UNFSS-White paper

Potential and limitations of soil organic carbon sequestration in croplands: the role of sustainable fertility management

Co-authors Rachid Moussadek[1,5], Ngonidzashe Chirinda[2], Leonardus Vergutz[2], Kaushik Majumdar[2,3], Shamie Zingore[2,3], Abdelmohssin El Mokkadem[2], Amarjit Basra[4]

[1] International Centre for Agricultural Research in the Dry Areas (ICARDA),

[2] Mohammed VI Polytechnic University (UM6P)

[3] African Plant Nutrition Institute (APNI)

[4] OCP North America (OCP NA)

[5] Institut National de la Recherche Agronomique (INRA)

In memory of our colleague, brother and friend, Mr Younes Berrada

Glossary

Mineral associated organic matter: Organic matter adsorbed to soil minerals and thereby protected from further microbial decomposition.

Particulate organic matter: Organic matter of partly undecomposed or charred plant litter and decomposed microbial products that are not adsorbed to soil minerals.

Rhizodeposition: organic material released from plant roots including exudates, sloughed cells and mucilage. It can also include mycorrhizal biomass depending on how it is measured (e.g., it is often included in carbon isotope-based methods).

Rhizosphere: the region of soil that is directly influenced by rhizodeposition, root growth and death, and nutrient and water uptake.

SOC stabilization: any process that makes SOC persist longer and decompose at a much slower rate than the unstabilized SOC.

SOC destabilization: any process that activates stabilized SOC.

Abstract

Poor land and soil management practices are associated with widespread severe degradation in global agricultural systems. Urgent attention to judicious land use and prudent soil/crop/water management is required to restore degraded soils and improve the environment (Lal 2019a). Maintaining or enhancing the SOC stocks is one of the most critical interventions to fight against climate change, soil degradation and ensuring the sustainability of agriculture. The global soil organic carbon (SOC) contents are 677 Pg to 0.3 m, 993 Pg to 0.5 m and 1,505 Pg to 1 m depth. Thus, ~55% of the SOC in the top 1 m soil depth is below 0.3 m depth. However, the average SOC stocks are relatively lower in agroecosystems than in natural ecosystems due to lower biomass production, biomass removal/harvest, and land management practices such as tillage that increase the loss of SOC. The low carbon stocks place croplands as high priority areas for SOC sequestration. The strategy of enhancing SOC sequestration for climate and food security was adopted at COP_{21} in Paris in November 2015 under the program "4 per Thousand" (https://www.4p1000.org/). The goal is to sequester SOC in soils of the world at the rate of 0.4% per year to 0.4 m depth. The AAA (Adapting African Agriculture) (https://www.aaainitiative.org/) initiative proposed at COP_{22} in Marrakech is complementary to the "4 per Thousand" as both initiatives aim to enhance SOC stock in agricultural systems. Although the goal of sequestering C in croplands appears straightforward, it faces several challenges and tradeoffs that need to be considered. This report aims to review and synthesize the current scientific evidence on the potential of various crop, soil and nutrient management practices to enhance soil C sequestration in different regions. This report highlighted the need for more research to provide policy-makers and farmers with the evidence base that will encourage them to adopt SOC-enhancing practices. Current evidence is clear that a site-specific nutrient management using a combination of mineral and organic fertilizers, combined with other techniques, can deliver optimal results for farmers and for food security.

The basics of carbon sequestration

Globally, there is growing need to reduce atmospheric carbon dioxide (CO_2) levels by both reducing anthropogenic emissions (sources) and removing CO_2 from the atmosphere to sequester it in terrestrial plants or soils (sinks). The scientific community is generating knowledge on managing the cropland area needed to meet food requirements and simultaneously store more carbon for extended periods (Teluguntla et al., 2015). In fact, soil organic carbon (SOC) sequestration on agricultural lands contributes towards maintaining soil health, preventing soil degradation and decreasing the costs of climate change mitigation while promoting increased food security. It's important to note that in croplands, the amount of C sequestered (C stocks) in soil depends on the amounts of photosynthetic C annually incorporated in the soil and the rate of its decay, mineralization and stabilization as soil organic matter (SOM) and the decomposition rate of the resultant SOM (Paustian et al., 1998; Janzen, 2004).

Since C mineralization represents an energy source for microbes that are responsible for nutrient cycling (e.g., nitrogen and phosphorus), there is a need for balance between the C stocks and amounts mineralized (C flows) to support crop production (Janzen, 2006). Addressing the balance between C stocks and flows requires an in-depth understanding of soil C inputs, stabilization mechanisms and loss pathways which largely depend on the quantity and quality of C inputs, climatic variables (i.e., temperature and precipitation), soil characteristics (soil type, clay content and initial C stocks) and adopted management practices (Zingore et al., 2003; Stockmann et al., 2013). Whereas SOC formation and decomposition are dependent on biophysical factors (i.e., soil texture, climate), the amounts and types of biomass added to the soil each year largely depend on land use (types of crops or vegetation) and management (e.g. weed and pest control, irrigation, fertilizer use) (Hijbeek et al., 2019). These factors vary enormously over space, time and cropping systems, and so do the resultant soil carbon stocks. Corbeels et al. (2019) have also shown that the SOM content in sub-Saharan African soils is highly variable and attributed to management practices, soil types and landscape (Godde et al., 2016). The critical/threshold level of SOC may be about 2% in soils of the temperate zone and ~1% for those of the tropics. Additional research is needed to establish critical limits/ranges of SOM content for diverse soils, climates, and ecoregions (Lal, 2020).

In December of 2015, members of COP21 initiated the "4 per mille" Soils for Food Security and Climate program (Paustian et al. 2016, Minasny et al. 2017). The basic concept of this initiative is to operationalize a plan to sequester carbon in soils around the world at a rate that would offset the estimated 8,900 Mt of annual GHG emissions from fossil-fuel based carbon

(C). The plan is based on the idea that implementing farming practices that maintain or enhance SOC stocks in croplands and protecting C-rich soils globally by even just a small percentage could have a substantial impact on net emissions. Given the estimate that 2,400,000 Mt of C is stored in the top 2 metres of soil (Batjes, 1996), small changes in this stock can have large impacts on global atmospheric CO_2 concentrations and Africa have a great capacity to contribute on this mitigation effort as Africa's production potential is immense. In fact, 60% of the planet's unexploited arable lands are in this continent. On the other hand, the generally low soil carbon contents in African cropland soils imply greater capacity to hold more carbon than they currently do, if farmers adopt improved management practices that promote increased carbon input.

Soil C inputs in cropland soil

In croplands, soil C inputs are mainly derived from organic material released from soil microbes, growing roots (i.e., root exudates, lysates, mucilages, sloughed cells), shoot and root residues and applied manures (Chirinda et al., 2012). The soil C stocks reflect a balance between C input and C loss during decomposition, erosion and leaching (Bationo and Fenning, 2018). In croplands, if C loss processes are of similar magnitude, cropping systems with different C inputs give rise to different soil C contents. Wang et al. (2015) estimated that an average critical C input of 2.0 Mg C ha^{-1} yr^{-1} is needed to maintain existing soil C level in global wheat systems and soil, management and climatic conditions lead to large spatial variability. However, the actual amount sequestered will depend on management strategies (e.g., residue retention and fertilizer application) and environmental conditions. For instance, by enhancing primary production, high-input crop production systems tend to have higher shoot biomass and thus generate larger quantities of belowground and aboveground crop residues, with the former being a more direct carbon input and the later resulting in substantial C inputs if returned to the soil (Chirinda et al., 2010a; Zhou et al., 2017; Chenu et al., 2019; Guo et al., 2019).

Organic matter quality

Factors that regulate the initial decomposition rate of crop residues include the crop residue quality mostly linked to chemical composition, such as carbon-to-nitrogen ratio (Ma et al., 2021). However, recent findings suggest that we cannot extrapolate the initial stages of litter decomposition to explain long-term storage of organic compounds and suggest that other mechanisms (i.e., missing compounds required for co-metabolism of organic compounds, restricted access of decomposer enzymes to organic compounds) protect organic matter against decomposition (Schmidt et al., 2011). In addition, the fraction of recalcitrant constituents, such as lignin, can also play a key role in C sequestration due to chemical stabilization. These new insights suggest that the long-term decomposition of soil C is regulated by biotic and environmental factors more than the inherent molecular structure of the C inputs (Dynarski et al., 2021).

