

# Benefits and trade-offs of soil organic carbon sequestration

C. Rumpel, CNRS, Sorbonne University, Institute of Ecology and Environmental Sciences Paris, France; B. Henry, Queensland University of Technology, Australia; C. Chenu, AgroParisTech, UMR Ecosys INRA, AgroParisTech, Université Paris-Saclay, France; and F. Amiraslani, Ulster University, UK



---

# Benefits and trade-offs of soil organic carbon sequestration

*C. Rumpel, CNRS, Sorbonne University, Institute of Ecology and Environmental Sciences Paris, France; B. Henry, Queensland University of Technology, Australia; C. Chenu, AgroParisTech, UMR Ecosys INRA, AgroParisTech, Université Paris-Saclay, France; and F. Amiraslani, Ulster University, UK*

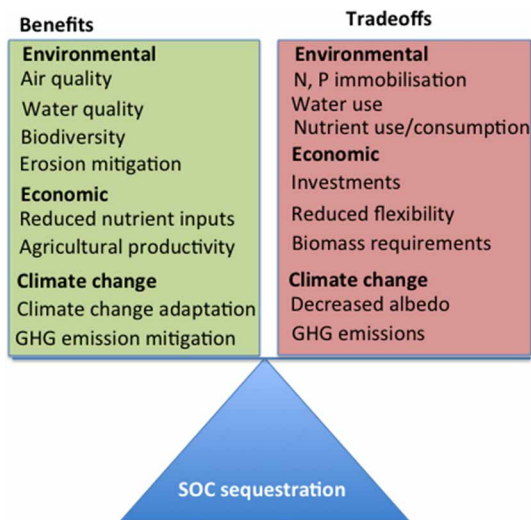
- 1 Introduction
- 2 Should soil organic carbon concentrations or stocks be considered to evaluate the benefits and trade-offs of soil organic carbon sequestration?
- 3 Quantitative evidence of benefits related to soil carbon sequestration
- 4 Quantitative evidence for trade-offs related to soil carbon sequestration
- 5 Different carbon forms may have contrasting benefits and trade-offs
- 6 Greenhouse gas balance of soil organic carbon sequestering practices
- 7 Socioeconomic benefits and trade-offs of soil organic carbon sequestration
- 8 Conclusion and future trends
- 9 Where to look for further information
- 10 References

## 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

the identification of its potential role in climate change mitigation (Balesdent and Arrouays, 1999), SOC sequestration received policy attention. Indeed, removal of atmospheric CO<sub>2</sub> 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<sub>2</sub>e year<sup>-1</sup>, 2.0 Gt CO<sub>2</sub>e year<sup>-1</sup> and 2.3 Gt CO<sub>2</sub>e year<sup>-1</sup>, 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.

can be achieved from the implementation of SOC sequestering practices are uncertain. Accounting for changes in carbon dioxide ( $\text{CO}_2$ ), nitrous oxide ( $\text{N}_2\text{O}$ ) and methane ( $\text{CH}_4$ ) 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  $\text{N}_2\text{O}$  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  $\text{CO}_2$ ,  $\text{N}_2\text{O}$  and  $\text{CH}_4$  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  $\text{CO}_2$  into terrestrial reservoirs, implies that this process needs to consider changes in the amount

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<sub>2</sub> 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

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

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-analysis 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<sup>-1</sup> 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<sup>-1</sup>, 17 kg ha<sup>-1</sup> and 11 kg ha<sup>-1</sup> 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 (Condrón 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 (Troost 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<sub>2</sub> concentrations may be offset by increased emissions of other GHGs, i.e. N<sub>2</sub>O and CH<sub>4</sub>. The global warming potential of these emissions is 273 and 27.9 times higher than that of CO<sub>2</sub> over 100 years, respectively (IPCC, 2021). Although the processes leading to N<sub>2</sub>O 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

