the contribution SOC sequestration can make to climate change mitigation. SOC stocks are measured by taking into account SOC concentration, soil depth and bulk density (see Chapter 11 of this book). Thus, a higher SOC concentration may or may not be associated with an increase in SOC stocks, and, therefore, with CO_2 transfer from atmosphere to the soil. A specific example is the implementation of the no-till practice, which commonly leads to increases in SOC concentrations in the topsoil. However, because of associated bulk density changes, this increase does not necessarily translate into corresponding increases in SOC stocks, but may rather reflect re-distribution of SOC between different layers of the soil profile (Virto et al., 2012; Angers and Eriksen-Hamel, 2008). As a result, SOC sequestration due to introducing no-till may be less important for climate change mitigation than previously thought. However, these processes may be soil type and climate dependent (see Chapters 16 and 22 of this book). In addition, increasing SOC content in the upper soil horizon through no-till practices may have benefits resulting from reduced erosion risk (Skaalsveen et al., 2019) and more favorable biogeochemical cycling compared to regular tillage (Mbuthia et al., 2015).

When evaluating SOC benefits regarding soil physical, chemical and biological properties, such as water holding capacity, plant nutrient availability, erosion control and biodiversity, but also mitigation of GHG emissions through decreased albedo, SOC concentration is frequently a more appropriate variable than SOC stocks. This can be illustrated using the example of deep soil horizons, which may contain high carbon stocks at low concentrations because of their high bulk density and depth (Rumpel et al., 2002). Because of the dilution of SOM in subsoil horizons, the biological activity of most subsoil horizons is low and restricted to the root zone, whereas SOC-rich topsoils with low bulk density and lower SOC stocks may be more biologically active and productive because of more favorable physical conditions that are prone to support plant growth and microbial functioning. SOC concentration may thus be a useful variable to evaluate benefits and trade-offs in ecosystem services related to soil fertility and biological activity, whereas SOC stock changes need to be assessed to quantify SOC sequestration. However, N stocks calculated based on SOC stocks may be useful to predict N availability for plant growth and to manage N fertilization (e.g. Thorup-Kristensen and Nielsen, 1998; Chalhoub et al., 2013).

3 Quantitative evidence of benefits related to soil carbon sequestration

In this section, we review quantitative evidence for the effects of increasing SOC concentrations and stocks on soil functionality and ecosystem services other than GHG emission mitigation (Table 1). It is generally accepted that

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SOC increases improve most soil functions and the soil properties determining them, and here we discuss three examples of related ecosystem service benefits: water infiltration and retention, plant growth and yields (related to food provision), and biodiversity.

Correlations between SOC content and water infiltration rate as well as aggregate mean diameter have been reported (Singh Brar et al., 2015). SOC correlates positively with aggregate stability (Blanco-Canqui and Lal, 2007; Chaney and Swift, 1984; Chenu et al., 2000; Pikul et al., 2009), and the presence of SOM was found to reduce the maximum compactability of soils (e.g. Diaz-Zorita and Grosso, 2000). Regarding the role of soils in infiltrating and retaining water, bulk density is generally negatively correlated with SOC, which indicates its important contribution to porosity (e.g. Rawls, 1983). Although specific studies commonly indicate strong relationships between SOC content and physical, chemical and biological variables, these relationships were not confirmed in other (general) studies using larger datasets. For example, in a global meta-analysis, Minasny and McBratney (2018) showed that increasing

Table 1 Studies providing quantitative evidence for benefits between SOC and soil properties that are relevant for ecosystem services provision

Ecosystem service	Effect of SOC	Reference
Nutrients and metals retention	Increased cation exchange capacity	*van Erp et al. (2001); Curtin and Rostad (1997); Bigorre et al. (2000); Krogh et al. (2000)*
Infiltrating and retaining water	Decreased bulk density (increased soil porosity)	*Rawls (1983); Lettens et al. (2005)*
	Increased infiltration rate	*Singh Brar et al. (2015)*
	Very small increase in soil water content	*Minasny and McBratney (2018)*
Supporting traffic	Reduces soil compactability	*Diaz-Zorita and Grosso (2000); Quiroga et al. (1999)*
Food provision	Higher yields	Pan et al. (2009); *Oldfield et al. (2019)*
	Lower yield variability	Pan et al. (2009)
	Lower amounts of N fertilizer needed for similar yields	*Oldfield at al. (2019)*
Climate change resilience	Drought tolerance	Iizumi and Wagai (2019)
Protection against erosion	Mean weight diameter	*Singh Brar et al. (2015)*
	Aggregate stability	*Blanco-Canqui and Lal (2007); Chaney and Swift (1984); Chenu et al. (2000); Pikul et al. (2009)*
Biodiversity	Higher insect diversity	Flores-Rios et al. (2020)

