Fertiliser use and soil carbon sequestration: trade-offs and opportunities

Working Paper No. 264

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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Photos:

Abstract

Current initiatives to store carbon in soils as a measure to mitigate climate change are gaining momentum. Agriculture plays an important role in soil carbon initiatives, as almost 40% of the world's soils are currently used as cropland and grassland. Thus, a major research and policy question is how different agricultural management practices affect soil carbon sequestration. This working paper focuses on the impact of mineral fertiliser use on soil carbon sequestration, including synergies with the use of organic inputs (for example crop residues, animal manure) and trade-offs with greenhouse gas (GHG) emissions. Findings from scientific literature show that fertiliser use contributes to soil carbon sequestration in agriculture by increasing biomass production and by improving carbon:nitrogen (C:N) ratios of residues returned to the field. The use of mineral fertiliser can also support the maintenance of carbon stocks in non-agricultural land if improved fertility on agricultural land reduces demand for land conversion. Combining organic inputs with mineral fertiliser seems most promising to sequester carbon in agricultural soils. Increasing nutrient inputs (either organic or mineral fertilisers) may however lead to trade-offs with GHG emissions such as N_2O. Improving the agronomic nitrogen use efficiency of nutrient inputs (i.e., additional grain yield per kg N applied) can alleviate this trade-off. While soil carbon sequestration can benefit soil fertility under some conditions and compensate for some GHG emissions related to agriculture (first assessments indicate up to 25% of the emissions related to crop production, depending on region and cropping system), it seems unlikely it can compensate for GHG emissions from other economic sectors. If soil carbon sequestration is a policy objective, priorities should be areas with higher storage potential (wetter and colder climates) and/or regions where synergies with soil fertility and food security are likely to occur (for example farming systems in tropical regions, on sandy soils and/or when cultivating more specialized crops). However, regions with the highest storage potential most likely do not overlap with regions where the largest benefits for soil fertility and food security occur.

Keywords

Mineral fertiliser; Organic inputs; Soil carbon sequestration; N_2O emissions

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Contents

Introduction

Historical context of soil carbon sequestration as a policy objective

Since the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988, soil carbon sequestration in agriculture and nature has been included under climate change mitigation. In the first IPCC assessment report (Melillo et al. 1990), scientists did not think that soil carbon could be sequestered in agriculture through human intervention, and soil carbon sequestration therefore was not listed as a potential measure. Rather, it was considered a positive unintended effect of the increased use of mineral fertilisers in the Northern hemisphere. This was summarized as: “this increased nitrogen availability may result in net carbon storage in plants and soils” (Melillo et al. 1990).

This view changed by 1992, when an assessment of the potential of different management options to increase soil carbon in agricultural soils was proposed, to include reduced or no-till practices, cover crops, green manures and animal manure, and reducing fallow land (Barnwell et al. 1992). Soon after, it was understood that storing carbon in soils is only a temporary measure for mitigating climate change, as there are limits to how much carbon can be stored in soils, and that the change in management needs to be permanent in order not to reverse the carbon flux (Ingram and Fernandes 2001). Rattan Lal (2001) explained the role of soil carbon sequestration in climate change mitigation in a keynote speech in the same year: “The potential of C sequestration… is finite and can be filled within 25 to 50 years. The long-term solution to the risk of potential global warming lies in finding alternatives to fossil fuel. Therefore, the strategy of soil C sequestration is a bridge to the future”.

Soil carbon and soil fertility

Organic carbon in soils is the main element of soil organic matter (SOM); thus, increasing soil carbon is equivalent to increasing SOM. SOM is composed of plant, microbial and animal debris in various stages of decomposition and includes the living organisms in the soil (Oades 1988). SOM is an important indicator of soil fertility, as it improves soil structure and nutrient supply for crop growth. The specific contribution of SOM to crop growth depends on the farming system (van Noordwijk et al. 1997). In general, crops cultivated in more intensively managed farming systems (with more use of fertiliser, irrigation and tillage options) depend less on SOM for soil fertility. Yet, even intensively managed farming systems can benefit from adding organic matter inputs, especially on sandy soils or when cultivating specialized crops such as potatoes or sugar beets (Hijbeek et al. 2017).

