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Editorial

Managing Soil Organic Carbon for Mitigating Climate Change and Increasing Food Security

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Abstract: This Special Issue contains articles presenting advances in soil organic carbon (SOC) sequestration practices, considering their benefits, trade-offs and monitoring. The studies deal with (1) agricultural practices and climate change, (2) the effect of organic matter amendments, and (3) the development of monitoring, reporting and verification (MRV) strategies. It is concluded that region-specific approaches are required for the implementation and monitoring of SOC sequestering practices.

Keywords: soil organic carbon sequestration; sustainability; MRV strategies; organic amendments

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1. Introduction

To prevent food shortages, agricultural production was intensified after 1961, during the green revolution [1]. This intensification had a very positive effect, as human losses due to famine were prevented. However, it also has had many negative effects on the environment through the externalities from agriculture, including greenhouse gas emissions, declining biodiversity and the pollution of waterways. Food prices decreased, and so did the farmers' income and the quality of human diets [2]. In order to stay in a safe work space for humankind and provide nutritious, healthy food and other raw materials for a growing world population, agricultural practices need to be revised to make agricultural production sustainable [3]. It has been suggested that carbon sequestration in soils could play a key role in this process, due to its multiple roles in the ecosystem services provided by agricultural systems [4]. Indeed, soil organic matter is the biggest terrestrial carbon reservoir, and small changes in soil carbon may have the potential to impact atmospheric CO_2 concentrations [5]. Therefore, it has been suggested that soil organic carbon (SOC) increases from the use of sustainable agricultural practices could be a solution to mitigate climate change while resolving broader societal problems [6]. Indeed, agricultural soils are impoverished in SOC; they have lost 116 Gt of SOC since agriculture began [7]. This has important consequences for soil properties and the provision of ecosystem services derived from soil: SOC-depleted soils are characterized by their low available nutrient contents and high erosion rates due to poor aggregation and structure, leading to compaction. Moreover, they contain few soil organisms and have low water infiltration and storage abilities. The restoration of these soil functions is possible, and (agroecological) practices leading to the recarbonization of SOC-depleted agricultural soils are known [8]. They rely on increasing organic matter inputs and/or reducing SOC loss through minimal soil disturbance. Applying these practices to already existing agricultural land may also increase food security by providing more fertile soils and resistance to climate change [9]. Indeed, recent studies indicated that increasing SOC stocks could increase yields and reduce yield variability [10], and also drought-related yield gaps [11]. On the other hand, intensification without increasing sustainability may have contrasting effects.

However, to have a global impact in terms of climate change mitigation, adaptation and food security, the implementation of sustainable practices must be employed at scale by millions of farmers in contrasting regions of the world [12]. To facilitate the transition of agriculture towards sustainable soil use and change the farmers' role in the climate change debate, the 4p1000 initiative (www.4p1000.org) was launched in 2015. This policy initiative aims towards sustainable changes in agricultural production systems in order to increase soil carbon sequestration, with three objectives: (1) climate change mitigation, (2) climate change adaptation, and (3) food security. Although increasing SOC is generally seen as a win–win strategy [13,14], it may have trade-offs in terms of the nutrients, water and investments required to implement sustainable agricultural practices [15]. To implement sustainable SOC sequestering practices, and to develop (financial) tools that will encourage the agroecological transition, it is crucial to take its benefits and trade-offs into consideration, and to develop monitoring strategies that can assess the resulting changes in terms of SOC gains and/or greenhouse gaz release [16]. Moreover, collaboration between multiple stakeholders and policy-makers from the climate and the agricultural sectors are needed to elaborate region-specific policies, allowing for the upscaling of SOC sequestration as a global (mitigation) strategy [12,17].

2. Special Issue Overview

In this Special Issue (SI), we invited contributions dealing with sustainable agricultural practices and their effects on soil organic matter quantity and quality, addressing their link with climate change and food security. The SI comprises 13 papers from contrasting regions of the world dealing with the assessment of (1) the effects of climate change and agricultural practices on agricultural production, SOC, and farmers' income, (2) the consequences of increasing organic matter inputs in different agricultural systems, and (3) monitoring SOC changes in response to management.

