Info Note

Fertiliser use and soil carbon sequestration

Key messages for climate change mitigation strategies

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Key messages

- Use of fertiliser (either mineral or organic) can increase soil carbon sequestration. More focus is needed on potential trade-offs with increases in nitrous oxide (N_2O) emissions and synergies with prevention of land conversion from forests or grasslands to agricultural land.
- Empirical evidence suggests that a combination of mineral fertiliser and organic fertiliser seems most promising for sequestering soil carbon in agricultural soils.
- Climate change mitigation policies focusing on fertiliser use and soil carbon sequestration should distinguish between regions with low yields and low fertiliser use and regions with high mineral fertiliser use.
- In regions with low yields and low fertiliser use, increasing fertiliser use can increase soil carbon, improve soil fertility, enhance crop yields and in some setting, save carbon stored in forests; however, net emissions from a field will likely increase due to increased N_2O emissions.
- In regions with high fertiliser use, efforts should focus on reducing mineral fertiliser use, preventing nutrient leaching and maximizing nutrient use efficiency to reduce greenhouse gas emissions.

Reducing greenhouse gas (GHG) emissions and increasing soil or biomass carbon stocks are the main agricultural pathways to mitigate climate change. Scientific and policy attention has recently turned to evaluating the potential of practices that can increase soil carbon sequestration. Forty percent of the world's soils are used as cropland and grassland, therefore agricultural policies and practices are critical to maintaining or increasing the global soil carbon pool.

This info note explains the current understanding of the impact of mineral fertiliser use on soil carbon sequestration as a mitigation strategy in agriculture. The science and understanding on soil carbon sequestration and mitigation is still emerging, especially in tropical regions. Taking this into consideration, this info note discusses related effects of fertiliser use on climate change mitigation, such as nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions from nitrogen fertiliser use and production, and the potential effects of mineral fertiliser use on land use change.

How to increase soil organic carbon stocks and its contribution to soil fertility

The stock of organic carbon in a given soil depends on:

- historical land use;
- the annual amount of organic carbon inputs (biomass added to soil) together with the rate at which the organic carbon inputs are transformed into soil organic carbon (composition rate); and
- the amount of soil organic carbon that decomposes each year (decomposition rate).

The amount and type of biomass added to a soil largely depends on land use (types of crops or vegetation) and management (e.g., irrigation, fertiliser use, weed and pest control). Soil organic carbon composition and decomposition rates depend on biophysical factors such as soil texture and climate. In general, colder climates have slower decomposition rates while soils with more clay content can store larger amounts of carbon. As such, for a given land use or management, clay soils in colder climates will store more carbon than sandy soils in warmer climates.

Changes in land use or management increase or decrease soil organic carbon and thus carbon stocks, until a new soil carbon stock equilibrium is reached. While the annual increase in soil carbon is therefore limited to a certain time period, maintaining the achieved soil carbon stocks requires a continuation of the new land use and management beyond the time period of carbon gains, to prevent CO_2 losses.

In general, increased soil organic carbon improves soil structure, nutrient supply and moisture retention, thereby improving the conditions that increase crop yields and improving resilience in water-stressed environments. Crops cultivated with more mineral fertiliser, irrigation and tillage tend to depend less on soil organic carbon for soil fertility. Yet, even intensively managed farming systems can benefit from adding organic carbon, especially on sandy soils or when cultivating specialized crops such as potatoes or sugar beets which depend more on a supportive soil structure (Hijbeek et al. 2017).

Several management practices–including cultivating green manures and reducing periods under which land is fallow–increase soil organic carbon stocks, although at different rates depending on the soil and climate. This info note focuses on how the use of mineral fertiliser affects soil carbon sequestration and climate change mitigation. Mineral fertiliser is defined as fertiliser based on inorganic substances, in contrast to organic fertiliser, such as manure, crop residues or compost, derived from animals or plants. Nitrogen-based mineral fertilisers in particular are a major source of nitrous oxide (N_2O), and depending on the use of fossil fuels in their production, can also be a major source of carbon dioxide (CO_2) emissions.