Extensive soil analyses of long-term arable farming across five Canadian Prairie sites showed that "…management for optimum soil fertility may not produce the highest C sequestration" (Paul et al. 2004). A study in the Midwest United States, however, showed that most soil carbon was gained at agronomic nitrogen rates optimal for yields (Poffenbarger et al. 2017). These contrasting findings indicate that in some cases farmers might need financial support to increase soil carbon stocks as synergies between soil fertility and soil carbon sequestration do not always occur. In the tropics, there might be relatively more soil fertility and yield benefits from increasing SOM (Vanlauwe et al. 2011, Hijbeek et al. 2018). However, in the tropics, higher temperature leads to faster decomposition of SOM, thereby reducing the potential for carbon sequestration and limiting the scope of this win-win situation.

Objective of this paper

Despite the stated limitations, efforts to store carbon in agricultural soils can contribute to climate change mitigation, especially in situations with 1) high potential for storage (for example colder and wetter climates); 2) soils with high risks of losing much carbon (for example peat soils); and 3) cases in which increased carbon sequestration are tied with improving soil fertility. Different management practices can be used to sequester carbon in agricultural soils, including cultivating green manures, reducing fallow land or following reduced or no-tillage regimes, although the effects of the latter remain unclear (Baker et al. 2007, Luo et al. 2010).

In this review, we focus on examining the effect of mineral fertiliser use on soil carbon sequestration in agriculture. We examine potential relations between fertiliser use and climate change mitigation in Section 2; the effect of mineral fertiliser use on soil carbon sequestration in Section 3; trade-offs with GHG emissions in Section 4; and conclusions, limitations and opportunities in Section 5.

Relations between fertiliser use and climate change mitigation

At first sight, one might think that the more mineral fertiliser is used, the higher the GHG emissions will be, as each kg of nitrogen (N) applied results in an estimated 0.01 kg of direct N_2O emissions (De Klein et al. 2006), although exact magnitudes of N_2O emissions can vary widely by location (Rochette et al. 2008). In addition, each kg of fertiliser produced causes CO_2 emissions, depending on the production process. Estimated rates are 0.8-1.3 kg CO_2 emissions per kg NPK in Europe and 0.9-3.0 kg CO_2 emissions per kg urea in China (Zhang et al. 2013, Stork and Bourgault 2015). These processes have been well documented, and related emission factors are included in IPCC reporting guidelines (Eggleston et al. 2006) and are under review.

Focus on these emission factors has led some to argue in favour of agricultural systems without mineral fertilisers, such as regenerative agriculture (Hawken 2017). Regenerative agriculture aims to sustain soil health by using a combination of no tillage, diverse cover crops, multiple crop rotations and in-farm fertility (in which no nutrients are imported from outside of the farm). While some aspects of regenerative agriculture (such as diverse cover crops and multiple crop rotations) can increase soil carbon and benefit crop yields under specific conditions - especially true for places with degraded soils - crops still need nutrient inputs to sustain yields.

In agriculture, there is an inherent loss of nutrients from a farm or field by both exporting the edible part or other products from the field and leaching and gaseous emissions. This loss needs to be replaced if yields are to be maintained and soil mining to be prevented. Mineral fertilisers can replace these exported or lost nutrients. Without the use of mineral fertiliser, there would not be sufficient nutrients globally to meet current and growing food demands (Dawson and Hilton 2011), especially considering current production and distribution systems and without full recycling of nutrients from waste streams. In addition, supplying nutrients by other means than mineral fertilisers does not necessarily result in less GHG emissions. For example, direct N_2O emissions from animal manure are similar to mineral fertiliser per kg of N applied (De Klein et al. 2006).