Climatic conditions

The climatic conditions (i.e., precipitation and temperature) influence the soil moisture and temperature experienced in cultivated soils. Soil moisture and temperature are the major factors controlling the rate of organic matter decomposition through their influence on microbial activity. Soil organic carbon stocks tend to increase in regions that experience extended periods under low temperatures, which reduce microbial activity (Chenu et al., 2019; Post et al., 1982). Conversely, regions with high temperatures experience high rates of C decomposition due to high microbial activity and simultaneously high net primary productivity. At optimum soil water content (near field capacity), the diffusion of both air and soluble substrates creates conditions conducive to crop growth and microbial activity. Conversely, drier and wetter soils create conditions that may not be ideal for crop production and microbial activity, influencing C inputs and microbial activity (Xu et al., 2004). Therefore, in response to high temperatures and rainfall, net C changes may be small (Kirschbaum, 2000) or large (Sitch et al., 2008) depending on the magnitudes of increase in C inputs and microbial activity (Stockmann et al., 2013).

Deep-Rooting Crops

Cultivation of deep-rooting crop species and varieties such as alfalfa (Medicago sativa), sunflower (Helianthus annuus), or perennial crops such as grass, grass-clover, and legume- and alfalfa-grass mixtures can transfer carbon into the subsurface through root exudates (e.g., sugars, amino acids, and other organic acids), where a high carbon sequestration potential exists (Sokol et al., 2019), especially if organic substances are protected in organo-mineral aggregates (Paustian et al., 2016). For instance, in Sweden, the implementation of grass-clover into the crop rotation increased SOC contents by 8% in 20 years (Poeplau et al., 2015). Overall, the cultivation of deep-rooting crops can sequester 374 ± 117 kg C ha^{-1} y−1 (Tiefenbacher et al., 2021). It has become increasingly clear that organic matter inputs from roots tend to contribute to SOC stabilization significantly more than aboveground plant inputs (Rasse et al., 2005; Jackson et al., 2017). Another advantage is that deep-rooting crops can use resources such as water and nutrients from the subsurface horizon, preventing N leaching and making plants more resilient to drought. Plant breeding has focused on yield increases by partitioning more carbon to harvested yield. However, generating this carbon has been driven by both optimized fertilization and genetic selection that resulted in crops with a high total plant biomass accumulation compared to unfertilized plants. There is much need for understanding the relative importance of the different modes of action by which carbon inputs affect the magnitude of SOC stabilization and destabilization that will provide a better understanding of soil C sequestration, and new opportunities for understanding the sensitivity of SOC pools to climate and land-use changes (Dijkstra et al., 2021).

Management practices

Many annual crops have shallow rooting systems as the focus of current breeding programmes has been on increasing the harvestable biomass removed from the croplands resulting in limited amounts of organic matter being returned to the soil. Several studies show that inadequate nitrogen and phosphorus supply limit plant productivity and, consequently, C accumulation and the amount of C available to incorporate in the soil (van Groenigen et al., 2006; Wieder et al., 2015). Concurrently, the conventional tillage practices used to prepare soils for annual crop production are based on deliberate soil disturbances, which increase organic matter decomposition and increase CO_2 loss to the atmosphere. Previous estimates have suggested that, globally, croplands store over 140 Pg C (1 Pg = 10^{15} g) in the top 30 cm of soil (Zomer et al., 2017). However, the tillage of croplands is estimated to have already contributed to soil losing ~78 ± 12 Pg of C to the atmosphere (Lal, 2003). It is estimated that pursuing management practices that increase C input and its stabilization and reduce its loss can recapitalize up to 70% of the lost C (Lal, 2002).

Challenges of sequestering soil C

Competing use for biomass

Increasing the amount of biomass that is returned to the soil is complicated by growing competition for biomass. For instance, competing uses of crop residues include animal feed and biofuel production. Therefore, while C inputs can be enhanced by returning more plant litter directly to the soil in the form of manures, there is a need to consider the tradeoffs and exploit the potential synergies (i.e., in crop-livestock systems).

Saturation

Soil C storage potential is finite as soils become saturated with C. Soil C saturation is defined as the limits a soil has to stabilize C as a function of C inputs based and the amount of protected and non-protected C (Stewart et al., 2007). Therefore, the potential to sequester C increases the further a soil is from C saturation (Six et al., 2002). Consequently, to increase C stocks, the focus needs to be placed on cropland soils with large SOC deficits , such as African soils, that have a generally higher potential to sequester more C compared to natural ecosystems. Texture is a significant determinant of SOC storage capacity due to the influence of clay and silt fractions on SOC stabilization (Korschens et al., 1998).

Permanence

Despite the amount of C sequestered, tremendous uncertainty exists regarding the periods stored C remains sequestered in soil. A significant cause of uncertainty is the fact that C sequestration is reversible. This implies that stored C is vulnerable to being re-emitted to the atmosphere if farmers adopt management practices that increase C oxidation (e.g., ploughing). Improved knowledge on drivers for adopting appropriate management practices (i.e., social and economic factors) and the longevity of C storage (i.e., chemical and biophysical factors) will inform the policy and regulatory framework needed to incentivize needed actions (Baveye et al., 2020).

Methane and nitrous oxide emissions

Several previous studies have reported that increasing C stocks may increase N_2O emission (Brettar et al., 2002; Li et al., 2005). However, a recent review concluded that the climate mitigation benefits of increased C sequestration would be overestimated if the related N_2O

emissions are not considered, but the benefits are never completely offset (Guenet et al., 2021). On the other hand, increasing C input and C storage in flooded soils (i.e., straw return in paddy rice systems) increase methane emissions that could offset benefits accrued from C benefits (Lu et al., 2010).

Best management practices (BMP) to C sequestration and food security

According to Horwath and Kuzyakov (2018), consistent (often up to decades) investment in best-fit soil or crop management practices is required to enhance C sequestration. Specifically, management practices that support C sequestration include: reducing or eliminating tillage (Baker et al., 2007); use of cover crops (Mazzoncini et al., 2011); application of mineral fertilizers (Majumder et al., 2008; Zhao et al., 2017); use of organic amendments including green compost or manure; crop residue management (i.e., eliminate open field burning or removal), and crop rotation diversity (i.e., including deep root crops (Peixoto et al., 2020). The average lower limit and upper limit for agricultural SOC sequestration are 0.14 and 0.38 Mg g C ha^{-1} y^{-1}, respectively (Horwath and Kuzyakov, 2018). This demonstrates the scope for developing appropriate solutions toward climate-friendly agricultural systems, but socio-economic determinants constrain their practical application at the farm level. Table 1 includes data on representative values for SOC sequestration potential in agriculture for various regions.

Table 1: Representative Agricultural Soil C Sequestration Rates for Different Management Practices and Countries (Horwath and Kuzyakov 2018).

Country	Management practice	C Sequestration Rate ($t\ C\ ha^{-1}\ y^{-1}$)		Reference
		Low	High	
Australia	Reduced tillage		0.34	Sanderman et al. (2010)
Australia	Crop rotation		0.20	Sanderman et al. (2010)
China	Organic amendment		0.62	Wang et al. (2010)
Canada	Conventional to no-till	0.05	0.16	VandenBygaart et al. (2008)
France	Conservation tillage		0.10	Metay et al. (2009)
India	Rice + Wheat + NPK + manure		0.99	Majumder et al. (2008)
Nigeria	Manure + residue return	0.10	0.30	FAO (2004)
United States	No-till + cover crop		0.77	Mitchell et al. (2016)

According to Lal (2018b), the strategy of best management practices (BMPs) for ecosystems implies the choice of context-specific practices that (1) maintain continuous soil cover year-round with crop residues, mulch, and cover cropping; (2) replace nutrients harvested in the production through integrated nutrient management; (3) enhance soil structure and rhizospheric processes; and (4) improve eco-efficiency by reducing losses (by erosion, volatilization, or leaching). (Lal 2018a). This indicates the potential of conservation agriculture in effective soil C sequestration. However, the basic principles of conservation agriculture have been in practice for over 50 years, and researchers should strive for new viable technologies to hasten sequestration and improve soil productivity and function. This is a significant challenge for soil scientists and agronomists (Lal 2018a). Another study by Lal (Lal 2018b) concluded that adopting best management practices based on continuous ground cover, complex rotations, integrated nutrient management and no soil disturbance can protect the SOC stock and strengthen the ecosystem services.