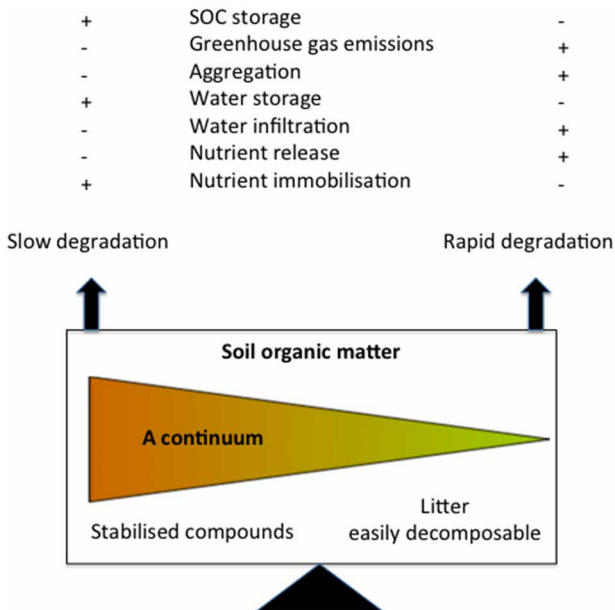


existing SOC and enhanced CO<sub>2</sub> emissions via priming effects (Guenet et al., 2018) and, if reactive N is present, also to N<sub>2</sub>O emissions (Guenet et al., 2020). However, the drivers of N<sub>2</sub>O emissions are insufficiently understood to trigger appropriate soil management to reduce this loss. In terms of CH<sub>4</sub> 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<sub>2</sub> (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<sub>4</sub> emissions in many systems will be less predictable than that of N<sub>2</sub>O. A New Zealand study found that methane uptake ranged from 10 to 11 kg CH<sub>4</sub> ha<sup>-1</sup> year<sup>-1</sup> in beech forest soils down to <1 kg CH<sub>4</sub> ha<sup>-1</sup> year<sup>-1</sup> in most pasture soils (Saggar et al., 2008), while other studies indicated net soil CH<sub>4</sub> emissions from pasture sites (Allen et al., 2009). In grazing systems, CH<sub>4</sub> emissions from ruminants greatly exceed those from soil (see Chapter 18 of this book). Fluxes of GHG other than CO<sub>2</sub> 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.

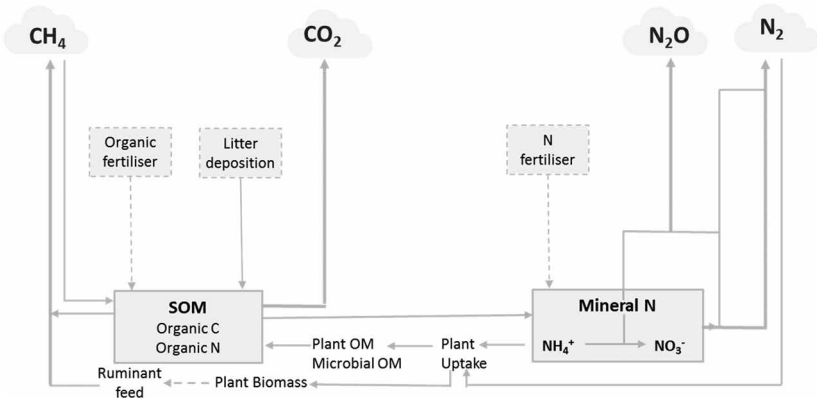
While the major benefits derived from labile SOC may be related to its degradability, which results in readily available energy and nutrient release for soil microorganisms and plants, the same properties can also result in significant trade-offs as their rapid degradation may lead to losses of nitrate, and release of CO<sub>2</sub> 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<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> 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<sub>2</sub>, generated mainly by agricultural activities.

### 6.1 Nitrous oxide (N<sub>2</sub>O)

The close linkages between C and N cycling in soils mean that changes in SOC turnover affect N transformations and consequently N<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O 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 <sub>2</sub> N <sub>2</sub> O	Reduced loss of SOC	Reduced fuel use; higher denitrification
Synthetic fertilizer	CO <sub>2</sub> N <sub>2</sub> O CH <sub>4</sub>	Higher C inputs (higher yields)	Fossil fuel use for application; higher N availability; higher N <sub>2</sub> O loss; urea can also increase CO <sub>2</sub> emissions
Liming	CO <sub>2</sub>	Higher C inputs (neutralize acid soils)	Carbonates react to release CO <sub>2</sub>
Irrigation	CO <sub>2</sub> N <sub>2</sub> O CH <sub>4</sub>	Higher C inputs (higher yields)	Fossil fuel use (diesel); higher soil moisture can increase N <sub>2</sub> O and CH <sub>4</sub>
Organic amendments	CO <sub>2</sub> N <sub>2</sub> O CH <sub>4</sub>	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 <sub>2</sub> N <sub>2</sub> O	Higher C inputs + lower C loss	Lower denitrification due to higher plant uptake (non-legume); higher N availability (legume) may increase loss
Agroforestry	CO <sub>2</sub> N <sub>2</sub> O CH <sub>4</sub>	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 <sub>4</sub> sink (lower bulk density)
Grazing management	CO <sub>2</sub> N <sub>2</sub> O CH <sub>4</sub>	Higher C inputs; added N through dung, urine	Changed SOM dynamics through trampling; dung and urine C, N inputs and N <sub>2</sub> O, CH <sub>4</sub> emissions; enteric CH <sub>4</sub> 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<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O and CH<sub>4</sub> emissions. The intensity and timing of livestock grazing affect N<sub>2</sub>O 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<sub>4</sub> 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<sub>4</sub>)**

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<sub>4</sub> 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<sub>4</sub> (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<sub>4</sub> pathways with practice change (Table 3). A comparison of agroforestry and adjacent agricultural lands revealed only minor differences in net CH<sub>4</sub> and N<sub>2</sub>O emissions, with no clear overall change direction (Kim et al., 2016). Improved fallow systems showed a CH<sub>4</sub> uptake of  $-0.109 \pm 0.034$  t CO<sub>2</sub>-e ha<sup>-1</sup> y<sup>-1</sup>, but agroforestry practices increased the CH<sub>4</sub> sink by only  $0.003 \pm$  t CO<sub>2</sub>-e ha<sup>-1</sup> y<sup>-1</sup>