To avoid mining of soil nutrients, nutrients lost during fertilizer application or exported from the field as produce need to be replaced with either mineral and/or organic fertiliser. Ten

Berge et al. (2019) defined the minimum amount of nutrients needed to meet a certain target yield to minimize losses as much as possible. Estimates for sub-Saharan Africa can be found at www.yieldgap.org. Assuming a certain food demand, applying less than the optimal amount of nutrients may result in either farmers expanding agricultural area to meet food demands or increasing food insecurity. Neither is a desirable alternative.

The discussion above shows that from a systems perspective, the relation between fertiliser use and climate change is more complex than only the emission factors related to production and application. Reducing production or application of fertiliser might seem a logical way to decrease GHG emissions, but if yields decrease as a result then such reductions may have unintended and undesirable consequences including deforestation or food insecurity (Burney et al. 2010). On the contrary, when use of mineral fertilisers leads to increased yields, more biomass becomes available to increase carbon in agricultural soils (Han et al. 2018). As described here, indirect effects of fertiliser use include positive effects on carbon stored in soils, forests and grasslands either through increased productivity or avoided area expansion.

Figure 1 displays the different relations between mineral fertiliser use and climate change mitigation and highlights uncertainties and feedbacks. Arrows 1 and 2 indicate CO_2 and N_2O emissions related to mineral fertiliser production and application. Arrow 3 indicates increases in yields due to nutrient supply from either mineral fertilisers or organic inputs. This is simplified, as in practice different types of mineral fertilisers (urea, NPK) will have different yield effects. Similarly, a range of organic inputs exist, some relatively nutrient-rich (manures or slurries) and others relatively carbon-rich (compost) with differing effects on crop yields and soil carbon sequestration.

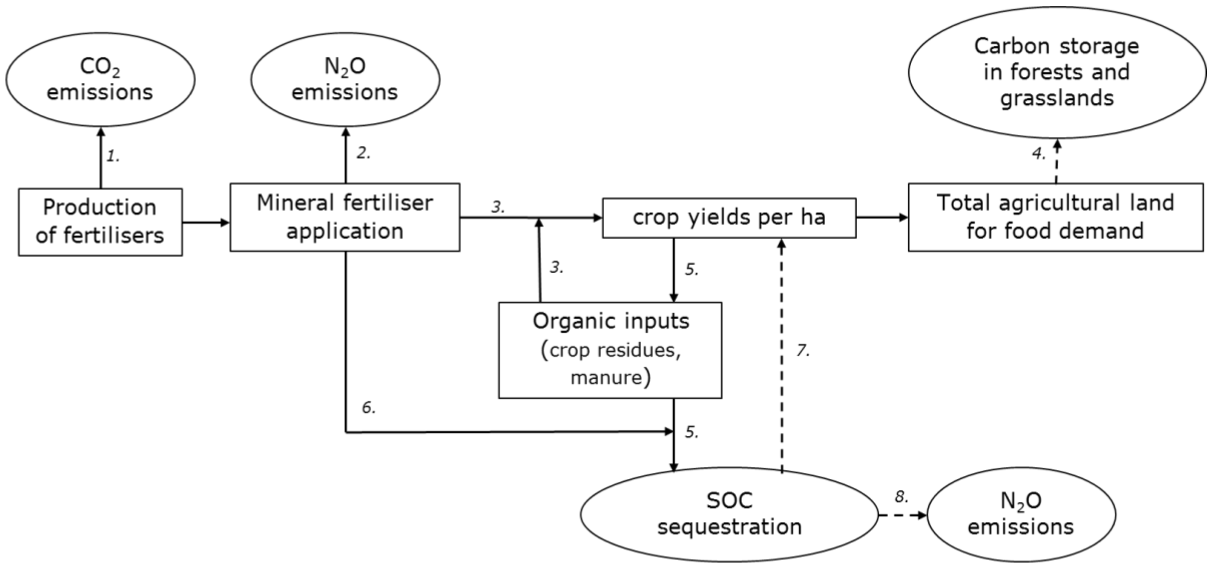

Figure 1. Simplified diagram showing the different relations between mineral fertiliser use and climate change mitigation. Solid lines indicate effects with high certainty. Dashed lines indicate indirect effects with less certainty that require more research.