Links between soil fertility management and C sequestration

The adoption of fertilizer management practices such as chemical fertilization, manure application and straw retention are among the most efficient and effective way to increase SOC accumulation or reduce SOC loss rates in arable soils. In areas with nutrient deficiency, mineral fertilizers support the dual agronomic and environmental benefits by increasing crop yields and biomass and thus the crop residue and root C input to soil (Han et al., 2016). In addition to higher C inputs (e.g., crop residues and roots), N fertilizers also create more favourable C:N ratios for the formation of SOM (Campbell et al., 2000; Hijbeek et al., 2019).

Two past meta-analyses based on 64 and 114 field experiments across the world found that the mean SOM content was 8.5% and 8% higher in the topsoil of fields with mineral fertilizer application compared to unfertilized plots (Ladha et al. 2011; Geisseler and Scow 2014). Similarly, Gao et al. (2018) found that long-term increases in soil carbon were associated with improved agronomic management, including increased fertilizer use. In Punjab, India, the intensification of the rice-wheat cropping system improved SOC by 38% over 25 years (Benbi and Brar, 2009). The enhanced C sequestration resulted from the increased productivity of rice and wheat. Mandal et al. (2007), while assessing the impact of soil amendments on carbon sequestration in long-term experiments in sub-tropical India, reported that balanced fertilization with NPK increased SOC stocks (9.3–51.8% over the control), and the selected cropping system influenced the magnitude increase. Long-term addition of farmyard manure or compost (5–10 Mg ha^{-1} yr^{-1}) hardly increased SOC by 10.7%, representing only 18% of the applied C, as the rest was lost through oxidation. The impact of fertilizer in SOC sequestration tends to be less pronounced in coarse-textured soils in the tropics due to very high rates of C turnover. Under long-term field experiments in the West African agroecosystems, the use of mineral fertilizers without recycling of organic materials resulted in initially higher yields, but the effects on SOC were insignificant (Bationo et al., 2012).

Intensification of agriculture in several countries resulted in improved crop yields and saved emissions that would have occurred because of obligatory land-use changes for meeting the food demands of the growing population (Barney et al., 2010). Contrary to the common belief, supplying nutrients through other means than mineral fertilizers does not necessarily result in less GHG emissions (Chirinda et al., 2010a). For example, direct N_2O emissions from animal manure are similar to mineral fertilizer per kg of N applied (De Klein et al., 2006). No-till (NT) systems provide opportunities to sequester carbon and reduce loss of SOM. However, on the long-term biomass accumulation and soil carbon storage effects are amplified through balanced application of organic amendments in combination with mineral fertilizers - NPK (Su et al., 2006; Ortas and Bykova, 2020). A 50-year long-term experiment in an Australian Vertisol showed that N fertilizers significantly increased SOC stocks in the upper 0.1 m of the soil profile. N fertilizers applied at 90 kg ha^{-1} resulted in SOC increases of 18%, while the use of NT resulted in 5% increases. (Jha et al., 2020).

Fertilizer management to stimulate crop productivity and enhance carbon inputs through additional biomass in highly variable soil-crop-climate systems requires a site-specific approach. Soils fertilized with N in wheat and maize cropping systems in the northern region of China had higher C storage than unfertilized plots. The most significant increase in C storage occurred in soils fertilized with N and P in rice-wheat systems. In addition, the inverse relationship between the N:P ratio of added fertilizer and soil C storage highlights the importance of P in determining the strength of soil C sinks (Bradford et al. 2008). Where N, P, and K were co-applied, while N and P fertilizers explained 49 and 11% of the variability in soil

C storage, the contribution of K was unclear (Zhao et al., 2017). Pan et al. (2019) observed that soil C stocks were maximized at N rates that maximized yields. The optimum N application rate stimulated crop growth, enhanced crop yield, increased crop residue inputs to the soil, and improved SOC and other soil quality parameters. The necessity for a field-specific strategy for mineral fertilizer and manure application was well highlighted from several studies (Zingore et al., 2007; Tittonell et al., 2005) in Africa where high variability in SOM within short ranges was reported, mainly driven by a history of mineral fertilizer and manure application within homestead fields.

The complex variability of soils at various spatial scales brought about by inherent differences and management practices has a significant influence on the suitability of nutrient management practices, which in turn affects SOC. Data from multi-location nutrient omission trials from a wide range of studies has consistently shown N and P to be the most limiting nutrients and reveal a highly variable response to the application of macronutrients. Kihara et al. (2016), assessing more than 400 fertilizer response trial sites, established that nutrient response patterns can be divided into two broad cluster - 'responsive' and 'non-responsive'. The responsive soils showed three characteristic macronutrient response patterns: (i) fields that respond strongly to N alone, (ii) fields that respond strongly to combined application of N and P; and (iii) fields that show a solid response to N, P and K. Across all the responsive clusters, yields were increased by 10-30% by the addition of secondary and micronutrients. Tailoring fertilizer application to site-specific soil fertility conditions to address complex nutrient deficiencies is a crucial strategy to enhance the productivity of smallholder farming systems and maintain high levels of SOC. Currently, more than 40% of Africa's 220 Mha of farmland is experiencing annual losses of at least 30 kg per ha of nutrients due to inadequate nutrient application. Hence, fertilizer application is a necessary intervention to restore productivity, soil fertility and SOM.

Large pieces of evidence are now available to support the hypothesis that site-specific and balanced fertilization promotes SOC through more considerable biomass inputs in the soil to convert to organic matter. Besides increasing C inputs to the soil (Parihar et al., 2017), some of these studies also highlight the co-benefit of reduced GHG emission. Parihar et al. (2020) reported that crop demand-based nutrient application through SSNM resulted in better utilization and assimilation of applied nutrients, which promoted better above and below-ground biomass production in intensive cereal systems. Site-specific nutrient application promoted SOC stabilization, thus enhancing SOC concentration in surface soil and overall C-sequestration potential. A recent article (Mustafa et al., 2021) reiterated that long-term balanced fertilization using mineral fertilizer alone or combined with manure is the best choice to improve the SOC sequestration and mineralization, as well as the crop yields. Specifically, Mustafa et al (2021), reported that in comparison to the unfertilized control treatments that combined pig manure and NPK significantly increased different soil organic carbon fractions. For instance, they report that unprotected carbon in the form of coarse particulate organic carbon and free particulate organic carbon fractions increased by >57%, and >91% respectively. Physically protected carbon in the form of intra-aggregate particulate organic carbon fractions increased by >113% while biochemically protected carbon in the on free silt plus clay and micro-aggregate derived silt plus clay fractions correspondingly increased by >39 and >50%.

Plant nutrients are exported out of agricultural fields through harvested products or by leaching and gaseous emission. Exported nutrients must be reinstated to maintain soil fertility and support adequate crop yields. Mineral fertilizers are the most cost-effective and efficient means of replacing the exported or lost nutrients considering the limited availability of biomass in most food and nutritionally insecure regions of the world. Without mineral fertilizer, there would not be sufficient nutrients globally to meet current and growing food demands (Dawson and Hilton 2011). Balanced use of mineral fertilizers increases yields, more biomass becomes available to increase carbon in soils (Han et al., 2018), and creates a positive feedback loop through increased productivity or avoided area expansion. Specifically, besides increasing crop production, improved cultivation practices (i.e., fertilization and straw return contributed to SOC stock increases in both surface (0-20 cm) and deeper soils (20-40 cm). Average increases were 9.4 Mg C ha^{-1} (0-20 cm) and 5.1 Mg C ha^{-1} which corresponded to 73 and 56% C stock increases compared to the 1980s. Fertilizer use and crop yields generally tend to be lower in developing countries, especially in most African countries (FAO 2019). Therefore, as evidenced by previous studies, increasing nutrient inputs using both mineral fertilizer and manure can improve crop yields, increase nutrient use efficiency and increase the availability of biomass that can be returned to the fields to sequester carbon (Hijbeek et al., 2019). Zomer et al. (2017) suggest large potential carbon storage rates ranging from 0.15 to 0.31 Pg C/yr in African croplands.