2.1. Effect of Climate Change and Agricultural Practices

The expected impacts of climate change on agriculture are significant in terms of the increased risk and vulnerability of agricultural systems to rainfall variability and extreme climatic events. The adaptation of agriculture to the changing climate conditions and adoption of (innovative) sustainable practices will be necessary to reduce the negative consequences, such as reduced yields and crop failure. In this context, Drebenstedt et al. [18] assessed changes in soil temperature and precipitation patterns on crop production in agricultural systems in Germany. Their results showed that oilseed rape performed well under moderate changes in soil temperature and rainfall regimes; hence, stable seed yields were observed, with no negative impact on seed nutrient quality. Wei et al. [19] carried out a comparative study of rotation patterns on SOC in China's arid and semi-arid regions. They found that rotation practices of lentil–wheat–corn and corn–pea are the most appropriate models for optimizing simultaneous economic and ecological development, including water conservation and SOC sequestration. Dai et al. [20] investigated tillage practice impacts on the SOC sequestration potential of topsoil microbial communities in China. They observed that specific tillage practices altered the composition of soil microbial communities and the functions related to SOC cycling. Notably, deep tillage treatment increased the relative abundance of genes involved in carbohydrate transport and metabolism. Therefore, it may increase the potential of straw-C transformation to SOC in the North China Plain, where large amounts of wheat and corn straw are returned to the field each year. Finally, the paper by Prokopyeva et al. [21] predicted the effect of crop rotation and cultivation history on SOC sequestration in soils of two experimental fields in the Moscow region in Russia. Their findings showed that there is a large uncertainty in the estimation of C inputs related to the long-term effects of land-use history. The non-Chernozem zone may have the greatest potential for SOC sequestration in arable soils under future climate conditions.

2.2. Organic Inputs

The quantity and quality of organic inputs have an important role to play in SOC accumulation and dynamics. For instance, studies suggested that C input from roots and manures have a greater impact on SOC stocks than C input from straw [22]. Root carbon may contribute more to stable SOC as compared to shoot carbon [23]. While increased organic input generally increases SOC stocks in the topsoil [24], SOC loss may occur in subsoils under long-term compost amendments [25]. Innovative organic amendments and smart fertilization strategies may be suitable to increase sustainability through their effect on physical properties, biogeochemical cycling and SOC storage in agricultural soils [26–28]. In this sense, Meena et al. [29] analysed the effect of rice residue retention and the foliar application of K on water productivity and the profitability of wheat in Northwest India. The authors showed that residue retention increased water use efficiency, especially under conditions of limited water availability, leading to higher yields. The use of residue retention in rice and wheat areas has the potential to significantly reduce environmental degradation compared to their burning. Wang et al. [30] carried out a meta-analysis to evaluate the effects of residue return on the SOC storage and sequestration rate in China's croplands. Their analyses indicated that improved management practices can increase the SOC sequestration capacity. Different residue return methods, including residue chopping, evenly incorporating, and burying combined with a low rate of nitrogen fertilizer application were all recommended to improve SOC storage. Overall, long-term residue retention can be used as an effective and climate-smart practice. Barlog et al. [31] assessed the effect of digestate on SOC and plant-available nutrient content compared to cattle slurry and mineral fertilization in an Ortic Luvisol in the Czech Republic. They reported that the short-term use of digestate, cattle manure and straw significantly altered the soil's content of plant-available P and K, as well as mineral N. In contrast, the four-year study showed no effect on the SOC and TN contents compared to mineral NPK fertilization. Koishi et al. [32] investigated the long-term effect of different organic amendments on soil organic matter quantity and quality in conventional cropping systems in Switzerland. Their results demonstrated a close relationship between the biological reactivity, the distribution of SOC in soil particle-size fractions and, potentially, long-term sequestration trends. It seems that animal manure is more appropriate than green manure and straw amendments for increasing C retention, due to its high nutrient availability. Finally, Doan et al. [33] studied the short-term effects of biochar, compost and their mixture on the parameters of tropical agricultural soils and yield in three countries in Southeast Asia. The authors' results indicated that biomass and maize cob yields are highly dependent on the pedoclimatic conditions in the three Southeast Asian countries, despite the similar use of mineral fertilizers and irrigation. While the positive effects of organic amendments on biomass production and/or yield in a tropical context have often been reported, the authors' conclusion is that these effects were not as large as expected.