1. **Energy requirements**
2. **Losses during application**
3. **Nutrient supply**
4. **Potentially less agricultural land expansion**
5. **Increased availability of biomass**
6. **Improving C:N ratios**
7. **Potentially increased nutrient use efficiency or increased attainable yields (additional yield effects)**
8. **Potentially more decomposition**

Considering equal demands for agricultural produce (food as well as feed, fibre and fuels), increased yields can lead to less expansion of agricultural land into forest or savannah areas (arrow 4). This relation is uncertain and difficult to quantify, as it depends on enforcement of policies prohibiting or controlling deforestation when agriculture intensifies. In 2007, global forests stored approximately 479 + 37 Pg C in above- and below-ground biomass, litter and deadwood (Pan et al. 2011). In addition, forest soils contained about 383 ± 30 Pg C in the upper meter of soil (id), which could partially be lost if converted to agriculture. In total, the carbon stored in forests (862 Pg C) in 2011 was similar to the total carbon in the atmosphere (829 Pg C) (Ciais et al. 2013).

Increased yields lead to increased availability of biomass, which can be returned to the field and – with the appropriate C:N ratios – sequester carbon in soils (arrows 5 and 6). Increasing soil carbon in agricultural soils may create a positive feedback loop with yields in cases where nutrient use efficiency or attainable yields are increased (arrow 7). However, increasing soil carbon may also lead to increases in (indirect) N_2O emissions in the long-term (arrow 8), as each year more SOM decomposes, and associated nutrients released are not necessarily taken up by the crop.

Increasing the agronomic nutrient use efficiency from either mineral or organic fertilisers (defined as the kg additional yield per kg nutrient applied) is central to climate change mitigation, as it means fewer nutrient losses and thus less N_2O emissions (Powlson et al. 2018). Especially under tropical conditions, the agronomic nitrogen use efficiency of mineral fertilisers can be increased when applied in combination with organic fertilisers, such as farmyard manure (Vanlauwe et al. 2011). Agronomic nitrogen use efficiency can also be increased through improved agronomic management practices such as weed and pest control, using lime on acid soils, optimizing rate, timing and placement of fertilisers or using nitrification inhibitors.

While the magnitude and processes of relations 1 and 2 (GHG emissions from production and application of mineral fertilizer) are relatively well-known, the magnitudes and processes involved in relations 3 to 8 are less well understood. In the following section, the existing scientific literature is reviewed to gain insight into the relationship between mineral fertiliser use and soil carbon sequestration.

Mineral fertiliser use and soil carbon sequestration

The stock of carbon in a given soil depends on 1) the annual amount of carbon inputs (biomass added to the soil each year) together with the rate at which the carbon inputs are transformed into SOM (composition rate) and 2) the amount of SOM which is decomposed each year (decomposition rates). Composition and decomposition rates mainly depend on biophysical factors (soil texture, climate), while 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, fertiliser use). Colder and wetter climates slow down decomposition rates (Gonçalves and Carlyle 1994, Verheijen et al. 2005) while soils with more clay particles have, on average, a higher potential to store carbon (Reeves 1997, Körschens et al. 1998).

As such, the carbon stock of a soil depends on biophysical factors, land use and management. Of these, only land use and management can be altered on a human time scale. A given change in land use or management will slowly lead to a new soil carbon stock equilibrium (a new equilibrium between carbon inputs and outputs). When the new equilibrium is reached, no additional carbon is stored or lost unless land use or management is changed again. Any measure to sequester soil carbon is therefore time-bound. Annual increases in soil carbon only take place in the initial years after changes in land use or management, and until a new soil carbon equilibrium is reached.