Case study: management of weathered tropical soils to improve C sequestration

In Africa, 83% of rural people depend on agriculture for their livelihood, yet up to 80% of the soils suffer from widespread nutrient depletion and erosion (Gro-intelligence, 2016). Despite the low fertility of soils, fertilizer use in sub-Saharan Africa is still very low and currently estimated at 18 kg nutrients/ha/year, which is the leading cause for its low yields and a major issue for Africa's food security. Considering that sub-Saharan Africa will be the region where the most significant population growth will occur in the following decades, designing sustainable, productive and resilient agricultural systems is crucial for achieving food security and environmental sustainability. Sub-Saharan Africa and Latin America have comparable environmental conditions with large areas dominated by rainy (Af and Am) and seasonal (Aw) climates and have similar vegetation (savannas, grasslands, and broadleaf evergreen forests) and soil moisture regimes (Sanchez, 2019). The Brazilian savanna and the African dystrophic savanna show even higher similarities regarding soil acidity, low availability of nutrients, low content of soil organic C, and high P fixing capacity.

It is because of these similarities that Dr Borlaug (the father of the Green Revolution) mentioned during his speech for the 2006 World Food Prize that he wished "the Cerrado technology, or one similar to it, would move into central and southern Africa where similar soil problems are found". This year, two Brazilians and one American were the recipients of the same prize due to their vital role in transforming the Cerrado (Brazilian savanna), a vast region of infertile tropical soils, into highly productive cropland. With technology, the Cerrado went from having only 200,000 ha of arable land in 1955 to over 40 million ha in cultivation by 2005. Dr Borlaug said it was "one of the great achievements of agricultural science in the 20th century, which has transformed a wasteland into one of the most productive agricultural areas in the world". This transformation is even more impressive if one considers that the Cerrado was considered of little (if any) value for agriculture due to many failed attempts to fertilize and produce proportionate crop harvests (Wright and Bennema, 1965). A common situation in many sub-Saharan Africa countries has been non-responsive soils (Assenga et al., 2016).

Taking the Brazilian case as an example for the weathered infertile soils in sub-Saharan Africa and following Dr Borlaug's suggestions, agronomic practices are a prerequisite to creating sustainable cropping systems in the tropics. Highly weathered tropical soils are known for their natural low soil fertility, associated with other challenges such as acidity, Al toxicity, Ca, and

Mg deficiency (Lopes & Guilherme, 1994). For plants that do not tolerate acidity (and Al toxicity), liming is mandatory in these soils. However, even for those that tolerate acidity and Al (e.g. eucalypt), liming increases its productivity (personal data). Liming, besides providing Ca and Mg, also offers several synergistic benefits, including increased soil biological activities and root system development (Lopes, 1983; Goedert, 1987; Lopes & Guilherme, 1994).

In conventional systems, lime is usually incorporated to 20 cm depths. As it does not move in the soil profile, the effects are limited to where it is applied. Thus, root system development is usually limited by a chemical barrier and confined to where lime is applied. Promoting root development through the soil profile is an essential component of C input for SOM formation, a prerequisite for sustainable and productive agricultural systems in the tropics. Thus, if we want to produce SOM, especially in deeper soil layers, we must have a good distribution of Ca in the soil profile. The use of phosphogypsum has shown great promise in this regard. Phosphogypsum ($CaSO_4$) has two nutrients that are highly depleted in such soils and very important for plant growth, Ca and S. Sulphate is essential not only for plant growth but also for microorganisms.

Furthermore, despite not changing pH, sulfate can complex Al^{3+}, decrease its toxicity to plants, and compete for binding sites with P, improving P availability. An outstanding characteristic of $CaSO_4$ is that, unlike limestone, it can move in the soil profile. This characteristic is fundamental for building highly productive conservationist agricultural systems in the tropics, especially because no-till is also promoted. Distributing Ca and S in the soil profile helps boost root system growth, which increases nutrients and water absorption by plants, increasing nutrients and water use efficiency, and C inputs to the soil.

To build productive and sustainable agricultural systems in weathered soils like those in Sub-Saharan Africa, it is imperative to focus on perennial and annual crops. The use of phosphogypsum has allowed plants to grow more, have higher yields, improve SOM, and shield them against drought events, which is very important under drier climatic conditions where water availability is low. Improvement of the soil conditions by using the proper amendments (lime and phosphogypsum) is necessary to optimize the response of plants to nutrient application. In a field experiment with sugarcane in highly weathered soils, Araujo (2015) showed that after five years of the proper fertilization practices, including phosphogypsum, the C sequestration up to 100 cm depth had increased by 5.4 t ha^{-1}. The most exciting part is that phosphogypsum, which allows the improvement of deeper layers of the soil profile and the development of the root system, led 80 % of this C to be stabilized in the deeper soil layers (40-100 cm). This finding is significant for climate change, as C in deeper layers is less influenced by land management and stabilized for more extended periods.

As part of conservation agriculture, no-till practices are essential for building soil structure and sequestering C as soil organic matter (SOM) in the tropics. When the soils are disturbed, aggregates are broken down and expose SOM to mineralization, leading the soils to become a source of C to the atmosphere. Moreover, losing SOM is one of the main drivers of soil degradation in the tropics. However, adopting no-till management alone does not solve the SOM issue in the tropics. In the same way, adding external sources of C can help increase SOM, but usually, the effect is localized in the top layers of the soil, and the application rate should be very high each year, in the order of tons per ha of magnitude, to be significant. The practical means to increase C sequestration in tropical soils is by increasing C input to the soils through increased plant biomass production, especially root biomass. Soil incorporation of crop residues and cover crops is mandatory for sustainable and productive tropical agriculture (Valadares et al., 2016). They provide an essential range of services, including better water infiltration, better water storage in the soil, improving the cycling of all nutrients, increasing soil organic matter, and increasing microorganisms biodiversity. Thus, the use of cover crops, also called biological intensification, is vital to building sustainable and productive agricultural systems in the tropics. Cover crops can play a crucial function for sustainable, productive, resilient and smart agriculture in the tropics. As shown above, soil fertilization and correction are major components to increase the productivity of the crop of interest and increase the biomass production of the cover crops, improving all their environmental services. In addition, a wide range of microorganisms are of great importance for tropical agriculture, including those that can fix N, improve nutrients use efficiency, and improve plants ability to fight/adapt to biotic and abiotic stresses.

Despite showing the high biomass production potential globally, there are limitations for sequestering C in tropical soils. Due to soil and climate conditions, soils in the tropics show the lowest C content in the world (Figure 1). It means that the natural “steady state” for C content in the soil in tropical conditions is kept low. As land-use changes tend to decrease soil C content even further, if proper land-use practices are not put in place, the soil organic C may be mineralized and lost to the atmosphere, contributing to the CO_2 emissions. In order to improve C in tropical soils and unlock its vast potential to help sequester CO_2 and fight climate change, we must overcome the issues listed above, improving soil chemical, physical and biological properties/characteristics and promoting the biological intensification of our agricultural/forestry systems.