Studies reporting concentrations are printed in *italic*, those reporting stocks in normal fonts.

SOC content had only a small effect on soil water content and available water holding capacity, depending on soil texture. As a result, they concluded that SOC changes following the adoption of agricultural practices may have negligible impacts on soil hydrological properties. In contrast, a meta-analysis investigating the effect of organic amendments on soil properties using long-term experiments concluded that there is a positive effect of SOC on water retention, but that the main effect is on water content at saturation (Eden et al., 2017). It therefore seems that the impact of SOC on soil (hydrological) properties cannot be generalized and that the controlling factors leading to a quantifiable effect of SOC increases are not completely understood. The effect of SOC on soil properties is largely controlled by soil texture, and increases as the clay content of soils decreases (e.g. Curtin and Rostad, 1997 for CEC; Kay et al., 1997 for water retention).

Many studies have investigated the beneficial effect of SOC for plant growth and yields as often sustainable soil management options that enable an increase in SOC are associated with increased yields (e.g. Han et al., 2018; Yeboah et al., 2016; Olson et al., 2010). For example, Pan et al. (2009) and Zhang et al. (2016) showed that higher SOC stocks in Chinese croplands led to higher yields and greater yield stability. In contrast, Oelofse et al. (2015) and Hijbeek et al. (2016) observed non-significant effects of SOC contents on yields in long-term European experiments. They explained their results by the sufficient nutrient levels supplied by mineral fertilizers in these trials, indicating that the effects of SOC on crop yields may be influenced by other confounding factors. However, a meta-analyses of a global dataset indicated that, regardless of initial SOC stocks, increasing the SOC concentration up to a critical level of 2% (20 mg g^{-1} soil) could enhance agricultural yields (Oldfield et al., 2019). The authors noted that two-thirds of global croplands are below this level. Moreover less N fertilizer may be required to achieve similar yields in soils with higher SOC concentrations (Oldfield et al., 2019). In terms of climate change impact mitigation (e.g. improved resilience to extreme events), increasing the SOC stocks in the topsoil seems to decrease the drought-related yield gap, in particular in arid regions, as shown by Iizumi and Wagai (2019) based on a global data set.

While SOC is often higher in systems with high biodiversity (e.g. Lange et al., 2015), the effect of SOC on biodiversity has rarely been quantified. Flores-Rios et al. (2020) observed that insect diversity was positively correlated with SOC stocks. This may be a benefit in terms of system stability, which, in turn, could prevent pathogenic insect invasions. However, to the best of our knowledge, no studies have analyzed the effects of SOC on biodiversity at other trophic levels (soil microorganisms, plant communities, fauna) with a quantitative approach.

4 Quantitative evidence for trade-offs related to soil carbon sequestration

Fostering SOC storage requires carbon input, usually in the form of plant-derived organic matter. Due to stoichiometric constraints because of the low C:N:P ratios of SOM, nutrient inputs are also necessary. If nutrient sources are not provided, organic matter addition to soils can lead to SOC decrease due to nutrient mining (Fontaine et al., 2014). It was suggested that to meet stoichiometric requirements, some 73 kg ha^{-1}, 17 kg ha^{-1} and 11 kg ha^{-1} of nitrogen, phosphorus and sulfur are necessary to store one additional t of SOC per ha (Richardson et al., 2014). This nutrient cost of SOC storage may constitute a significant trade-off and must be considered in large-scale SOC sequestration programs (van Groeningen et al., 2017).