2.3. Monitoring

To characterize and monitor the spatial variability in SOC content and stocks, large sample sets are required. The availability of bulk density data, as well as the volumes of coarse material, are crucial for determining SOC stocks, while the acquisition of both parameters remains a challenge [34]. In situations where the stoniness and spatial variability of soil bulk density are low, infrared spectroscopy can sometimes directly predict SOC stocks at the plot scale [35]. The spatial monitoring of C balances [36], SOC contents of surface soil (e.g., [37,38]), or mapping of disturbances and land-use/land-cover changes [39], can be carried out also via remote sensing images. The potential of new space missions such as Sentinel-2 needs to be further explored for large-scale SOC monitoring. Whichever approach is taken to monitor SOC stocks, an interaction between laboratory analysis, field measurements and upscaling using satellite remote-sensing is thought to be the most effective and should be evaluated [40]. In addition, simple approximations of SOC sequestration, by farmers' assessment or through routine analysis by extension services, will raise awareness of SOC dynamics and contribute to the identification of the most promising areas for sequestration. In this context, it is necessary to take all the components of the system into account, to bring together several disciplines and to consider various temporal and spatial scales. It is also necessary to consider the pedoclimatic context, the land-use history of the soil and the socio-economic and political conditions, at present and in the future. For SOC storage in soils, and especially in the long term, residence times and location (deep or superficial horizons; landscape location) must be taken into account. It is also necessary to identify the spatial and temporal scale of its evaluation (local versus global; year versus decades or even centuries) and to assess trade-offs in terms of other greenhouse gas emissions.

Four papers address the SOC-monitoring aspects discussed above. Novara et al. [41] provided a vineyard carbon budget (vCB) tool for the assessment of sustainable vineyard management in terms of GHG emissions and SOC storage in Spain. The small amount of data requested allowed for the application of the vCB tool to the territory. This application highlighted the environmental variability of CO_2 emission, considering constant soil management; it could, therefore, be useful to modulate vineyard management protocols or incentives according to the environmental characteristics of the farm. Creme et al. [42] assessed SOC stock changes in grassland soils under different management at multiple spatial scales in western France. They showed, at the plot scale, that the introduction of mown grassland during cropping resulted in SOC maintenance, irrespective of its management. At larger spatial scales, the results were different, as areas of carbon gain and loss appeared for most treatments at a scale of several ha. These contrasting patterns within a treatment were related to the soil characteristics. For a detailed comprehension of the SOC changes, the authors recommended a combination of measurements at different scales. Squire et al. [43] defined targets for reversing declines in SOC in high-intensity arable cropping systems in the European Atlantic zone. The authors indicated that an achievable SOC target of slightly above 3% was defined for high-intensity sites. There is an unexpected biophysical barrier to increasing SOC above 3% in the high-input areas. The authors argued against considering the cultivated land as uniform: assessment and remediation must be implemented at the field scale. Finally, Yang et al. [44] used a grid sampling approach to assess the magnitude of SOC variability and determined the current SOC stocks in three typical agricultural fields in Maryland, United States. The low variability (~10% coefficient of variation) of SOC stocks across eight sampling grids in each field suggested that resampling these grids in three-to-five-year intervals would allow for the tracking of SOC stock changes and other parameters related to soil health.

3. Conclusions

The significance of building and maintaining SOC contents and stocks for soil health and CO_2 mitigation is of growing interest to a wide audience, including policy makers, NGOs and land managers. Any approach to promoting SOC sequestration practices in managed soils must include reliable, accurate and cost-effective means to quantify changes in SOC stocks and to predict SOC responses to different management, climatic and edaphic conditions. In this context, this Special Issue has brought together research addressing different aspects related to agricultural practices and MRV approaches, aiming to increase and evaluate SOC sequestration and its trade-offs under climate change. The results of the studies showed that crop rotations, tillage regimes and organic inputs, as well as MRV approaches, are most efficient when they are adapted to region and/or site-specific conditions.

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