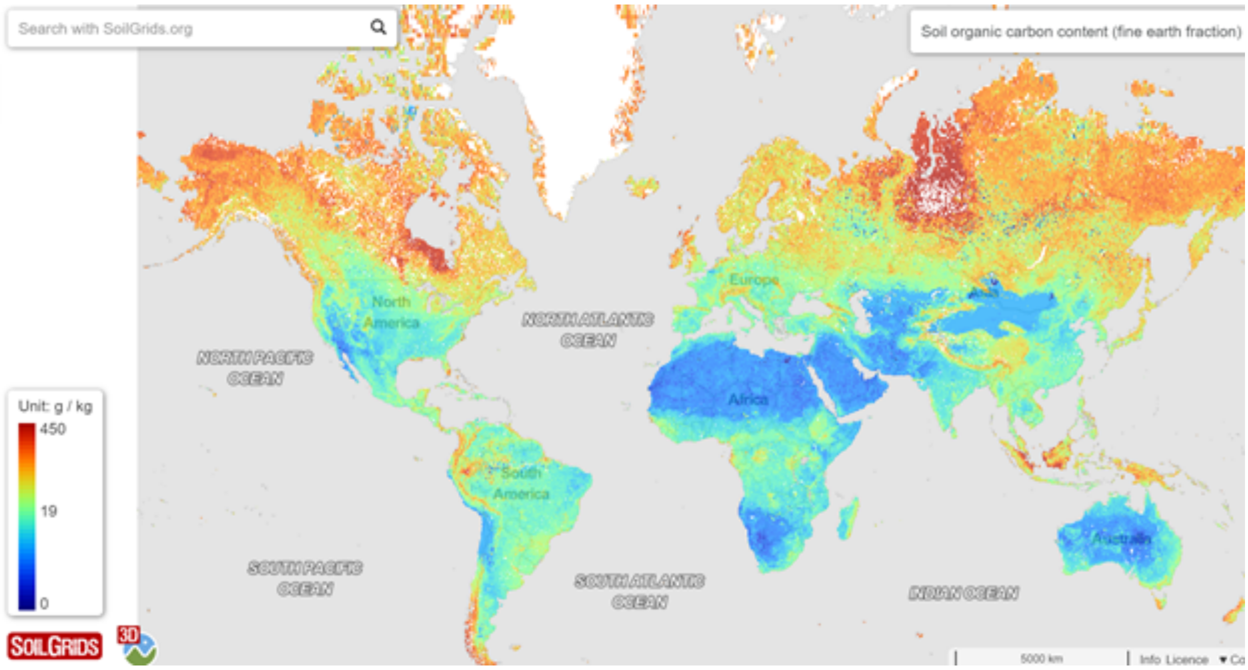

Figure 1 – Soil organic C content in soils around the world (SoilGrids – ISRIC).

Ecosystem services, policies and the adoption of BMP

The health of soils is gaining attention in global and national discussions. For instance, it was recently included in the SDG goals under Target 15.3 (Land Degradation Neutrality) and other targets under the United Nations Convention to Combat Desertification. Under drylands, the importance of SOC implies a need to improve soil stewardship and strengthens the underlying message of considering soil as a public good, requiring economic valuation and creative institutional mechanisms to protect it for the welfare of the greater society. In the following sections, we outline several operational considerations, drawing lessons from practical experiences across the globe on development wins that could be gained from sustainable land management.

Managing soil biodiversity in the drylands

Management practices are among the most important factors that influence SOC sequestration in soils besides soil type, vegetation cover and climate. However, despite awareness of the importance of management methods and techniques, the sustainability of proposed methods and techniques remains a severe unresolved issue. The sustainability of land ecosystems management techniques is twofold: (i) management implemented voluntarily by farmers; (ii) management techniques incentivized by public policies encouraging SOC sequestration.

(i) Voluntary management strategies to sustain soil fertility and avoid soil degradation

Traditional agricultural production systems are based on soil/land management strategies adopted for centuries, allowing farmers to avoid crop productivity losses. Effective management practices have been developed voluntarily by farmers, especially in areas exposed to degradation. Construction of terraces to protect slopes against water erosion, installing hedges to limit wind erosion, and using crop rotation techniques to save soil fertility are some well-known and widespread examples. Nevertheless, the cost-effectiveness and the contribution of these practices to sustain food availability remain neglected by policymakers and are often not recognized as effective. This is because the outcomes of these practices remain, on one side, context-specific, and, on the other, the benefits they provide are not evaluated and not used in decision making, particularly in developing countries where both soil degradation and food availability are problematic.

Moreover, given the multifunctionality of natural systems, the benefits produced by a given management technique are numerous (e.g. carbon sequestration, increasing food productivity, water availability and quality, biodiversity), which raises fundamental questions about cost-effectiveness and the economic outcomes of the actions implemented. In this sense, the existence of these spontaneous and voluntary practices produces invisible benefits that public policies must consider in order to compensate farmers and encourage them to maintain these practices (El Mokaddem et al., 2014). However, these interventions are costly while the traditional agricultural systems have minimal economic incentives, which could lead to the abandonment of these management techniques in the long term.

(ii) Policies incentivizing soil-water protection and agriculture sustainability

Most current policies aiming to protect natural resources, including soils/lands, are oriented towards water and nutrient management, soil fertility management, stopping desertification and erosion control, and groundcover maintenance. These objectives are enveloped under sound policy programs such as sustainable ecologically intensive agriculture, conservation agriculture, agroforestry, rangeland management and integrated soil-water management policies. The first aim of these policies is to enhance the resilience of agricultural production systems and to sustain the productive base that soils and water provide as natural capital stocks (El Mokaddem, 2016). Subsidies are used to incentivize farmers to adhere to these policies, and in some specific countries, a new generation of policies based on payment for ecosystem services schemes have started to emerge over the last few decades. The latter is proving popular for protecting and restoring degraded land in a growing number of developed and developing countries. However, despite their popularity among decision-makers, these policies are, so far, faced with difficult and limited acceptance among farmers. They are perceived as less intensive and with low productivity. This perception, which is sometimes shared even by public decision-makers, impedes the acceptance by farmers. Moreover, farmer production decisions tend to be based on relatively short-term analyses and wrong perceptions that fail to capture the long-term impacts of soil management practices on soil natural capital and associated regulating and supporting ecosystem services that underpin crop yields (Tilman et al., 2002). This suggests that one of the key focal issues remains finding ways to enhance the acceptance of soil protection policies through science-based advocacy, which remains insufficient.

Policy options to conserve soil and soil organic carbon

For a little more than three decades, public policies have gradually begun to take an interest in preserving the natural environment and the resources with which it supports economies. As a result, the design of sustainable policies should consider the role the natural environment plays in supporting economic activity and the importance of managing natural assets to efficiently and sustainably secure long-term food security and economic prosperity.

Conservation policies suggested since the early 1990s, are based on mechanisms such as Integrated Conservation and Development Programs that focus on economic development through the engagement of local communities in environmental conservation. However, recently, an increasing interest is paid to market-based conservation mechanisms for ecosystem conservation generally and for specific ecosystem services like water and soil. In this sense, payment for ecosystem services (PES) mechanisms represents an interesting mechanism for its acceptability, popularity, and cost-effectiveness (Wegner, 2016).

This type of market-based mechanism consists of rewarding farmers for increasing soil carbon to ensure cost-effective conservation of the whole bundle of ecosystem services depends on reliable measurements of changes in soil carbon contents. The payment could also be differentiated (Núñez-Regueiro et al., 2019) to reflect potential spatial and temporal variation in the value of soil ecosystem services (e.g. nitrogen retention in regions suffering from water pollution). These payments could also be considered investment support and could decrease over time since increasing soil carbon would also increase farmers' profits.

Besides, the increase of productivity and farmers' profits is then evaluated by combining production functions - to quantify the impacts of alternative management practices on agricultural productivity and soil ecosystem services – farmers also take advantage of (financial and/or in-kind). This incentivizes them to adopt sustainable conservation practices and earn revenues equivalent to the value of the benefits "sold" on the new "market" where PES allow for evaluating changes in soil ecosystem services (fertility, SOC, soil humidity) and thus quantifying physically respective farmers' contributions (Grima et al., 2016).

Incentives based policies such as PES schemes influence farmer decision-making, impacting the relationships between agriculture, resource use, and the environment. Despite the constraints imposed on farmers to conserve soil under PES programs, mechanisms based on PES logic (PES & PES-like) are becoming increasingly popular and attractive for several reasons, including the conditionality of payments, which requires tangible and measurable ecosystem service outcomes to trigger payments, as opposed to subsidy incentives where there is no outcome requirement. The types and the characteristics of different PES schemes differ from one political and socio-economic context to another. Most of these programs are based on the simultaneous valorization of bundles of ecosystem services. The multifunctionality of natural ecosystems and the objective of maximizing the impact of investments in environmental conservation lead to a context where targeting the conservation of SOC facilitates the conservation of a series of services (e.g., soil biodiversity, soil moisture, water) that synergistically contribute to increased agricultural productivity (Deluz et al., 2020). Table

2 presents three examples of PES schemes where soil carbon is considered through different perspectives.