Moreover, water requirements for enhancing biomass inputs via plant growth could constitute a significant trade-off, especially under climate change. For example, the high SOC stocks in paddy rice and organic soils rely on waterlogged conditions (see Chapters 17 and 21 of this book). In addition, with the frequency of drought projected to increase in the future, more irrigation will likely be required to maintain agricultural growth and hence organic matter input in (rainfed) agricultural systems. The effect of this practice on SOC sequestration has been found to be positive (Kelliher et al., 2015), negative (Condron et al., 2014), or neutral (Hunt et al., 2016). The mechanisms leading to these effects are poorly understood. They may be related to changes in photosynthate allocation (Carmona et al., 2020) and/or changes in soil texture due to clay translocation, depending on the type of irrigation water (Warrington et al., 2007). A global meta-analysis indicated that irrigated agriculture could increase SOC stocks in the soil profile by on average 5.9%, depending on climate, soil type and irrigation method (Emde et al., 2021). The highest increases of 11–35% were noted for semi-arid sites (Trost et al., 2013). In contrast, the amount of water needed to store 1 kg of SOC in different pedoclimatic conditions has not yet been determined.

Moreover, it has been suggested that the beneficial effects of SOC sequestration on reducing atmospheric CO_2 concentrations may be offset by increased emissions of other GHGs, i.e. N_2O and CH_4. The global warming potential of these emissions is 273 and 27.9 times higher than that of CO_2 over 100 years, respectively (IPCC, 2021). Although the processes leading to N_2O emissions from soil are not entirely understood (Lugato et al., 2018; Pärn et al., 2018; Tian et al., 2020), it seems generally accepted that increased soil N supply, decreased soil pH, high C availability, high water content and soil compaction lead to increased emissions (Skinner et al., 2014; Smith, 2016). Moreover, the input of labile plant litter and/or organic amendments can lead to loss of existing SOC and enhanced CO_2 emissions via priming effects (Guenet et al., 2018) and, if reactive N is present, also to N_2O emissions (Guenet et al., 2020). However, the drivers of N_2O emissions are insufficiently understood to trigger appropriate soil management to reduce this loss. In terms of CH_4 emissions, rice paddies and other waterlogged anaerobic systems are net emitters of large amounts of this GHG (see Chapters 17 and 21 of this book), produced by methanogenic *Archaea*, during the decomposition of root exudates or dead roots from recently assimilated CO_2 (Conrad, 2009). The controls of these emissions, i.e. the microbial methanogenesis pathway, need to be better understood to predict net abatement from SOC sequestration practices and to inform the development of mitigation strategies (Conrad, 2020). The impact of soil CH_4 emissions in many systems will be less predictable than that of N_2O. A New Zealand study found that methane uptake ranged from 10 to 11 kg CH_4 ha^{-1} $year^{-1}$ in beech forest soils down to <1 kg CH_4 ha^{-1} $year^{-1}$ in most pasture soils (Saggar et al., 2008), while other studies indicated net soil CH_4 emissions from pasture sites (Allen et al., 2009). In grazing systems, CH_4 emissions from ruminants greatly exceed those from soil (see Chapter 18 of this book). Fluxes of GHG other than CO^2 can thus be important under certain conditions and should be included in estimates of the net GHG mitigation benefits of SOC stock changes.

Sustainable practices adopted to increase SOC in agricultural land may also alter surface albedo thereby influencing the energy balance of the system. This may be a benefit or a trade-off. Higher albedo results in more reflection of solar energy back to space, thereby reducing climate warming. In the case of cover crops, often used to enhance SOC, surface albedo and, therefore, reflection of solar energy may be increased because vegetation has a higher albedo than bare soil (Carrer et al., 2018). In Europe, the beneficial albedo effect of cover crops may enhance their climate change mitigation potential in addition to their positive effect on SOC sequestration (Carrer et al., 2018). In contrast, soil application of biochar may result in a darker surface, less effective at reflecting solar radiation to space, therefore leading to increased surface temperature and evaporation (Genesio et al., 2012) when vegetation cover is low. As higher SOC concentrations generally darken the soils' color, a change in albedo is a trade-off when the soil is bare. For example, an assessment of the albedo impact of biochar systems indicated that the overall GHG emission mitigation effect may be reduced by 13–22% due to the albedo effect (Meyer et al., 2012). Despite their potential importance, these albedo effects are rarely considered when assessing the climate change mitigation potential of agricultural practices, because the focus is generally on the GHG balance.