**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 <sub>2</sub> e ha <sup>-1</sup> year <sup>-1</sup> ) <sup>a</sup>	Reference	Indicative balance with SOC
<i>N<sub>2</sub>O</i>			
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) <sup>b</sup>	N <sub>2</sub> O approx. unchanged or slightly decreased
Cover crops	0.08 <sup>c</sup>	Abdalla et al. (2019)	On av. N <sub>2</sub> O 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) <sup>b</sup>	Agroforestry increases SOC storage; only minor change to N <sub>2</sub> O (higher if N-fixing trees)
<i>CH<sub>4</sub></i>			
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.

<sup>a</sup> Positive values indicate net emissions to the atmosphere; negative values are net removal from the atmosphere.

<sup>b</sup> Change (± SE, if reported) in N<sub>2</sub>O emissions relative to without practice scenario, and relationship with SOC climate change benefit from meta-analyses (Guenet et al., 2020, and Supporting Information).

<sup>c</sup> Net of direct (-0.08 t CO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>) and indirect (0.16 t CO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>) emissions.

compared to adjacent conventional agricultural land (Kim et al., 2016). The increase in the CH<sub>4</sub> 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<sub>4</sub> (Christiansen and Gundersen 2011).

In livestock production systems, CH<sub>4</sub> emissions from urine patches and from enteric fermentation in ruminants can be high, while in aerated cropping soils, CH<sub>4</sub> 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<sub>4</sub> and N<sub>2</sub>O 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<sub>2</sub> 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

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.
- Tiefenbacher, A., Sandén, T., Haslmayr, H.-P., Miloczki, J., Wenzel, W., and Spiegel, H. 2021: Optimizing Carbon Sequestration in Croplands: A Synthesis. *Agronomy*, 11, 882.

## 10 References

- Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R. M. and Smith, P. 2019. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology* 25(8), 2530-2543.
- Abdalla, M., Osborne, B., Lanigan, G., Forristal, D., Williams, M., Smith, P. and Jones, M. B. 2013. Conservation tillage systems: a review of its consequences for greenhouse gas emissions. *Soil Use and Management* 29(2), 199-209.
- Abiven, S., Menasseri, S. and Chenu, C. 2009. The effects of organic inputs over time on soil aggregate stability - a literature analysis. *Soil Biology and Biochemistry* 41(1), 1-12.
- Allen, D. E., Mendham, D. S., Bhupinderpal, S., Cowie, A., Wang, W., Dalal, R. C. and Raison, R. J. 2009. Nitrous oxide and methane emissions from soil are reduced following afforestation of pasture lands in three contrasting climatic zones. *Soil Research* 47(5), 443-458.
- Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., Mooney, S., van Wesemael, B., Wander, M.

- and Chabbi, A. 2020. Towards a global-scale soil climate mitigation strategy. *Nature Communications* 11(1), 5427.
- Amiraslani, F. 2021. Tackling rural health, energy, ... and technological issues all at once: a call for a global interdisciplinary platform for strengthening rural setting Amid the COVID-19 pandemic. *Challenges* 12(2). DOI: 10.3390/challe12020016.
- Angers, D. A. and Eriksen-Hamel, N. S. 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. *Soil Science Society of America Journal* 72(5), 1370-1374.
- Angst, G., Mueller, K. E., Nierop, K. G. J. and Simpson, M. J. 2021. Plant- or microbial-derived? A review on the molecular composition of stabilized soil organic matter. *Soil Biology and Biochemistry* 156, 108189.
- Baldock, J. and Burgess, R. (2017). Soil Carbon Accounting—the Australian example. In: Workshop on “Soil Organic Carbon Measurement for Management and Management for Measurement”. Available at: <https://jahnresearchgroup.cals.wisc.edu/wp-content/uploads/sites/200/2017/08/3.-Soil-carbon-accounting-in-Australia-1.pdf> [Accessed July 2021].
- Balesdent, J. 1996. The significance of organic separates to carbon dynamics and its modelling in some cultivated soils. *European Journal of Soil Science* 47(4), 485-493.
- Balesdent, J. and Arrouays, D. 1999. Usage des terres et stockage de carbone dans les sols du territoire français. Une estimation des flux nets annuels pour la période 1900-1999. *C. R. Acad. Agricultrists* 85, 265-277.
- Barre, P., Quenea, K., Vidal, A., Cecillon, L., Christensen, B. T., Katterer, T., Macdonald, A. J., Petit, L., Plante, A. F., Van Oort, F. and Chenu, C. 2018. Microbial and plant-derived compounds both contribute to persistent soil organic carbon in temperate soils. *Biogeochemistry* 140(1), 81-92.
- Bigorre, F., Tessier, D. and Pédro, G. 2000. Contribution des argiles et des matières organiques à la rétention de l'eau dans les sols. Signification et rôle fondamental de la capacité d'échange en cations. *Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Sciences*.
- Blanco-Canqui, H. and Lal, R. 2007. Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. *Soil and Tillage Research* 95(1-2), 240-254.
- Borchard, N., Schirrmann, M., Cayuela, M. L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., Ippolito, J. A. and Novak, J. 2019. Biochar, soil and land-use interactions that reduce nitrate leaching and N<sub>2</sub>O emissions: a meta-analysis. *Science of the Total Environment* 651(2), 2354-2364.
- Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R. J., von Unger, M., Emmer, I. M. and Griscom, B. W. 2020. The role of soil carbon in natural climate solutions. *Nature Sustainability* 3(5), 391-398.
- Carmona, C. R., Clough, T. J., McNally, S. R., Beare, M. H., Tregurtha, C. S. and Hunt, J. E. 2020. Seasonal irrigation affects the partitioning of new photosynthate carbon in soil. *Soil Biology and Biochemistry* 143, 107751.
- Carrer, D., Pique, G., Fericoq, M., Ceamanos, X. and Ceschia, E. 2018. What is the potential of cropland albedo management in the fight against global warming? A case study based on the use of cover crops. *Environmental Research Letters* 13(4), 044030.
- Chabbi, A., Lehmann, J., Ciais, P., Loescher, H. W., Cotrufo, M. F., Don, A., SanClements, M., Schipper, L., Six, J., Smith, P. and Rumpel, C. 2017. Aligning agriculture and climate policy. *Nature Climate Change* 7(5), 307-309.