Table 2: Three examples of PES schemes

Policy	**Objective**	**Area**	**Investment**	**Principle**	**Institutions**
USDA voluntary incentive conservation programs	providing financial and technical assistance to support the adoption of conservation practices on US farms.	No specific limit	Nearly $6 billion annually	Provide financial assistance to farmers adopting conservation practices on land in agricultural production. The top five crop management practices (in terms of expenditures) awarded support have been conservation crop rotation, cover crops, nutrient management, terraces, and conservation tillage (residue management).	The USDA and voluntary farmers lead the program.
Sustainable rangeland investments in Jordan	Create local and societal ecosystem benefits, and contribute globally to biodiversity conservation, climate change mitigation and other goals	30% of Jordan's rangelands	20 million USD/year	Proposals have been developed for a PES services scheme comprising two service payments: (1) green pasture credit as a subsidy to herder cooperatives responsible for sustainable rangeland management and (2) green water credit for enhancing groundwater recharge. Both PES modalities could provide the financing flows needed to invest in increased biomass production and biodiversity, soil conservation, improved water flows, carbon sequestration, and required local governance structures.	Jordan's government leads the program. Rangeland protection and associated local governance mechanisms can make the program successful and sustainable.

Sustainable rangeland investments in Portugal	Soil C offset scheme that is based on dryland pasture improvement	Improve around 42,000 ha of grasslands to sequester 0.91 million tonnes of carbon dioxide equivalent	8.5 million € to pay an estimated 400 participating farmers (farmers would earn about from 150 € to 200€ per hectare of planted pastures	The farmers use legume-rich and biodiverse permanent pastures to increase C in degraded soils.	A PES could justify international financial flows from external beneficiaries to those implementers of sustainable land management practices that maintain and/or increase SOC

Conclusion

While there is a fundamental understanding of SOC dynamics and the driving factors, political and socio-economic considerations make increasing soil C stocks a complex problem. These complexities may be discouraging as they may make the task seem impossible. However, a more site- and systems-specific focus is needed to choose best-fit and cost-effective solutions for increasing SOC stocks. The key is to seek practices that creatively balance investments, livelihoods, profits and carbon stock increases or maintenance.

The literature is conclusive on the fact that there is substantial spare capacity in cropland soil to increase SOC. This capacity is generally more in croplands than in natural ecosystems and higher is some regions (i.e., Africa) than others (i.e., Europe). It is unambiguous that enhancing or maintaining SOC stocks is a win-win strategy that delivers multiple benefits at different scales including combatting climate change, preventing soil degradation, ensuring the sustainability of agriculture, enhancing biodiversity, and increasing farm productivity and profits.

Relatively straightforward and site-specific practices that can significantly enhance SOC include optimal nutrient management (mineral + organic fertilization), no tillage, cover crops, rotation with deep-rooting crops. However, within different contexts these practices inevitably have trade-offs. For example, in mixed crop-livestock smallholder systems in developing countries returning crop residues to the soil can compete with other uses such as using crop residue as animal feed or biofuel, but there is scope for synergies where the resulting manure can be applied as a soil amendment.

While the African continent is a special case, with a rapidly growing population, degraded soils, low crop productivity, the example of the Brazilian Cerrado illustrates what is possible through changes in agronomic practices e.g., liming and ferilization using phosphogypsum can increase SOC stocks in both surface and deeper soils. The needed agronomic changes can be accelerated through government policies that incentivize practices such as balanced fertilization. However, the enactment of the policies is impeded by a perception – fueled by a lack of scientific evidence – that balanced fertilization practices result in low productivity. In fact, the opposite is the case. What is needed is more research to provide policy-makers and farmers with the evidence base that will encourage them to adopt SOC-enhancing practices and to improve understanding of which practices are most effective. Current evidence is clear that, contrary to some assumptions that such practices should involve only organic or inorganic inputs, in fact site-specific nutrient management using a combination of mineral and organic fertilizers, combined with other techniques, can deliver optimal results for farmers and for food security.

References

Baker, J.M., Ochsner, T.E., Venterea, R.T., and Griffis, T.J. (2007. Tillage and soil carbon sequestration – what do we really know? Agriculture, Ecosystems and Environment 118:1–5

Bationo, A., Waswa, B., Abdou, A. et al. (2012). Overview of long-term experiments in Africa. In: Bationo, A., Waswa, B., Kihara, J., Adolwa, I., Vanlauwe, B., and Saidou, K. (Eds.). Lessons learned from Long-term Soil Fertility Management Experiments in Africa. Springer, Netherlands, pp. 1-26

Bationo, A., Fening, J. O. (2018). Soil Organic Carbon and Proper Fertilizer Recommendation, in: Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., Fening, Joseph Opoku (Eds.), Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site-Specific Fertilizer Recommendations in West Africa Agro-Ecosystems: Volume 1. Springer International Publishing, Cham, pp. 1–10. https://doi.org/10.1007/978-3-319-58789-9_1

Baveye, P. C., Schnee, L. S., Boivin, P., Laba, M., and Radulovich, R. (2020). Soil organic matter research and climate change: merely re-storing carbon versus restoring soil functions. Front. Environ. Sci. 8:579904. doi: 10.3389/fenvs.2020. 579904

Benbi, D. K., Brar, J. S. (2009) A 25-year record of carbon sequestration and soil properties in intensive agriculture. Agron Sustain Develop 29: 257-265.

Bradford, M.A., Fierer, N., Reynolds, J.F. (2008) Soil carbon stocks in experimental mesocosms are dependent on the rate of labile carbon, nitrogen and phosphorus inputs to soils. Funct Ecol 22:964–974

Brettar, I., Sanchez-Perez, J.M., Trémolières, M. (2002). Nitrate elimination by denitrification in hardwood forest soils of the Upper Rhine floodplain – Correlation with redox potential and organic matter. Hydrobiologia, 469, 11–21

Burney, J. A., Davis, S. J., Lobell D.B. (2010) Greenhouse gas mitigation by agricultural intensification. Proc Nat Acad Sci 107: 12052-12057).

Campbell, C.A., Zentner, R.P. Liang, B.C. Roloff, G., Gregorich, E.G., Blomert B. (2000) Organic C accumulation in oil over 30 years in semiarid southwestern Saskatchewan: Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80:179–192. doi:10.4141/S99-028.

Chenu, C., Denis A., Angersb, D. A., Barréc, P., Derriend, D., Arrouayse, D., Balesdent, J. (2019). Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. Soil & Tillage Research 188: 41–52.

Chirinda, N., Olesen, J.E., Porter, J.R. Schjønning, P. (2010a). Soil properties, crop production and greenhouse gas emissions from organic and inorganic fertilizer-based arable cropping systems. Agriculture, Ecosystems and Environment 139, 584–594.

Chirinda, N., Carter, M.S., Albert, K.R, Ambus, P., Olesen, J.E., Porter, J.R., Petersen, S.O. (2010b). Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types. Agriculture, Ecosystems and Environment 136, 199−208.

Chirinda, N., Olesen, J.E., Porter J.R. (2012). Root carbon input in organic and inorganic fertilizer-based systems. Plant and Soil 359, 321-333.

Corbeels, M., Cardinael, R., Naudin, K., Guibert, H., Torquebiau, E. (2019). The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil Tillage Res. 188, 16–26. https://doi.org/10.1016/j.still.2018.02.015)

Dawson, C.J., Hilton, J. (2011). Fertilizer availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. Food Policy, 36, S14-S22

De Klein, C., Novoa, R.S., Ogle, S., et al. (2006). N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. IPCC guidelines for National greenhouse gas inventories, prepared by the National greenhouse gas inventories programme, 4: 1-54.

Deluz, C., Nussbaum, M., Sauzet, et al. (2020). Evaluation of the potential for soil organic carbon content monitoring with farmers. Frontiers in Environmental Science, 8, 113.

Dijkstra, F. A., Zhu, B., & Cheng, W. (2021). Root effects on soil organic carbon: a double-edged sword. New Phytologist, 230(1), 60-65.