5 Different carbon forms may have contrasting benefits and trade-offs

The SOM is a continuum ranging from fresh plant material consisting of intact plant litter compounds, wholly or partly degraded material, and microbial-processed carbon, which may be contributing to stabilized SOC compounds (Kogel-Knabner, 2002; Fig. 2). In particular for modeling purposes, SOM has been partitioned into three pools with contrasting turnover time and thus stability (Parton et al., 1987). Labile OM consisting of fresh OM inputs is distinguished from an intermediate pool comprising SOC stabilized within soil aggregates and a stable pool composed of mineral-associated SOC and combusted and/or pyrolyzed SOC compounds, such as black carbon and/or biochar (Krull et al., 2003). The labile SOC pool may be degraded rapidly and/or incorporated into the mineral soil, thereby fueling microbial activity necessary for promoting soil aggregation (e.g. Cosentino et al., 2006; Abiven et al., 2009). Labile SOC compounds may be incorporated into aggregates, and stabilized until the disintegration of such structures lead to microbial access and their mineralization. After degradation, microbial necromass and/or partly degraded plant material may be stabilized by mineral interactions (Barre et al., 2018; Angst et al., 2021, Chapter 2 of this book). The earlier conceptualization of soil particulate organic

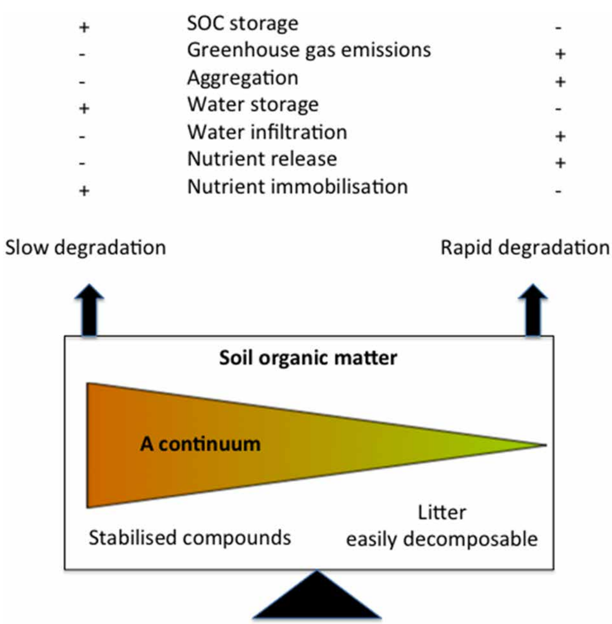

Figure 2 Effects of specific SOM compounds on benefits and trade-off.

matter (POM) and mineral-associated organic matter (MAOM) fractions into SOC kinetic pools (Balesdent, 1996) and into SOC functional pools (Gregorich et al., 1995, 2006; Feller et al., 2001) has been recently promoted as a useful framework to assess SOC dynamics (Lavallee et al., 2020) and therefore SOC sequestration.

While the major benefits derived from labile SOC may be related to its degradability, which results in readily available energy and nutrient release for soil microorganisms and plants, the same properties can also result in significant trade-offs as their rapid degradation may lead to losses of nitrate, and release of CO_2 and other GHGs. The availability of nutrients and energy for microbial activity decreases with increasing SOC stability, while its benefits for other soil functions, such as carbon and water storage may increase. The benefits of very stable SOM compounds may be mostly related to their SOC storage function, although, they may also improve physical soil functions and microbial habitat (Janzen, 2006, Fig. 2).

It has been pointed out that labile and stable SOC and, in particular OM decay processes, are needed for good soil functioning and to secure the multiple roles of SOM for plant growth and the provision of ecosystem services derived from soil (Janzen, 2006). It seems that the balance between both SOC types is essential. However, at the moment, the most beneficial ratio between labile and stable SOM compounds to optimize ecosystem services from the soil is not known.