Fertiliser use can increase soil carbon stocks by 1) increasing the amount of annual carbon inputs (crop residues) due to more biomass from higher yields; and 2) improvement of stoichiometric relations of crop residues returned to the soil, thereby increasing the formation rates of SOM. The first mechanism includes cases in which mineral fertiliser increases crop yields and availability of organic residues increases, which can increase soil carbon stocks if returned to the soil directly, after composting or as animal manure. The second mechanism may require more explanation. Here, stoichiometric relations refer mainly to the ratios between C and N in crop residues and soil. In straw, for example, the C:N ratio is around 70 (Lal 1995), while SOM typically has a C:N ratio of 12 (Batjes 1996). This means that to sequester carbon from straw in the soil; additional N is needed (van Groenigen et al. 2017). Using a modelling approach Lugato et al. (2018) showed that more carbon is sequestered in soils when using residues from N-fixing cover crops with a lower C:N ratio (more similar to the C:N ratio of SOM) than when using crop residues with a higher C:N ratio. In the latter case, using mineral fertiliser can add N to the soil and enhance soil carbon sequestration (Kirkby et al. 2016).

Actual impacts of mineral fertiliser on soil carbon can be assessed by analysing long-term trends from national survey data or by analysing data from long-term field experiments. Two recent meta-analyses based on 64 and 114 field experiments across the world found that SOM content was on average 8.5% and 8% higher in the topsoil of fields with mineral fertiliser application compared to unfertilized plots (Ladha et al. 2011, Geisseler and Scow 2014). In the large majority of these studies, soil was sampled between 0 and 15-30 cm, though sampling depth varied. Similarly, using soil surveys in China, Gao et al. (2018) found that long-term increases in soil carbon were associated with improved agronomic management, including increased fertiliser use.

To assess which combinations of nutrient inputs (mineral fertiliser, organic inputs or a combination of both) contribute most to soil carbon sequestration, more in-depth analyses of long-term experiments is helpful. In the interpretation of results of such experiments, the initial SOM content is an important aspect to consider. When an experiment is set up on a field with previous grass or forest, the SOM content will decrease in all treatments, but a more optimal combination of nutrient inputs will lead to a smaller reduction in the soil carbon stock. Alternatively, if the SOM content at the start of an experiment is relatively low, particular combinations of nutrient management might be able to increase soil carbon stocks.

A long-term experiment in Muencheberg, Germany shows that after 41 years the carbon stocks of the soils were higher when organic inputs were combined with mineral fertiliser, compared to only organic inputs or only mineral fertiliser (Figure 2). This is most visible in the treatment with a yearly addition of 4 t/ha straw alone. Adding straw for 41 years did not lead to a different carbon stock compared to the control treatment. However, a combination of the same amount of straw application with NPK mineral fertiliser did lead to an increase in carbon stock.

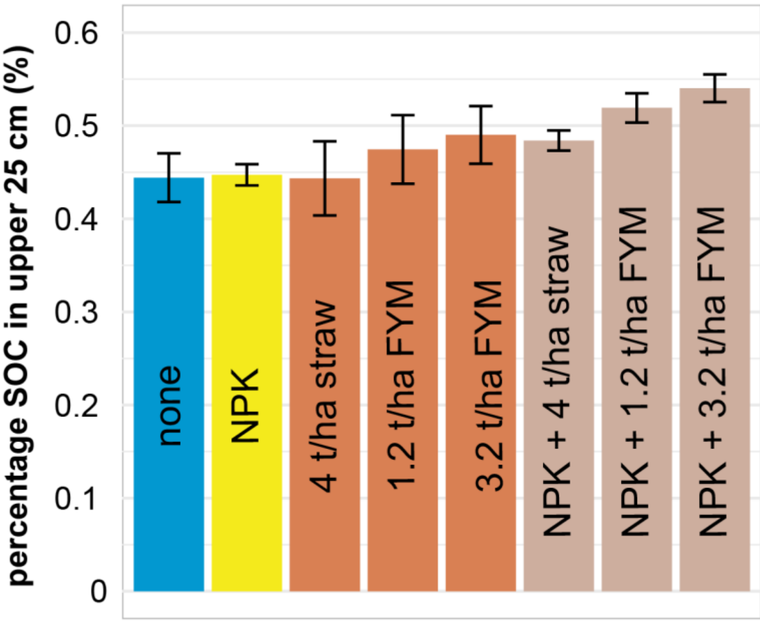

Figure 2. Percentage soil organic carbon in the upper 25 cm after 41 years of different nutrient management combinations at the long-term experiment in Muencheberg, Germany (Data: personal communication Dietmar Barkusky, ZALF). FYM = farmyard manure. SOC = soil organic carbon.