- Chalhoub, M., Garnier, P., Coquet, Y., Mary, B., Lafolie, F. and Houot, S. 2013. Increased nitrogen availability in soil after repeated compost applications: use of the PASTIS model to separate short and long-term effects. *Soil Biology and Biochemistry* 65, 144-157.
- Chaney, K. and Swift, R. S. 1984. The influence of organic matter on aggregate stability in some British soils. *Journal of Soil Science* 35(2), 223-230.
- Chenu, C., Le Bissonnais, Y. and Arrouays, D. 2000. Organic matter influence on clay wettability and soil aggregate. *Soil Science Society of America Journal* 64(4), 1479-1486.
- Christiansen, J. R. and Gundersen, P. 2011. Stand age and tree species affect N<sub>2</sub>O and CH<sub>4</sub> exchange from afforested soils. *Biogeosciences* 8(9), 2535-2546.
- Condrón, L. M., Hopkins, D. W., Gregorich, E. G., Black, A. and Wakelin, S. A. 2014. Long-term irrigation effects on soil organic matter under temperate grazed pasture. *European Journal of Soil Science* 65, 741-750.
- Conrad, R. 2009. The global methane cycle: recent advances in understanding the microbial processes involved. *Environmental Microbiology Reports* 1(5), 285-292.
- Conrad, R. 2020. Importance of hydrogenotrophic, acetoclastic and methylophilic methanogenesis for methane production in terrestrial, aquatic and other anoxic environments: a mini review. *Pedosphere* 30(1), 25-39.
- Cosentino, D., Chenu, C. and Le Bissonnais, Y. 2006. Aggregate stability and microbial community dynamics under drying-wetting cycles in a silt loam soil. *Soil Biology and Biochemistry* 38(8), 2053-2062.
- Curtin, D. and Rostad, H. P. W. 1997. Cation exchange and buffer potential of Saskatchewan soils estimated from texture, organic matter and pH. *Canadian Journal of Soil Science* 77(4), 621-626. 10.4141/S97-015.
- Demenois, J., Torquebiau, E., Arnoult, M. H., Eglin, T., Masse, D., Assouma, M. H., Blanfort, V., Chenu, C., Chapuis-Lardy, L., Medoc, J.-M. and Sall, S. N. 2020. Barriers and strategies to boost soil carbon sequestration in agriculture. *Frontiers in Sustainable Food Systems* 4. 10.3389/fsufs.2020.00037.
- Díaz-Zorita, M. and Grosso, G. A. 2000. Effect of soil texture, organic carbon and water retention on the compactability of soils from the Argentinean pampas. *Soil and Tillage Research* 54(1-2), 121-126.
- Eden, M., Gerke, H. H. and Houot, S. 2017. Organic waste recycling in agriculture and related effects on soil water retention and plant available water: a review. *Agronomy for Sustainable Development* 37(2), 11.
- Emde, D., Hannam, K. D., Most, I., Nelson, L. M. and Jones, M. D. 2021. Soil organic carbon in irrigated agricultural systems: a meta-analysis. *Global Change Biology* 27(16), 3898-3910.
- Feliciano, D., Ledo, A., Hillier, J. and Nayak, D. R. 2018. Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? *Agriculture, Ecosystems and Environment* 254, 117-129.
- Feller, C., Balesdent, J., Nicolardot, B. and Cerri, C. 2001. Approaching "functional" soil organic matter pools through particle-size fractionation: examples for tropical soils. In: Lal, R., Kimble, J. M. and Stewart, B. A. (Eds), *Assessment Methods for Soil Carbon*. CRC Press, Boca Raton, pp. 53-67.
- Flores-Rios, A., Thomas, E., Peri, P. P., Amelung, W., Duarte-Guardia, S., Borchard, N., Lizárraga-Travaglini, A., Vélez-Azañero, A., Sheil, D., Tschardtke, T., Steffan-Dewenter,