The ratio of SOC forms may be managed to some extent through addition of organic amendments. Indeed, the chemical composition of OM amendments was found to control their fate in soil and therefore their contribution to SOC sequestration (Peltre et al., 2012) through enhancing SOC storage in organo-mineral fractions (Paetsch et al., 2018). While high microbial use efficiency may be required to stabilize plant-derived compounds, aromatic carbon types such as those produced by pyrolysis, i.e. biochar, may show high stability after soil addition. The high carbon sequestration potential of biochar is relatively well documented (Schmidt et al., 2019; Woolf et al., 2010), and its addition to soil has also been shown to enhance soil properties and agronomic performance in some situations (Chapter 9 of this book). Therefore, soil addition of stable carbon compounds, such as biochar to soil, has been suggested in addition to SOC sequestration as a negative emission technology with numerous co-benefits (Smith, 2016; Schmidt et al., 2021).

6 Greenhouse gas balance of soil organic carbon sequestering practices

To assess the SOC sequestration benefits in climate change mitigation, its effects on all GHG emissions need to be quantified. We therefore collated

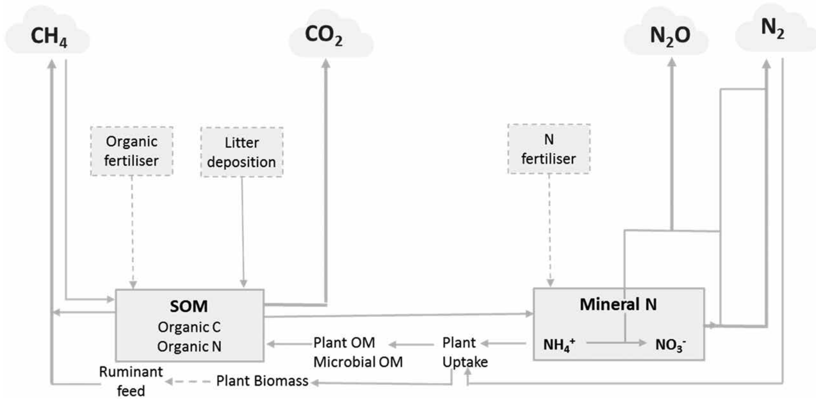

Figure 3 Simplified representation of key linkages between C and N cycling in soils. Sources and sinks of GHG emissions affected by practices that influence SOC stocks are shown.

published data for changes in CO_2, N_2O and CH_4 emissions (or removals) for several land management practice options that are widely promoted for increasing SOC sequestration. These data are helpful for understanding the likely GHG emission benefits and trade-offs from implementing practices that affect C and N cycling in agricultural lands (Fig. 3).

Recent research in response to growing global interest in the potential for SOC sequestration as a climate change mitigation strategy has provided some understanding of the balance between increasing C storage in soil and changes in other GHG net emissions resulting from selected management practices (Table 2). However, C and N cycle interactions are highly dynamic and generalizations of changes to net emissions are problematic. The relative effects tend to be dynamic and site and management specific and we discuss the processes responsible for GHG emissions other than CO_2, generated mainly by agricultural activities.

6.1 Nitrous oxide (N_2O)

The close linkages between C and N cycling in soils mean that changes in SOC turnover affect N transformations and consequently N_2O emissions (Soussana et al., 2019). The agricultural sector is a major contributor to these emissions, but due to their substantial spatial and temporal variability, robust scaling of estimates of N_2O emissions are scarce.

The complex and variable nature of the links between the C and N cycles and changing relationships over time make it difficult to generalize on the extent of any trade-off or synergy between N_2O emissions and C sequestration actions (Xu et al., 2021). However, the risk of significant offsets of the contribution of

Table 2 Potential impacts on GHG emissions of practices commonly undertaken to increase carbon stocks in agricultural and forestry soils