How mineral fertiliser use contributes to soil carbon sequestration

Mineral fertilisers can increase soil carbon stocks by:

- Increasing crop yields, which can lead to an increase in the availability of organic residues that can be returned to the soil either directly, after composting, or, after feeding to animals, as animal manure.
- Improving the carbon-to-nitrogen ratio (C:N ratio) when crop residues are incorporated into the soil, thereby increasing the rate at which soil organic carbon forms.

Generally, a combination of both mineral fertiliser and organic fertiliser is most promising for increasing crop yields, increasing nutrient use efficiency and soil carbon sequestration (Hijbeek et al. 2019; Vanlauwe et al. 2011).

Two global meta-analyses found that soil organic carbon content was on average 8 to 8.5% higher in the topsoil of plots with mineral fertiliser application compared to unfertilized plots (Ladha et al. 2011; Geisseler and Scow 2014). These are promising insights, but when assessing the potential climate mitigation, trade-offs with other GHG emissions such N_2O emissions also need to be taken into account, which we will discuss in the following section.

Can soil carbon sequestration compensate for agricultural greenhouse gas emissions?

Several studies have analysed whether soil carbon sequestration could achieve carbon-neutral agriculture.

- A modelling study using 8,000 soil sampling sites in the European Union found that incorporating residues from N-fixing cover crops (i.e. leguminous species) increased soil carbon sequestration; however, the resulting increase in N_2O emissions outweighed the potential carbon sequestered (Lugato et al. 2018).
- Similarly, a model-based analysis focusing on the Netherlands found that mineral fertiliser use increased soil carbon, and a combination of mineral fertiliser with slurry and in particular compost further increased soil carbon. However, depending on fertilization, yield level and type of organic amendment, associated N_2O emissions may outweigh climate change mitigation from soil carbon sequestration (Bos et al. 2017).
- A study across a range of different cropping systems in China showed that soil carbon sequestration compensated for less than 10% of the total GHG emissions associated with these cropping systems (Gao et al. 2018).
- Powlson et al. (2011) found that mineral fertiliser use increased soil carbon in an experiment in the United Kingdom, but that associated GHG emissions of all cropping management aspects (tillage, fertilisers, irrigation, crop protection, etc.) were four-fold higher.

Categorically reducing nitrogen fertilizer inputs (and thus reducing emissions) may have unintended negative effects. Particularly in areas with poor soil fertility and where nitrogen is not overused, yields can decrease, increasing the likelihood of food insecurity or accelerating deforestation of nearby forests for cash and cropland (Burney et al. 2010).

Low fertiliser use is typical in many developing countries, including almost all countries in sub-Saharan Africa. Given adequate production potential (Van Ittersum et al. 2016; Ten Berge et al. 2019), small increases in mineral fertiliser use and other nutrient inputs in these systems can increase the availability of biomass which can be returned to the fields to sequester carbon, creating a positive feedback loop between soils and crops. In addition, land conversion from forests or grasslands to agricultural land might be prevented by intensifying agriculture, thereby preserving more soil carbon stocks.

Especially in areas where fertiliser use is high, farmers should maximize nitrogen use efficiency (yield obtained per amount of nutrient applied) to keep emissions below environmental thresholds. This will reduce nutrient losses (to water and air) for total food production, and minimize CO_2 emissions from fertiliser production and N_2O emissions from fertiliser application (Powlson et al. 2018). Reducing fertiliser use—and therefore emissions—while maintaining crop yields achieves climate change mitigation every year in which this change in management is in place. This is in contrast to sequestration of soil carbon, which only has a positive effect on climate change mitigation in the initial years after a change in management.

Practices for improving nitrogen use efficiency include:

- Application of mineral fertilisers in combination with organic fertilisers, such as farmyard manure;
- Weed and pest control;
- Using lime on acid soils;
- Optimizing rate, type, timing and placement of fertilisers;
- Using nitrification inhibitors;
- High nitrogen-efficiency crop varieties.