- I. and Ladd, B. 2020. Co-benefits of soil carbon protection for invertebrate conservation. *Biological Conservation* 252, 108859.
- Fontaine, S., Bardoux, G., Abbadie, L. and Mariotti, A. 2014. Carbon input to soil may decrease soil carbon content. *Ecology Letters* 7(4), 314-320.
- Frank, S., Havlík, P., Soussana, J. F., Levesque, A., Valin, H., Wollenberg, E., Kleinwechter, U., Fricko, O., Gusti, M., Herrero, M. and Smith, P. (2017). Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters* 12(10), 105004.
- Genesio, L., Miglietta, F., Lugato, E., Baronti, S., Pieri, M. and Vaccari, F. P. 2012. Surface albedo following biochar application in durum wheat Surface albedo following biochar application in durum wheat. *Environmental Research Letters* 1623(7), 149-139.
- Graff-Zivin, J. and Lipper, L. 2008. Poverty, risk, and the supply of soil carbon sequestration. *Environment and Development Economics* 13(3), 353-373.
- Gregorich, E. G., Beare, M. H., McKim, U. F. and Skjemstad, J. O. 2006. Chemical and biological characteristics of physically uncomplexed organic matter. *Soil Science Society of America Journal* 70(3), 975-985.
- Gregorich, E. G., Carter, M. R., Angers, D. A., Monreal, C. M. and Ellert, B. H. 1995. Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Canadian Journal of Soil Science* 74(4), 367-385.
- Guenet, B., Camino-Serrano, M., Ciais, P., Tifafi, M., Maignan, F., Soong, J. L. and Janssens, I. A. 2018. Impact of priming on global soil carbon stocks. *Global Change Biology*, 24(5), 1873-1883.
- Guenet, B., Gabrielle, B., Chenu, C., Arrouays, D., Balesdent, J., Bernoux, M., Bruni, E., Caliman, J. P., Cardinael, R., Chen, S., Ciais, P., Desbois, D., Fouche, J., Frank, S., Henault, C., Lugato, E., Naipal, V., Nesme, T., Obersteiner, M., Pellerin, S., Powlson, D. S., Rasse, D. P., Rees, F., Soussana, J. F., Su, Y., Tian, H., Valin, H. and Zhou, F. 2020. Can N<sub>2</sub>O emissions offset the benefits from soil organic carbon storage? *Global Change Biology* 27(2), 237-256.
- Han, X., Xu, C., Dungait, J. A. J., Bol, R., Wang, X. J., Wu, W. L. and Meng, F. Q. 2018. Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: a system analysis. *Biogeosciences* 15(7), 1933-1946.
- Hijbeek, R., van Ittersum, M. K., Ten Berge, H. F. M., Gort, G., Spiegel, H. and Whitmore, A. P. 2016. Do organic inputs matter? A meta-analysis of additional yield effects for arable crops in Europe. *Plant and Soil* 411(1-2), 293-303.
- Hunt, J. E., Laubach, J., Bartel, M., Fraser, A. and Phillips, R. L. 2016. Carbon budgets for an irrigated intensively grazed dairy pasture and an unirrigated winter-grazed pasture. *Biogeosciences* 13(10), 2927-2944.
- Iizumi, T. and Wagai, R. 2019. Leveraging drought risk reduction for sustainable food, soil and climate via soil organic carbon sequestration. *Scientific Reports* 9(1), 19744.
- IPCC. 2019. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley,