Activity to increase SOC stocks	GHG flux changed	SOC impact	Possible GHG effects relative to baseline
Reduced- or no-till	CO_2 N_2O	Reduced loss of SOC	Reduced fuel use; higher denitrification
Synthetic fertilizer	CO_2 N_2O CH_4	Higher C inputs (higher yields)	Fossil fuel use for application; higher N availability; higher N_2O loss; urea can also increase CO_2 emissions
Liming	CO_2	Higher C inputs (neutralize acid soils)	Carbonates react to release CO_2
Irrigation	CO_2 N_2O CH_4	Higher C inputs (higher yields)	Fossil fuel use (diesel); higher soil moisture can increase N_2O and CH_4
Organic amendments	CO_2 N_2O CH_4	Higher C inputs (higher yields)	Higher N availability; higher denitrification; if organic amendment not from a waste stream; for biochar-enhanced adsorption of N may lower nitrification
Cover crops	CO_2 N_2O	Higher C inputs + lower C loss	Lower denitrification due to higher plant uptake (non-legume); higher N availability (legume) may increase loss
Agroforestry	CO_2 N_2O CH_4	Higher C inputs; lower C loss; increased stability (aggregates and increased depth)	Lower denitrification (lower bulk density; lower soil moisture); lower denitrification due to higher plant uptake; higher CH_4 sink (lower bulk density)
Grazing management	CO_2 N_2O CH_4	Higher C inputs; added N through dung, urine	Changed SOM dynamics through trampling; dung and urine C, N inputs and N_2O, CH_4 emissions; enteric CH_4 emissions

Sources: Baldock and Burgess (2017); Guenet et al. (2020); Meier et al. (2020). Effects on each GHG need to be quantified to calculate the net climate change mitigation due to a practice change.

N_2O to climate change mitigation benefits is expected to increase as the rate of sequestration slows toward a new equilibrium SOC concentration with the adoption of new management practices (Liu and Greaver, 2009; Lugato et al., 2018). This will be exacerbated if nutrients become limiting and fertilizer (synthetic or organic) containing N is applied to achieve a constant increase in SOC stocks over a long time (Kirkby et al., 2014). In these conditions, achieving reduced net GHG emissions becomes more difficult (van Groenigen et al., 2017), unless N_2O emissions can be reduced. Applying organic materials to soil (Lehmann et al., 2006) or adopting cover crop or agroforestry practices (Poeplau and Don, 2015; Feliciano et al., 2018) that increase C inputs and/or reduce C losses tend to enhance the GHG mitigation benefit of SOC sequestration. These materials and practices have been shown to lower N_2O emissions. This is likely a result of decreased denitrification in soil with lower bulk density and lower soil moisture and, in the case of biochar, due to adsorption of mineral N (Borchard et al., 2019; Guenet et al., 2020; see Table 2). Higher plant productivity in agroforestry systems with the use of cover crops will also reduce N_2O emissions due to increased N uptake. The exception is where N-fixing species are used, in which case soil N availability and therefore available substrate increases (Kim et al., 2016; Lugato et al., 2018). Table 3 provides indicative directions of these emissions from recent literature, but many are derived from short-term studies.

Accounting for GHG emissions from grasslands with livestock grazing may need to include additional N_2O sources. Practices that increase SOC sequestration in grasslands include management options that reduce periods with low or no ground cover and increase pasture organic matter inputs to soil (Chapter 18 of this book). In grazing systems, the reduction of grazing animals will have a major impact on reducing N_2O and CH_4 emissions. The intensity and timing of livestock grazing affect N_2O emissions directly through dung and urine deposition, offsetting SOC sequestration or potentially enhancing it through overcoming nutrient limitations for pasture growth. In ruminant production systems, improving pasture quality and feeding supplements can increase dietary N and reduce N losses from manure and also decrease ruminants' CH_4 emissions (Chapter 18 of this book). However, the animal feed and soil interactions are complex and the capacity to estimate by measurement or modeling the impact of management change in grazing systems on the GHG and SOC sequestration balance is currently limited.

6.2 Methane (CH_4)

Changes in soil management to increase SOC sequestration can also affect ecosystem methane emissions and removals. While wetland soils and paddy rice soils are CH_4 sources (Chapters 17 and 21 of this book), well-drained and aerated agricultural soils are generally thought to be a small net sink for CH_4 (Conrad, 2009), mediated by the action of methanotrophic bacteria. There are gaps in knowledge of how the biogeochemical methane cycle is regulated in both terrestrial aerated land and anaerobic systems. Studies show that a range of trade-offs or co-benefits are possible due to changes in CH_4 pathways with practice change (Table 3). A comparison of agroforestry and adjacent agricultural lands revealed only minor differences in net CH_4 and N_2O emissions, with no clear overall change direction (Kim et al., 2016). Improved fallow systems showed a CH_4 uptake of –0.109 ± 0.034 t CO_2-e ha^{-1} y^{-1}, but agroforestry practices increased the CH_4 sink by only 0.003 ± t CO_2-e ha^{-1} y^{-1}