A long-term experiment in Bet Dagan, Israel shows similar results. After 30 years, soil carbon stocks were higher when organic inputs were combined with mineral fertiliser, compared to only organic inputs or only mineral fertiliser (Figure 3), of which the difference can only partially be explained by the additional nutrients applied.

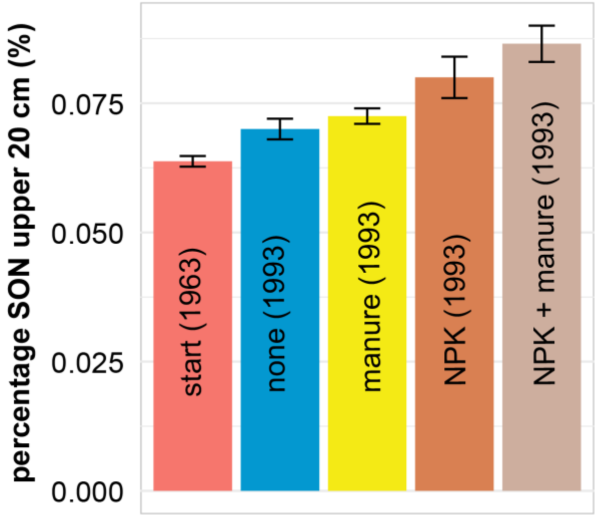

Figure 3. Percentage of soil organic nitrogen in the upper 20 cm after 30 years of different nutrient management combinations at the long-term experiment in Bet Dagan, Israel. SON = soil organic nitrogen. In the long-term, soil organic nitrogen has a fixed ratio of 1:12 with soil organic carbon and can therefore be used as an indicator for soil organic carbon. Based on Bar-Yosef and Kafkafi (2016)

Soil carbon sequestration and greenhouse gas emissions

As described in the previous section, carbon can be sequestered by using mineral fertilisers, organic inputs or a combination of both. However, soil carbon does not exist in solitude, and it is not a stable compound in the soil. Soil carbon is part of SOM, which decomposes over time, releasing CO_2 and N_2O, which might negate the benefits for climate change mitigation. The previously mentioned modelling study by Lugato et al. (2018) found that incorporation of residues from N-fixing cover crops (with a lower C:N ratio) increased soil carbon sequestration, the associated increased N_2O emissions outweighed the mitigation potential.

A model-based study in the Netherlands resulted in similar findings (Bos et al. 2017). Soil carbon increased by using solely mineral fertiliser, and more so by combining mineral fertiliser with slurry or compost, but at a certain point (depending on fertilisation and yield level) associated N_2O emissions outweighed climate change mitigation from carbon sequestration (Figure 4).