- E., Kissick, K., Belkacemi, M. and Malley, J. (Eds.). Cambridge University Press, Cambridge.
- IPCC. 2021. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., et al. (Eds.). Cambridge University Press, Cambridge.
- Janzen, H. 2006. The soil carbon dilemma: Shall we hoard it or use it. *Soil Biology and Biochemistry* 28, 419-424.
- Kay, B. D., da Silva, A. Pd and Baldock, J. A. 1997. Sensitivity of soil structure to changes in organic carbon content: predictions using pedotransfer functions. *Canadian Journal of Soil Science* 77(4), 655-667.
- Kelliher, F. M., West, P. S. J. and Moir, J. L. 2015. Soil carbon stocks beneath an established irrigated pasture grazed by dairy cattle. *New Zealand Journal of Agricultural Research* 58(1), 78-83.
- Kim, D. G., Kirschbaum, M. U. F. and Beedy, T. L. 2016. Carbon sequestration and net emissions of CH<sub>4</sub> and N<sub>2</sub>O under agroforestry: synthesizing available data and suggestions for future studies. *Agriculture, Ecosystems and Environment* 226, 65-78.
- Kirkby, C. A., Richardson, A. E., Wade, L. J., Passioura, J. B., Batten, G. D., Blanchard, C. and Kirkegaard, J. A. 2014. Nutrient availability limits carbon sequestration in arable soils. *Soil Biology and Biochemistry* 68, 402-409.
- Koegel-Knabner, I. 2002. The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. *Soil Biology and Biochemistry* 34(2), 139-162.
- Krogh, L., Breuning-Madsen, H. and Greve, M. H. 2000. Cation-exchange capacity pedotransfer functions for Danish soils. *Acta Agriculturae Scandinavica, Section B - Soil and Plant Science* 50(1), 1-12.
- Krull, E. S., Baldock, J. A. and Skjemstad, J. O. 2003. Importance of mechanisms and processes of the stabilisation of soil organic matter for modelling carbon turnover. *Functional Plant Biology: FPB* 30(2), 207-222.
- Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304(5677), 1623-1627.
- Lal, R. 2008. Carbon sequestration. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 363(1492), 815-830.
- Lal, R. 2016. Soil health and carbon management. *Food and Energy Security* 5(4), 212-222.
- Lavallee, J. M., Soong, J. L. and Cotrufo, M. F. 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology* 26(1), 261-273.
- Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I., Mellado-Vázquez, P. G., Malik, A. A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B. C., Trumbore, S. E. and Gleixner, G. 2015. Plant diversity increases soil microbial activity and soil carbon storage. *Nature Communications* 6, 6707.
- Lehmann, J., Gaunt, J. and Rondon, M. 2006. Bio-char sequestration in terrestrial ecosystems—a review. *Mitigation and Adaptation Strategies for Global Change* 11(2), 403-427.
- Letens, S., Van Orshoven, J., van Wesemael, B., De Vos, B. and Muys, B. 2005. Stocks and fluxes of soil organic carbon for landscape units in Belgium derived from heterogeneous data sets for 1990 and 2000. *Geoderma* 127(1-2), 11-23.

- Liu, L. and Greaver, T. L. 2009. A review of nitrogen enrichment effects on three biogenic GHGs: the CO<sub>2</sub> sink may be largely offset by stimulated N<sub>2</sub>O and CH<sub>4</sub> emission. *Ecology Letters* 12(10), 1103-1117.
- Lugato, E., Leip, A. and Jones, A. 2018. Mitigation potential of soil carbon management overestimated by neglecting N<sub>2</sub>O emissions. *Nature Climate Change* 8(3), 219-223.
- Mbuthia, L. W., Acosta-Martinez, V., DeBryun, J., Schaeffer, S., Tyler, D., Odoi, E., Mpheshea, M., Walker, F. and Eash, N. 2015. Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: implications for soil quality. *Soil Biology and Biochemistry* 89, 24-34.
- Mei, K., Wang, Z., Huang, H., Zhang, C., Shang, X., Dahlgren, R. A., Zhang, M. and Xia, F. 2018. Stimulation of N<sub>2</sub>O emission by conservation tillage management in agricultural lands: a meta-analysis. *Soil and Tillage Research* 182, 86-93.
- Meier, E. A., Thorburn, P. J., Bell, L. W., Harrison, M. T. and Biggs, J. S. 2020. Greenhouse gas emissions from cropping and grazed pastures are similar: a simulation analysis in Australia. *Frontiers in Sustainable Food Systems* 3, 121.
- Meyer, S., Bright, R. M., Fischer, D., Schulz, H. and Glaser, B. 2012. Albedo impacts on the suitability of biochar systems to mitigate global climate warming. *Environmental Science and Technology* 46(22), 12726-12734.
- Minasny, B. and McBratney, A. B. 2018. Limited effect of organic matter on soil available water capacity. *European Journal of Soil Science* 69(1), 39-47.
- Oelofse, M., Markussen, B., Knudsen, L., Schelde, K., Olesen, J. E., Stoumann, L. S., Bruun, S., Jensen, L. S. and Bruun, S. 2015. Do soil organic carbon levels affect potential yields and nitrogen use efficiency? An analysis of winter wheat and spring barley field trials. *European Journal of Agronomy* 66, 62-73.
- Oldfield, E. E., Bradford, M. A. and Wood, S. A. 2019. Global meta-analysis of the relationship between soil organic matter and crop yields. *SOIL* 5(1), 15-32.
- Olson, K. R., Ebelhar, S. A. and Lang, J. M. 2010. Cover crop effects on crop yields and soil organic carbon content. *Soil Science* 175(2), 89-98.
- Paetsch, L., Mueller, C. W., Kögel-Knabner, I., von Lütow, M., Girardin, C. and Rumpel, C. 2018. Effect of *in-situ* aged and fresh biochar on soil water holding capacity and microbial C use under drought conditions. *Scientific Reports* 8(1), 6852.
- Pan, G., Smith, P. and Pan, W. 2009. The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. *Agriculture, Ecosystems and Environment* 129(1-3), 344-348.
- Pärn, J., Verhoeven, J. T. A., Butterbach-Bahl, K., Dise, N. B., Ullah, S., Aasa, A., Egorov, S., Espenberg, M., Järveoja, J., Jauhiainen, J., Kasak, K., Klemmedtsson, L., Kull, A., Laggoun-Défarge, F., Lapshina, E. D., Lohila, A., Löhmus, K., Maddison, M., Mitsch, W. J., Müller, C., Niinemets, Ü., Osborne, B., Pae, T., Salm, J. O., Sgouridis, F., Sohar, K., Soosaar, K., Storey, K., Teemusk, A., Tenywa, M. M., Tournebize, J., Truu, J., Veber, G., Villa, J. A., Zaw, S. S. and Mander, Ü. 2018. Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots. *Nature Communications* 9(1), 1135.
- Parton, W. J., Schimel, D. S., Cole, C. V. and Ojima, D. S. 1987. Analysis of factors controlling soil organic levels of grasslands in the Great Plains. *Soil Science Society of America Journal* 51:1173-1179.
- Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P. and Smith, P. 2016. Climate-smart soils. *Nature* 532(7597), 49-57.