Table 3 Estimates of impact on nitrous oxide and methane emissions of practices recognized as likely to increase SOC storage in agricultural lands, expressed as the change relative to the 'without practice' scenario

Activity to increase SOC stocks	Change in emissions (t CO_2e ha^{-1} $year^{-1}$)[a]	Reference	Indicative balance with SOC
N_2O			
Conservation tillage	0.167	Mei et al. (2018)	Little or no offset of SOC increase
Conservation tillage	0.7 ± 0.13	Van Kessel et al. (2013)[b]	N_2O approx. unchanged or slightly decreased
Cover crops	0.08[c]	Abdalla et al. (2019)	On av. N_2O emissions partly but do not fully offset the SOC climate change benefits
Organic fertilizer (relative to synthetic)	−0.492 ± 0.16	Skinner et al. (2014)	Enhancement to SOC climate change benefit
Agroforestry	2.3	Kim et al. (2016)[b]	Agroforestry increases SOC storage; only minor change to N_2O (higher if N-fixing trees)
CH_4			
Conservation tillage	0	Abdalla et al. (2013)	No effect to minor enhancement to SOC climate change benefit
Cover crops	0	Abdalla et al. (2019)	Negligible effect on SOC climate change benefit
Organic fertilizer (relative to synthetic)	−0.003 ± 0.003	Skinner et al. (2014)	Enhancement to SOC climate change benefit (arable soils)
Organic fertilizer (relative to synthetic)	0.95 ± 0.415	Skinner et al. (2014)	Enhancement to SOC climate change benefit (rice paddies)
Agroforestry	−0.054 ± 0.034	Kim et al. (2016)	Minor enhancement to SOC climate change benefit

Effects on emissions of these GHGs are highly variable and depend on site-specific factors. The indicative trade-off or enhancement outcome is an average from published reviews or meta-analyses representing a range of timescales.
[a] Positive values indicate net emissions to the atmosphere; negative values are net removal from the atmosphere.
[b] Change (± SE, if reported) in N_2O emissions relative to without practice scenario, and relationship with SOC climate change benefit from meta-analyses (Guenet et al., 2020, and Supporting Information).
[c] Net of direct (−0.08 t CO_2e ha^{-1} $year^{-1}$) and indirect (0.16 t CO_2e ha^{-1} $year^{-1}$) emissions.

compared to adjacent conventional agricultural land (Kim et al., 2016). The increase in the CH_4 sink under agroforestry, which is very small relative to other GHG fluxes in these systems, may be due to larger soil pore spaces and lower bulk density which facilitates the rate of oxidation of CH_4 (Christiansen and Gundersen 2011).

In livestock production systems, CH_4 emissions from urine patches and from enteric fermentation in ruminants can be high, while in aerated cropping soils, CH_4 fluxes are generally minor. Therefore, in upland grazing systems, in particular, stocking rates should be monitored to maximize SOC sequestration benefits and avoid offsets due to livestock emissions (Chapter 18 of this book).

7 Socioeconomic benefits and trade-offs of soil organic carbon sequestration

While we target 2030 sustainable development goals (SDGs), we have to consider that the world population will surpass 8.5 billion (UN, 2017). This population growth will require increased food production and exerts enormous pressure on existing soil and water resources. SOC sequestration, especially with co-benefits in yield enhancement and stability and climate change adaptation, may be beneficial at the farm scale. The biophysical benefits and trade-offs of SOC sequestration may affect farmers' economic situation, especially if SOC sequestration enhances soil fertility and/or if carbon markets are operating. In such cases, direct economic benefits may include higher income and indirect benefits may be related to reduced risks of crop failure (Chapters 26 and 27 of this book). These socioeconomic benefits of SOC sequestration may contribute to agricultural development and poverty reduction particularly in low-income countries (Graff-Zivin and Lipper, 2008), as in these countries most of the complex social and economic challenges occur at the farm scale. Most of these farms are small and insufficiently fertile to provide income for the stakeholders. The situation has worsened amid the COVID-19 pandemic, so there is a global call to improve the structural settings of rural areas (Amiraslani, 2021). Consequently, implementation at scale is necessary, not only to take advantage of the GHG emission mitigation benefits of SOC sequestration, but also because of its potential broader impacts on the economic situation and well-being of societies (Chabbi et al., 2017). Social benefits of SOC sequestration may include the prevention of social unrest and mass migration. When SOC sequestration leads to biodiversity enhancement and healthier food production due to reduction of agrochemical input, and also to increasing recreation value of landscapes, health benefits can be expected (Rumpel et al., 2022).