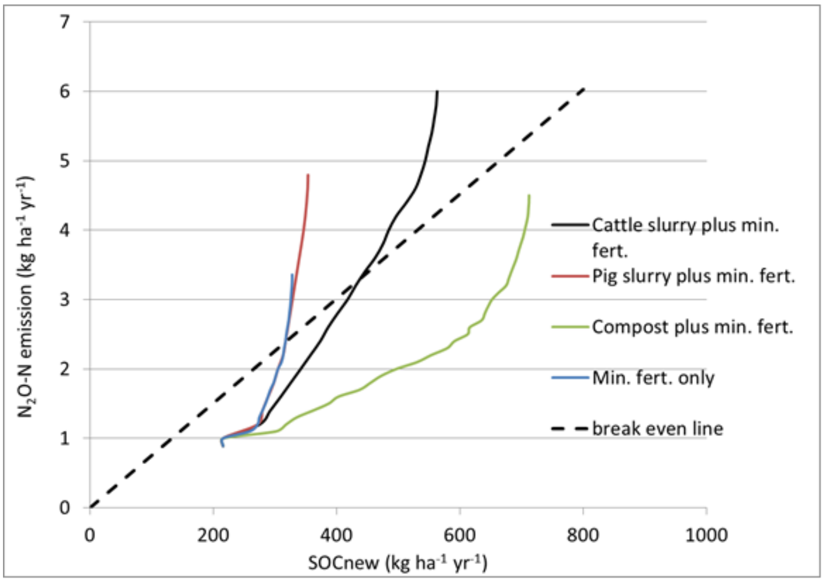

Figure 4. Trade-off between soil carbon sequestration and N_2O emissions from a modelling study in the Netherlands (Bos et al. 2017). Each coloured line represents a range of nutrient input levels (from low to high) for a given nutrient input type. The dotted line indicates the break even line where the gain in soil carbon sequestered equals the additional N_2O emissions.

The modelling study in the Netherlands only assessed trade-offs at field level. The additional GHG emissions associated with fertiliser production and transport (CO_2) and/or GHG emissions associated with storage and transport of manure were not included. These findings raise the question of how far soil carbon sequestration can compensate for GHG emissions in agriculture when looking at the farm or regional level. Can soil carbon sequestration be used as a negative emission technology to achieve carbon neutral agriculture?

A recent study in China showed that - across a range of different cropping systems – soil carbon sequestration compensated for less than 10% of the total GHG emissions (N_2O, CH_4, CO_2) associated with these cropping systems (Figure 5 Gao et al. 2018). Powlson et al. (2011) reported similar outcomes using data from the Broadbalk experiment in the UK. They found that soil carbon was increased by mineral fertiliser use, but that associated GHG emissions of all cropping management aspects (tillage, fertilisers, irrigation, crop protection, etc.) were four-fold higher. Interestingly, across the Chinese cropping systems investigated, N_2O emissions were of the same order of magnitude as CO_2 emissions (Figure 5), corresponding very well with the modelling study for the Netherlands (Figure 4).