- Peltre, C., Christensen, B. T., Dragon, S., Icard, C., Kätterer, T. and Houot, S. 2012. RothC simulation of carbon accumulation in soil after repeated application of widely different organic amendments. *Soil Biology and Biochemistry* 52, 49-60.
- Pikul, J. L., Chilom, G., Rice, J., Eynard, A., Schumacher, T. E., Nichols, K., Johnson, J. M. F., Wright, S., Caesar, T. and Ellsbury, M. 2009. Organic matter and water stability of field aggregates affected by tillage in South Dakota. *Soil Science Society of America Journal* 73(1), 197-206.
- Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A. M., Kinengyere, A., Opazo, C. M., Owoo, N., Page, J. R., Prager, S. D. and Torero, M. 2020. A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nature Sustainability* 3(10), 809-820.
- Plaza-Bonilla, D., Arrúe, J. L., Cantero-Martínez, C., Fanlo, R., Iglesias, A. and Álvaro-Fuentes, J. 2015. Carbon management in dryland agricultural systems: a review. *Agronomy for Sustainable Development* 35(4), 1319-1334, DOI: 10.1007/s13593-015-0326-x.
- Poeplau, C. and Don, A. 2015. Carbon sequestration in agricultural soils via cultivation of cover crops—a meta-analysis. *Agriculture, Ecosystems and Environment* 200, 33-41.
- Quiroga, A. R., Buschiazzo, D. E. and Peinemann, N. 1999. Soil compaction is related to management practices in the semi-arid Argentine pampas. *Soil and Tillage Research* 52(1-2), 21-28.
- Rawls, W. J. 1983. Estimating soil bulk density from particle size analysis and organic matter content. *Soil Science* 135, 124-124.
- Richardson, A. E., Kirkby, C. A., Bnerjee, S. and Kirkgaard, J. A. 2014. The inorganic nutrient cost of building soil carbon. *Carbon Management* 5(3), 265-268.
- Rumpel, C., Amiraslaj, F., Bossio, D., Chenu, C., Henry, B., Fuentes Espinoza, A. F., Koutika, L.-K., Ladha, J., Madari, B., Minasni, B., Olaleye, A. O., Shirato, Y., Sall, S. N., Soussana, J.-F. and Varela-Ortega, C. 2022. The role of soil carbon sequestration in enhancing human resilience in tackling global crises including pandemics. *Soil Security* 8, 100069.
- Rumpel, C. and Chabbi, A. 2021. Managing soil organic carbon for mitigating climate change and increasing food security. *Agronomy* 11(8), 1553.
- Rumpel, C., Kögel-Knabner, I. and Bruhn, F. 2002. Vertical distribution, age, and chemical composition of organic carbon in two forest soils of different pedogenesis. *Organic Geochemistry* 33(10), 1131-1142.
- Sagar, S., Tate, K. R., Giltrap, D. L. and Singh, J. 2008. Soil-atmosphere exchange of nitrous oxide and methane in New Zealand terrestrial ecosystems and their mitigation options: a review. *Plant and Soil* 309(1-2), 25-42.
- Schmidt, H. P., Anca-Couze, A., Hagemann, N., Werner, C., Gerten, D., Lucht, W. and Kammann, C. 2019. Pyrogenic carbon capture and storage. *GCB Bioenergy* 11(4), 573-591.
- Schmidt, H. P., Kamman, C., Hagemann, N., Leifeld, J., Buecheli, T., Sanchez Mandeno, M. A. and Cayuela, M. A. 2021. Biochar in agriculture. A systematic review of 26 meta-analyses. *Global Change Biology* 13, 1708-1730.
- Singh Brar, B., Sing, J., Singh, G. and Kaur, G. 2015. Effects of long-term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize-wheat rotations. *Agronomy* 5(2), 220-238.
- Skaalsveen, K., Ingram, J., Julie, L. E. and Clarke, L. E. 2019. The effect of no-till farming on the soil functions of water purification and retention in northwestern Europe: a literature review. *Soil and Tillage Research* 189, 98-109.