Adoption of SOC sequestering practices requires in most cases changing farming practices, which is a potential risk for the farmers. Decisions by farmers to adopt (new) sustainable SOC sequestering practices depend on many factors, related to the farmers personal situation (e.g. age, income, training), and to characteristics of their biophysical, political and institutional environment (Piñeiro et al., 2020). In many cases, capacity building and investments are required, potentially constituting an economic trade-off.

In addition, to have a global impact on climate change mitigation, changes need to be implemented by millions of farmers globally in very different pedoclimatic, socioeconomic and cultural contexts. For instance, dryland soils contain the largest pool of inorganic C (Plaza-Bonilla et al., 2015), and loss of inorganic C must be considered as well as the risk of salinity development (Chapters 7 and 23 of this book). Therefore, it is important to employ region-specific strategies to overcome biophysical, economic, social, legal and political barriers (Bossio et al., 2020; Amelung et al., 2020; Demenois et al., 2020).

Trade-offs concerning the enhancement of uptake of sustainable practices may include funding to pay for (1) changes in agricultural practices, (2) outreach and teaching of benefits of improved practices for all stakeholders in order to convince policymakers to remove legislative barriers and (3) investment in SOC sequestration strategies. Such funding will be important where the benefits of SOC sequestration require up-front costs and/or are not immediately profitable. Moreover, long-term solutions must be found in order to maintain sustainable management. To acknowledge the value of SOC sequestration in a global context, we suggest that socioeconomic benefits and trade-offs should be included in monitoring, reporting and verification (MRV) schemes.

8 Conclusion and future trends

SOC sequestration is a potential sustainable development strategy, which results in benefits and trade-offs for mitigating GHG emissions and climate change impacts. These include positive effects on soil properties and negative effects in form of GHG emissions, water requirements and/or costs of the practices employed to enhance soil carbon. Positive effects on soil properties are mostly related to the enhancement of SOC concentrations, while mitigation of GHG emissions requires SOC sequestration, measured as increase in SOC stocks. Both are linked but not synergistic in all cases.

In terms of GHG emission mitigation, trade-offs need to be quantified accurately. More efforts are necessary to consider the spatial and temporal variability of soil CH_4 and N_2O emissions. Other trade-offs such as water requirements and/or albedo changes have rarely been considered in the past, but they should be taken into account when assessing SOC sequestering practices. Factors controlling GHG emissions other than CO_2 should further be elucidated. This must include GHG emissions from grazing animals in addition to soil processes.

In terms of co-benefits, relationships between SOC and positive impacts on ecosystem services have rarely been quantified. In particular, the relationship between yield increases and SOC stocks is poorly understood and should be elucidated in various pedoclimatic environments. Moreover, quantitative

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relationships between SOC concentrations and soil properties need to be established and their confounding factors elucidated.

(Socio)economic benefits and trade-offs are related to the farmers' income and may be directly related to agricultural yields and indirectly to stability of the system and/or investments needed to change agricultural practices. Development of policy frameworks to encourage the implementation of strategies need to be regionspecific. These policies need to overcome barriers due to trade-offs, including (socio)economic ones. The latter should be included in monitoring, reporting and verification programs.

9 Where to look for further information

Benefits and trade-offs of specific agricultural practices are further detailed in the following two articles:

- Sykes, A. J., Macleod, M., Eory, V. Rees, R. M., Payen, F., Myrgiotis, V., Williams, M., Sohi, S., Hillier, J., Moran, D., Manning, D. A. C., Goglio, P., Seghetta, M., Williams, A., Harris, J., Dondini, M., Walton, J., House, J. and Smith, P. 2020. Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. *Global Change Biology*, 26:1085–1108.
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