Dynarski, K.A., Bossio, D.A., Scow, K.M. (2020) Dynamic Stability of Soil Carbon: Reassessing the “Permanence” of Soil Carbon Sequestration. Front. Environ. Sci. 8:514701. doi: 10.3389/fenvs.2020.514701

EL Mokaddem, A., Morardet, S., Lejars, C. et al (2016). Conception d'un paiement pour services environnementaux en pâturages collectifs. Une expérimentation des choix. Économie rurale. Agricultures, alimentations, territoires, (355), 67-89.
El Mokaddem, A., Lejars, C., Doukkali, R. (2014). Adaptation et conditions de formalisation des paiements pour services environnementaux pour la conservation des pÃ¢ turages collectifs au Maroc. Revue marocaine des sciences agronomiques et vétérinaires, 2(2).
FAO, (2004). Carbon Sequestration in Dryland Soils. World Soil Resources Reports 102. Food and Agriculture Organization of the United Nations, Rome.
FAO, (2004). Carbon Sequestration in Dryland Soils. World Soil Resources Reports 102. Food and Agriculture Organization of the United Nations, Rome.
FAO, (2019). FAOSTAT Database collections. Production/Crops and Resource/Fertilizer, Rome.
Gao, B., Huang, T., Ju, X., et al. (2018). Chinese cropping systems are a net source of greenhouse gases despite soil carbon sequestration. Global Change Biology, 24: 5590-5606.
Geisseler D., Scow K.M. (2014). Long-term effects of mineral fertilizers on soil microorganisms–A review. Soil Biology and Biochemistry, 75: 54-63.
Godde, C.M., Thorburn, P.J., Biggs, J.S., Meier, E.A. (2016). Understanding the impacts of soil, climate, and farming practices on soil organic carbon sequestration: A simulation study in Australia. Front. Plant Sci. https://doi.org/10.3389/fpls.2016.00661
Grima, N., Singh, S. J., Smetschka, B., Ringhofer, L. (2016). Payment for Ecosystem Services (PES) in Latin America: Analyzing the performance of 40 case studies. Ecosystem services, 17, 24-32.
Guenet, B., Gabrielle, B., Chenu, C., et al. (2020). Can N_2O emissions offset the benefits from soil organic carbon storage? Global Change Biology. https://doi.org/10.1111/gcb.15342.
Guo, Z., Zhang, Z., Zhou, H. et al. (2019). The Effect of 34-Year Continuous Fertilization on the SOC Physical Fractions and Its Chemical Composition in a Vertisol. Scientific Reports, 9, 2505.
Han, D., Wiesmeier, M., Conant, R. T. et al. (2018). Large soil organic carbon increase due to improved agronomic management in the North China Plain from 1980s to 2010s. Global Change Biology, 24: 987-1000.
Han, P., Zhang, W., Wang, G. et al. (2016). Changes in soil organic carbon in croplands subjected to fertilizer management: a global meta-analysis. Scientific Reports, 6:27199, DOI: 10.1038/srep27199
Hijbeek, R., van Loon, M. P., van Ittersum, M. K. (2019). Fertilizer use and soil carbon sequestration: opportunities and tradeoffs. CCAFS Working Paper no. 264. Wageningen, the Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Available online at: www.ccafs.cgiar.org.)
Horwath, W. R., Kuzyakov, Y. (2018). The potential for soils to mitigate climate change through carbon sequestration. In Developments in Soil Science (Vol. 35, pp. 61-92). Elsevier.

Jackson, R.B., Lajtha, K., Crow, S.E., Hugelius, G., Kramer, M.G., Piñeiro, G. (2017). The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. Annual Review of Ecology, Evolution, and Systematics 48: 419–445.
Janzen H.H. (2006). The soil carbon dilemma: Shall we hoard it or use it? Soil Biology & Biochemistry 38, 419–424
Janzen, H.H. (2004). Carbon cycling in earth systems—a soil science perspective. Agriculture Ecosystems & Environment 104, 399–417.
Jha, P., Hati, K. M., Dalal, R. C., et al. (2020). Soil carbon and nitrogen dynamics in a Vertisol following 50 years of no-tillage, crop stubble retention and nitrogen fertilization. Geoderma 358 (2020) 113996 https://doi.org/10.1016/j.geoderma.2019.113996)
Kihara, J., Nziguheba, G., Zingore, S., et al. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agriculture, Ecosystems and Environment 229, 1-12.
Kirschbaum, M. U. F. (2000). Will changes in soil organic carbon act as a positive or negative feedback on global warming? Biogeochemistry 48, 21–51. doi:10.1023/A:1006238902976.
Korschens, M., Weiger, A., and Shulz, E. (1998). Turn over of SOM and long-term balances-tools for evaluating sustainable productivity of soils. ZPflanzenernahr Bodenk, 161, 409-424. http://dx.doi.org/10.1002/jpln.1998.3581610409.
Laban, P., Metternicht, G., Davies, J. (2018). Soil Biodiversity and Soil Organic Carbon: keeping drylands alive. Gland, Switzerland: IUCN. viii + 24p
Ladha, J. K., Reddy, C. K., Padre, A. T. and van Kessel, C. (2011). Role of Nitrogen Fertilization in Sustaining Organic Matter in Cultivated Soils. Journal of Environmental Quality, 40, 1756-1766.
Lal, R. (2002). Soil carbon dynamics in cropland and rangeland. Environmental Pollution,116(3), 353-362. doi: 10.1016/s0269-7491(01)00211-1
Lal, R. (2003). Global potential of soil carbon sequestration to mitigate the greenhouse effect. Critical Reviews in Plant Science 22, 151–184
Lal, R. (2016). Soil health and carbon management. Food Energy Security 5, 212–222. doi: 10.1002/fes3.96
Lal, R. (2018). Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology, 24(8), 3285-3301.
Lal, R. (2019a). Eco-intensification through soil carbon sequestration: Harnessing ecosystem services and advancing sustainable development goals. Journal of Soil and Water Conservation, 74(3), 55A-61A.
Lal, R. (2019b). Promoting "4 Per Thousand" and "Adapting African Agriculture" by south-south cooperation: Conservation agriculture and sustainable intensification. Soil and Tillage Research, 188, 27-34
Lal, R., Smith, P., Jungkunst, H. F., et al (2018). The carbon sequestration potential of terrestrial ecosystems. Journal of Soil and Water Conservation, 73(6), 145A-152A.

Li, C., Frolking, S., Butterbach-Bahl, K. (2005). Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. Climatic Change, 72, 321–338. https://doi.org/10.1007/s10584-005-6791-5

Liang, F., Li, J., Yang, X. et al. (2016). Three-decade long fertilization-induced soil organic carbon sequestration depends on edaphic characteristics in six typical croplands. Sci Rep 6, 30350 (2016). https://doi.org/10.1038/srep30350

Lu, F., Wang X.K., Han, B., Ouyang, Z.Y., Zheng, H. (2010). Straw return to the paddy field: soil carbon sequestration and increased methane emission. Chin J Appl Ecol 21:99–108 (in Chinese)

Ma, Q., Watanabe, T., Zheng, J. et al. (2021). Interactive effects of crop residue quality and nitrogen fertilization on soil organic carbon priming in agricultural soils. J Soils Sediments 21, 83–95. https://doi.org/10.1007/s11368-020-02797-8.

Majumder, B., Mandal, B., Bandyopadhyay, P.K., et al. (2008). Organic amendments influence soil organic carbon pools and rice-wheat productivity. Soil Science Society of America Journal 72, 775-785.

Mandal, B., Majumder, B., Bandyopadhyay, P. K., et al. (2007). The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. Global Change Biology 13, 1–13, doi: 10.1111/j.1365-2486.2006.01309.x)

Metay, A., Mary, B., Arrouays, D., Martin, M.P., et al. (2009). Effets des techniques culturales sans labour (TCSL) sur le stockage de carbone dans le sol en contexte climatique tempéré. Canadian Journal of Soil Science 89 (5), 623-634

Minsany, B., Malone, B. P., McBratney, A. B., et al. (2017). Soil carbon 4 per mille. Geoderma, 292, 59–86.