Conclusions

Mineral fertilisers can increase soil carbon stocks by:

- Increasing crop yields, which can lead to an increase in the availability of organic residues that can be returned to the soil either directly, after composting, or, after feeding to animals, as animal manure.
- Improving the carbon to nitrogen ratio (C:N ratio) when crop residues are incorporated into the soil, thereby increasing the rate at which soil organic carbon forms.

Increased soil organic carbon supports improved soil productivity and enables resilience during times of water shortage. The increase in soil organic carbon can also offset some of the emissions from mineral nitrogen fertiliser to help mitigate climate change. Ambitions should however be modest as soil carbon sequestration currently cannot compensate for total agricultural GHG emissions, let alone for GHG emissions from other economic sectors.

Hotspots for soil carbon sequestration in agriculture are regions with higher storage potential (*e.g.* clay soils or colder climates) and regions where synergies with soil fertility and food security are likely to occur (farming systems in tropical regions, on sandy soils and/or when cultivating more specialized crops). Geographically, the two hotspots may however not overlap, making it challenging to find synergies between soil carbon sequestration potential, soil fertility and food security.

In regions with relatively low agricultural productivity and low fertiliser use, increasing mineral fertiliser use can benefit food security and soil carbon sequestration. In these areas, policies should support farmers to carefully increase nutrient inputs using both mineral and organic fertilisers. In areas where fertiliser use is high, policies should rather support farmers to maximize nutrient use efficiency and keep nutrient emissions per hectare below environmental thresholds.

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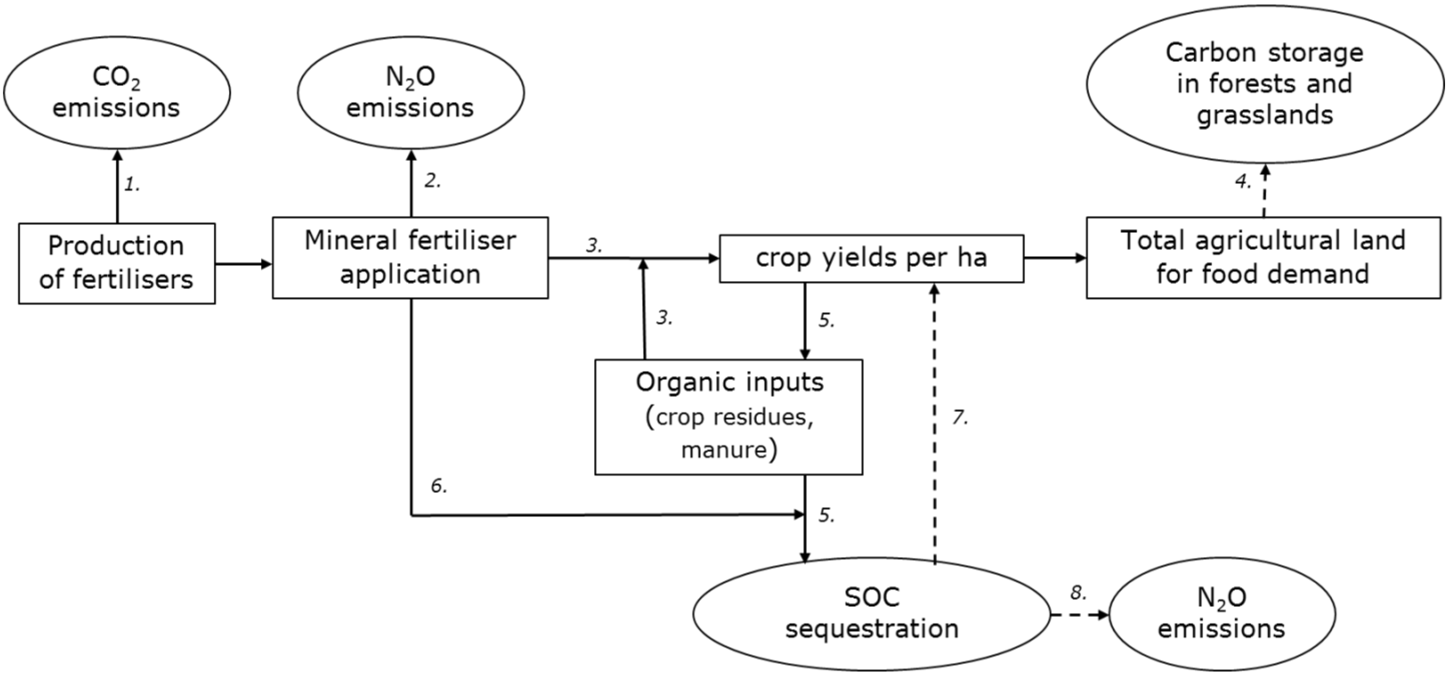