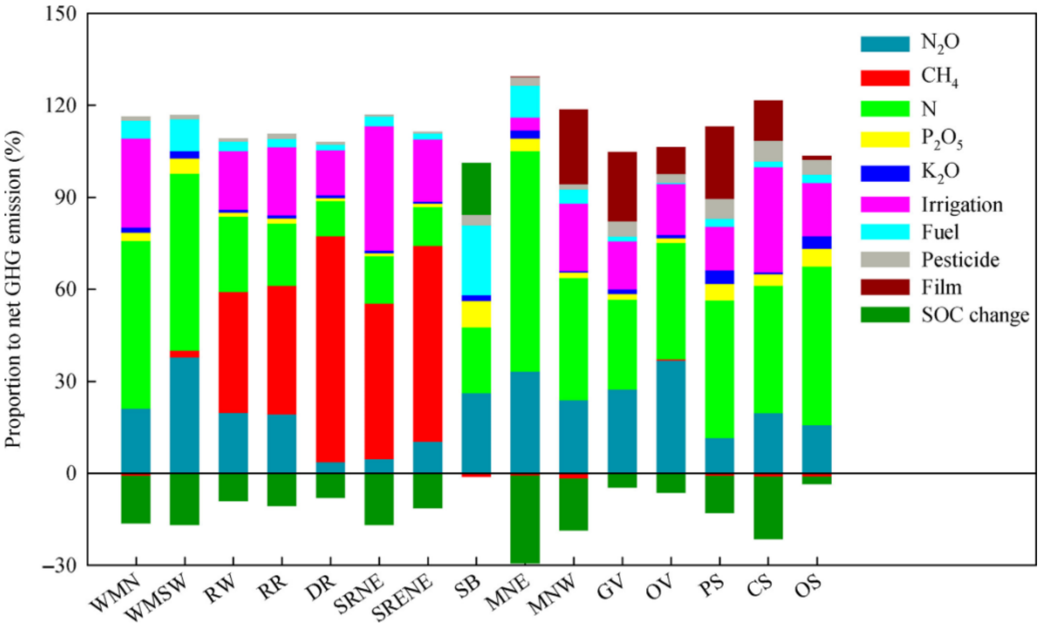

Figure 5. Soil carbon sequestration (negative, dark green part) relative to total GHG emissions of different cropping systems in China. WMN = winter wheat- summer maize Northern China; WMSW = winter wheat- summer maize South-western China; RW = rice-winter wheat; RR = rice-rapeseed; DR = double rice; SRNE = single rice North-eastern China; SRENE = single rice; SB = soybeans; MNE = single spring maize North-eastern China; MNW = single spring maize Northern and North-western China; GV = greenhouse vegetables; OV = open-field vegetables; PS = potato system; CS = cotton system; OS = orchard system. Source: Gao et al. (2018)

These findings show that while soil carbon sequestration might have a role to play in mitigating climate change, it cannot compensate for total agricultural GHG emissions, neither in the short or long-term, and it cannot compensate for GHG emissions from other economic sectors. In this light, it is also relevant to highlight that agronomic management has to be changed permanently to maintain a new soil carbon equilibrium, while the contribution to climate change mitigation only occurs in the first decades when the soil carbon stock is increasing. This means that when the new soil carbon equilibrium is reached, the changes in agronomic management have to be maintained while no additional carbon will be sequestered. Reducing N_2O emissions on the other hand – by increasing nutrient use efficiency – also requires a shift in agronomic management but gives a contribution to climate change mitigation every year that the shift in management is maintained.

Conclusion/recommendations

Evidence from scientific literature shows that use of mineral fertiliser can support carbon sequestration in agricultural soils. Pathways include increasing the availability of biomass (e.g., crop residues) and creating more favourable C:N ratios for the formation of SOM. Nevertheless, carbon sequestration in agricultural soils is only temporary and not sufficient to offset all GHG emissions from the agricultural sector. If given priority, efforts should focus on sequestering carbon in agricultural soils with the largest sequestration potential and/or cases where synergies with soil fertility and food security occur. These focus areas might however not overlap geographically, as the largest potential for carbon sequestration will be most likely be in colder and temperate regions while the largest soil fertility benefits are likely to occur in tropical regions. Today, there is a lack of data on soil carbon sequestration in the tropics, which is also a limitation for this review. This can be read as a case for more long-term field experiments in tropical regions which include regular soil analyses.

Fertiliser use, yields and soil conditions vary enormously among geographies and cropping systems. Recommendations on fertiliser use and climate change mitigation need to account for these differences. Generally, fertiliser use and crop yields tend to be lower in developing countries, especially in most African countries (FAO 2019). Here, given adequate production potential (Van Ittersum et al. 2016, Ten Berge et al. 2019), increasing nutrient inputs can increase the availability of biomass that can be returned to the fields to sequester carbon, creating a positive feedback loop between soils and crops. In other regions, fertiliser use is already high. In these regions, increasing the nutrient use efficiency and thereby reducing N_2O emissions is likely the most promising pathway to mitigate climate change.

When analysing the potential benefit of mineral fertiliser use and soil carbon sequestration, the scale of assessment (field, farm, region) is crucial. In principle, sequestering carbon in agricultural soils can have mutual benefits for climate change mitigation and food security if soil fertility is improved, if there is an addition of carbon sequestered and if increased GHG emissions do not offset the added carbon. At the field level, increasing the nutrient use efficiency of either mineral or organic fertilisers can support the latter. Considering the limited availability of biomass in some areas, mineral fertiliser can play an important role in soil carbon sequestration by supplying nutrients to crops and thereby increasing biomass production and availability and limiting agricultural area expansion. Experimental evidence suggests that using a combination of both mineral fertiliser and organic fertiliser seems most promising for increasing crop yields, increasing nutrient use efficiency and sequestering soil carbon.

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