Mitchell, J.P., Singh, P.N., Wallender, W.W., et al (2012). No-tillage and high-residue practices reduce soil water evaporation. California Agriculture 66, 55-61.

Mazzoncini, M., Sapkota, T. B., Barberi, P., Antichi, D., Risaliti, R. (2011). Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil Tillage Research 114, 165–174.

Mustafa, A., Hu, X., Abrar, M. M., et al. (2021). Long-term fertilization enhanced carbon mineralization and maize biomass through physical protection of organic carbon in fractions under continuous maize cropping. Applied Soil Ecology 165 103971. https://doi.org/10.1016/j.apsoil.2021.103971

Núñez-Regueiro, M. M., Fletcher Jr, R. J., Pienaar, E. F., et al. (2019). Adding the temporal dimension to spatial patterns of payment for ecosystem services enrollment. Ecosystem Services, 36, 100906.

Ortas, I., Bykova, A., (2020) Effects of long-term phosphorus fertilizer applications on soil carbon and CO2 flux. Communications in Soil Science and Plant Analysis, 51:17, 2270-2279, DOI: 10.1080/00103624.2020.1822381

Pan, J., Zhang, L., He, X., Chen, X. and Cui, Z. (2019). Long-term optimization of crop yield while concurrently improving soil quality. Land Degrad Dev. 1–13. DOI: 10.1002/ldr.3276

Parihar, C.M., Jat, S.L., Singh, A.K., et al. (2017). Bio-energy, water-use efficiency and economics of maize-wheat-mungbean system under precision-conservation agriculture in semiarid agroecosystems. Energy 119, 245 – 256.

Parihar, C.M., Singh, A.K., Jat, S.L., et al. (2020). Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system. Soil & Tillage Research 202 (2020) 104653. https://doi.org/10.1016/j.still.2020.104653

Paustian, K., Cole, C.V., Sauerbeck, D., Sampson, N. (1998). CO_2 mitigation by agriculture: an overview. Climatic Change 40, 135–162.

Paustian, K., Lehmann, J., Ogle, S., et al. (2016). Climate-Smart Soils. Nature, 532, 49–57, doi:10.1038/nature17174.

Peixoto, L., Elsgaard, L., Rasmussen, J., et al. (2020). Decreased rhizodeposition, but increased microbial carbon stabilization with soil depth down to 3.6 m. Soil Biology and Biochemistry, 150.

Poeplau, C., Bolinder, M.A., Eriksson, J., Lundblad, M., Kätterer, T. (2015). Positive Trends in Organic Carbon Storage in Swedish Agricultural Soils Due to Unexpected Socio-Economic Drivers. Biogeosciences 12, 3241–3251, doi:10.5194/bg-12-3241-2015.

Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G. (1982). Soil carbon pools and world life zones. Nature 298, 156–159.

Qaswar, M., Jing, H., Ahmed, W., et al. (2020). Yield sustainability, soil organic carbon sequestration and nutrients balance under long-term combined application of manure and inorganic fertilizers in acidic paddy soil. Soil and Tillage Research, 198, 104569.

Rasse, D.P., Rumpel, C., Dignac, M.F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil 269: 341–356.

Ren, W., Banger, K., Tao, B., Yang, J., Huang, Y., Tian, H. (2020). Global pattern and change of cropland soil organic carbon during 1901-2010: roles of climate, atmospheric chemistry, land use and management. Geography and Sustainability, 1(1), 59-69.

Sanderman, J., Farquharson, R., Baldock, J. (2010). Soil Carbon Sequestration Potential: A Review for Australian Agriculture. A report prepared for the Department of Climate Change and Energy Efficiency CSIRO National Research Flagships.

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., et al. (2011). Persistence of soil organic matter as an ecosystem property. Nature 478, 49–56. doi:10.1038/nature10386.

Six J., Conant R.T., Paul E.A., Paustian K. (2002). Stabilization mechanisms of soil organic matter: implications for C saturation of soils. Plant Soil 241:155–176

Sokol, N.W., Kuebbing, S.E., Karlsen-Ayala, E., Bradford, M.A. (2019). Evidence for the Primacy of Living Root Inputs, Not Root or Shoot Litter, in Forming Soil Organic Carbon. New Phytol. 221, 233–246, doi:10.1111/nph.15361.

Stewart, C.E., Paustian, K., Conant, R.T. et al. (2007). Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry 86, 19–31 https://doi.org/10.1007/s10533-007-9140-0

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., et al. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99. 10.1016/j.agee.2012.10.001.

Teluguntla, P. G., Thenkabail, P. S., Xiong, J. N., Gumma, M. K., Giri, C., Milesi, C., et al. (2015). Global Cropland Area Database (GCAD) derived from remote sensing in support of food security in the twenty-first century: Current achievements and future possibilities. In P. S. Thenkabail (Ed.), Remote sensing handbook. Volume II, Land resources monitoring, modeling, and mapping with remote sensing (Chap. 7, p. 849), Chapter 7. Boca Raton: CRC Press.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., Polasky, S. (2002). Agricultural sustainability and intensive production practices. Nature, 418(6898), 671-677.

Tiefenbacher, A., Sandén, T., Haslmayr, H. P., Miloczki, J., Wenzel, W., & Spiegel, H. (2021). Optimizing Carbon Sequestration in Croplands: A Synthesis. Agronomy, 11(5), 882

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture, Ecosystems and Environment 110, 166-184

van Groenigen, K.-J., Six, J., Hungate, B. A., de Graaff, M.-A., van Breemen, N., van Kessel, C. (2006). Element interactions limit soil carbon storage. Proc. Natl. Acad. Sci. U.S.A. 103, 6571–6574. doi: 10.1073/pnas.0509038103.

van Groenigen, K.-J., van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S., van Groenigen, K.J. (2017). Sequestering soil organic carbon: a nitrogen dilemma. Environmental Science & Technology 51, 4738-4739.

VandenBygaart, A.J., McConkey, B.G., Angers, D.A., Smith, W., De Gooijer, H., Bentham, M., Martin, T. (2008). Soil carbon change factors for the Canadian agriculture national greenhouse gas inventory. Canadian Journal of Soil Science 88, 671-680.

Wang, C.J., Pan, G.X., Tian, YG, Li, L.Q., Zhang, X.H., Han, X.J. (2010). Changes in cropland topsoil organic carbon with different fertilizations under long-term agroecosystem experiments across mainland China. Science China Life Sciences 53, 858-867.

Wang, G., Luo, Z., Han, P., Chen, H. and Xu, J. (2016). Critical carbon input to maintain current soil organic carbon stocks in global wheat systems. Scientific Reports, 6:19327, DOI: 10.1038/srep19327)

Wegner, G. I. (2016). Payments for ecosystem services (PES): a flexible, participatory, and integrated approach for improved conservation and equity outcomes. Environment, Development and Sustainability, 18(3), 617-644.

Whiting, G.J., Chanton, J.P. (2001) Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration, Tellus B: Chemical and Physical Meteorology, 53:5, 521-528, DOI: 10.3402/tellusb.v53i5.16628

Wieder, W. R., Cleveland, C. C., Smith, W. K., Todd-Brown, K. (2015). Future productivity and carbon storage limited by terrestrial nutrient availability. Nat. Geosci. 8, 441–444. doi: 10.1038/ngeo2413.

Xu, L., Baldocchi, D.D., Tang, J. (2004), How soil moisture, rain pulses, and growth alter the response of ecosystem respiration to temperature, Global Biogeochem. Cycles, 18, GB4002, doi:10.1029/2004GB002281

Zhao, H., Sun, B., Lu, F., Wang, X., Zhuang, T., Zhang, G. and Ouyang, Z. (2017). Roles of nitrogen, phosphorus, and potassium fertilizers in carbon sequestration in a Chinese agricultural Ecosystem. Climatic Change DOI 10.1007/s10584-017-1976-2.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E. (2007). Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. F. Crop. Res. 101, 296–305. https://doi.org/10.1016/j.fcr.2006.12.006

Zomer, R. J., Bossio, D. A., Sommer, R., Verchot, L. V. (2017). Global sequestration potential of increased organic carbon in cropland soils. Scientific Reports 7, 1–8. doi: 10.1038/s41598-017-15794-8