Simplified diagram showing the different relations between mineral fertiliser use and climate change mitigation. Solid lines indicate effects with high certainty whilst dashed lines indicate indirect effects with less certainty that require more research. Explanation of arrows:

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

Mineral fertiliser use can increase yield by either increasing yields (arrows 3 and 5) or improving C:N ratios or residues returned to the field (arrow 6). This might create a positive feedback loop with yields if soil fertility is increased (arrow 7). There might be trade-offs for climate change mitigation by increased CO2 and N2O emissions (arrows 1, 2 and 8) or synergies if increased yields lead to less expansion of agricultural land (arrow 4).

Further Reading

- Bos JFFP, ten Berge HFM, Verhagen J, van Ittersum MK. 2017. Trade-offs in soil fertility management on arable farms. *Agricultural Systems* 157:292-302.
- Burney JA, Davis SJ, Lobell DB. 2010. Greenhouse gas mitigation by agricultural intensification. *PNAS* 107:12052-12057.
- Gao B, Huang T, Ju X, Gu B, Huang W, Xu L, Rees RM, Powlson DS, Smith P, Cui S. 2018. Chinese cropping systems are a net source of greenhouse gases despite soil carbon sequestration. *Global Change Biology* 24:5590-5606.
- Geisseler D, Scow KM. 2014. Long-term effects of mineral fertilisers on soil microorganisms–A review. *Soil Biology and Biochemistry* 75:54-63.
- Hijbeek R, van Ittersum MK, ten Berge HFM, Gort G, Spiegel H, Whitmore AP. 2017. Do organic inputs matter – a meta-analysis of additional yield effects for arable crops in Europe. *Plant and Soil* 411:293-303.
- Ladha JK, Reddy CK, Padre AT, van Kessel C. 2011. Role of Nitrogen Fertilization in Sustaining Organic Matter in Cultivated Soils. *Journal of Environmental Quality* 40:1756-1766.
- Lugato E, Leip A, Jones A. 2018. Mitigation potential of soil carbon management overestimated by neglecting N2O emissions. *Nature Climate Change* 8:219-223.
- Powlson DS, Whitmore AP, Goulding KWT. 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. European *Journal of Soil Science* 62:42-55.
- Powlson DS, Poulton PR, Macdonald AJ, Johnston AE, White RP, Goulding KWT. 2018. 4 per mille - is it feasible to sequester soil carbon at this rate annually in agricultural soils? International Fertiliser Society. IFS, Cambridge.
- Ten Berge HFM, Hijbeek R, Van Loon MP, Rurinda J, Tesfaye K, Zingore S, Craufurd P, van Heerwaarden J, Brentrup F, Schröder JJ, Boogaard HL, de Groot HLE, van Ittersum MK. 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security* 23, 9-21.
- Van Ittersum MK, van Bussel LGJ, Wolf J, Grassini P, van Wart J, Guilpart N, et al. 2016. Can sub-Saharan Africa feed itself? *PNAS* 113:14964-14969.
- Vanlauwe B, Kihara J, Chivenge P, Pypers P, Coe R, Six J. 2011. Agronomic use efficiency of N fertiliser in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant and Soil* 339(1-2):35-50.

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