- Skinner, C., Gattinger, A., Muller, A., Mäder, P., Fließbach, A., Stolze, M., Ruser, R. and Niggli, U. 2014. Greenhouse gas fluxes from agricultural soils under organic and non-organic management—A global meta-analysis. *Science of the Total Environment* 468-469, 553-563.
- Smith, P. 2016. Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology* 22(3), 1315-1324.
- Soussana, J., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M., Wollenberg, E., Chotte, J., Torquebiau, E., Ciais, P., Smith, P. and Lal, R. 2019. Matching policy and science: rationale for the '4 per 1000-soils for food security and climate' initiative. *Soil and Tillage Research* 188, 3-15.
- Thorup-Kristensen, K. and Nielsen, N. E. 1998. Modelling and measuring the effect of nitrogen catch crops on the nitrogen supply for succeeding crops. *Plant and Soil* 203(1), 79-89.
- Tian, H., Xu, R., Canadell, J. G., Thompson, R. L., Winiwarter, W., Suntharalingam, P., Davidson, E. A., Ciais, P., Jackson, R. B., Janssens-Maenhout, G., Prather, M. J., Regnier, P., Pan, N., Pan, S., Peters, G. P., Shi, H., Tubiello, F. N., Zaehle, S., Zhou, F., Arneeth, A., Battaglia, G., Berthet, S., Bopp, L., Bouwman, A. F., Buitenhuis, E. T., Chang, J., Chipperfield, M. P., Dangal, S. R. S., Dlugokencky, E., Elkins, J. W., Eyre, B. D., Fu, B., Hall, B., Ito, A., Joos, F., Krummel, P. B., Landolfi, A., Laruelle, G. G., Lauerwald, R., Li, W., Lienert, S., Maavara, T., MacLeod, M., Millet, D. B., Olin, S., Patra, P. K., Prinn, R. G., Raymond, P. A., Ruiz, D. J., van der Werf, G. R., Vuichard, N., Wang, J., Weiss, R. F., Wells, K. C., Wilson, C., Yang, J. and Yao, Y. 2020. A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* 586(7828), 248-256.
- Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F. and Baumecker, M. 2013. Irrigation, soil organic carbon and N<sub>2</sub>O emissions: a review. *Agronomy for Sustainable Development* 33(4), 733-749.
- United Nations 2017. World population prospects: the 2017 revision, key findings and advance tables. Working Paper No. ESA/P/WP/248, Department of Economic and Social Affairs, Population Division (2017).
- van Erp, P. J., Houba, V. J. G. and van Beusichem, M. L. 2001. Actual cation exchange capacity of agricultural soils and its relationship with pH and content of organic carbon and clay. *Communications in Soil Science and Plant Analysis* 32(1-2), 19-31.
- van Groenigen, J. W., Van Kessel, C., Hungate, B. A., Oenema, O., Powlson, D. S. and Van Groenigen, K. J. 2017. Sequestering soil organic carbon: a nitrogen dilemma. *Environmental Science and Technology* 51(9), 4738-4739.
- Van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M. A., Linquist, B. and van Groenigen, K. J. 2013. Climate, duration, and N placement determine N<sub>2</sub>O emissions in reduced tillage systems: a meta-analysis. *Global Change Biology* 19(1), 33-44.
- Virto, I., Barré, P., Burlot, A. and Chenu, C. 2012. Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. *Biogeochemistry* 108(1-3), 17-26.
- Warrington, D. N., Goldstein, D. and Levy, G. J. 2007. Clay translocation Within the soil profile as affected by intensive irrigation with treated wastewater. *Soil Science* 172(9), 692-700.
- Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J. and Joseph, S. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications* 1, 56.

- Xu, C., Han, X., Zhuge, Y., Xiao, G., Ni, B., Xu, X. and Meng, F. 2021. Crop straw incorporation alleviates overall fertilizer-N losses and mitigates N<sub>2</sub>O emissions per unit applied N from intensively farmed soils: an in situ <sup>15</sup>N tracing study. *Science of the Total Environment* 764, 142884.
- Yeboah, S., Zhang, R., Cai, L., Li, L., Xie, J., Luo, Z., Liu, J. and Wu, J. 2016. Tillage effect on soil organic carbon, microbial biomass carbon and crop yield in spring wheat-field pea rotation. *Plant, Soil and Environment* 62(6), 279-285.
- Zhang, X., Sun, N., Wu, L., Xu, M., Bingham, I. J. and Li, Z. 2016. Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China. *Science of the Total Environment* 562, 247-259.

