https://doi.org/10.5194/egusphere-2025-4032
Preprint. Discussion started: 17 September 2025

Crop fertilization as a key determinant of croplands' soil carbon stocks

Running head**: Crop fertilization for 4P1000**

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Abstract

Soil organic matter (SOM), which associates organic carbon to key plant nutrients, is a corner stone of soil health, agricultural productivity and ecosystem functioning. While virgin lands (forest or grassland) exhibit the highest SOM stocks, their cultivation leads to their sharp decrease and that of crop yields in the first decade(s), even when zero tillage and cover crops are promoted. The decline in SOM is less acute when crops are fertilized with N, P, K at rates recommended to meet crop needs than when not fertilized, and is often reversed when nutrients are applied above recommendations. This points to the key role of fertilization to manage croplands' soil carbon that needs to be better understood to mitigate against soil degradation for promoting sustainable agriculture, while minimizing environmental hazards such as water pollution.

Short abstract

Virgin lands converted to croplands loose staggering amounts of soil organic carbon. The available litterature shows that proper soil fertiliation may allow to revert the decline in SOM which is less acute when crops are fertilized with N, P, K at rates recommended to meet crop needs than when not fertilized. The SOM decline is often reversed when nutrients are applied above recommendations thus pointing to necessary reconsideration of actual soils policies.

1. Virgin lands converted to croplands loose staggering amounts of soil organic carbon.

The level of organic matter (SOM) depends on the intrinsic capacity of the soil and the balance between carbon inflows and outflows. When this balance is changed as due to the conversion of pristine vegetation (forest or grassland) to cropland, SOM stocks tend to change until a new lower equilibrium is reached. Based on 134 paired comparisons worldwide, Guo and Gifford

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(2002) estimated that the transition from pristine vegetation to cropland decreases SOM stocks by an average 42% for native forest and 59% from grassland, with most of the carbon losses occurring during the first 30 years. According to Deng et al. (2016), this decline of which about 90% occurs during the first 20 years, would correspond to a respective loss of 1.74 and 0.89 Mg ha^{-1} yr^{-1}. None of the paired comparisons available in the literature pointed to an increase in SOM stocks, as a result of conversion to cropland. While these estimations have been performed from conversions that occurred during the last few decades, SOM stock changes associated to cropping are not a new phenomenon and was already observed long before the use of pesticides, heavy machinery, mineral fertilization and improved cultivars. Indeed, early modern scientists such as Swanson and Latshaw (1919) and Snyder and Marcille (1941) had shown a systematic decline in soil organic carbon following the conversion of virgin land in cropland. In their study of 37 paired sites in Arkansas Swanson and Latshaw (1919) pointed to an average SOM decline by 30% in the 0 to 20 cm layer and by 6% in the 20-50 cm layer.

Amongst the few studies on SOM dynamics following the clearing of virgin lands, Villarino et al. (2017) in a semi-arid region of Argentina showed that 30% of the SOM was lost after 10 years of cropping. Under tropical condition, Fujisaki et al (2015) pointed to SOM losses as high as 60% several decades after forest clearing. Soils cropped for centuries also experience a decline in SOM levels. For instance, the study by Heikkinen et al. (2013) under moist continental climate in Finland shows a SOM decline between 1974 and 2009 of 220 kg ha^{-1} yr^{-1} or 0.4% yr^{-1} as estimated from 611 observations in the entire country. Also, Hanegraaf et al. (2009), in their study of maize fields in the Netherlands, pointed to a decrease in SOM from 5.0 % in 1987 to 4.5% in 2003 (i.e. 0.03% yr^{-1}).

The available experiments worldwide also show that following the start of cultivation, SOM first decline sharply in the early years after conversion and then slowly in later stages. The Morrow plots, which are located at the University of Illinois, and which probably constitute the oldest soil observatory on Earth, have been under cultivation following grassland since 1876. The plots that were under continuous cultivation of maize with no fertilization experienced a decrease of soil C from 2.9 to 2.2% (or 24% of initial stocks; 0.029 % yr^{-1}) during the first 24 years, to 1.5% (or 48%; 0.014 % yr^{-1}) after 75 years and to 1.4% (or 52%; 0.0017% yr^{-1}) after 135 years (Nafziger and Dunker, 2011). Siband (1974) in the study of Casamence red soils from tropical Senegal, pointed out an initial decrease of SOM content following deforestation from 2.7 to 1.2% (i.e. a 55% decline or 0.33% yr^{-1}) during the first 45 years of cultivation, which was also followed by a slighter decrease to 0.6% (0.0044 % yr^{-1}) after 180 years, bringing the total SOM losses to 77.8% of the initial stocks. From 50 sites within South Africa, Du Toit (1992) pointed to a SOM decrease between 10 and 75% to a depth of 200 mm and for cultivation periods ranging from 1 to 85 years. Fujisaki et al (2015) who reviewed the literature on the conversion from forest to cropland in Amazonia pointed to an average SOM content loss of 40% (or 2.0% yr^{-1}) after 20 years and 60% (or 0.33% yr^{-1}) after 80 years. Wei et al. (2014) using 453 paired and chronosequential sites and across all forest types pointed to an average 35% (or 7% yr^{-1}) SOM decline in the first cultivation decade which was followed by a 45% at 11-50 years (or 0.26% yr^{-1}) and 53 % over 50 years. Therefore, significant decrease in SOM levels following the clearing of pristine vegetation to cropland thus appears to be a general trend and to our knowledge there is no report in the literature of increasing SOM levels from baseline.

2. Crop fertilization limits soil organic carbon losses

Fertilization to meet crop needs (i.e. compensate for exports by agricultural products) significantly lessens the rate of SOM decrease consecutive to cropping. Zingore et al. (2005) in their experiment in Zimbabwe following woodland clearance showed that, after 20 years, SOM stocks had decreased by 22 ton C ha^{-1} (or 52%, or 2.6% yr^{-1}) at unfertilized sites while the decrease at sites fertilized at rates recommended to meet crop needs (i.e. 160-200 kg N ha^{-1} yr^{-}

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^{1}; 30-35 kg P ha^{-1} yr^{-1}), SOM losses decreased by 12 ton C ha^{-1} (or 22% or 1.1% yr^{-1}), which corresponded to a 2.4 times differences, significant at p<0.01. Ludwig et al. (2007), in a Chernozium of Germany, pointed to a decrease of SOM stocks from 73 to 55 ton C ha^{-1} over 100 years (or 25% or 0.25% y^{-1}) of cultivation which was fully halted by fertilization at recommended rates over the course of the same century.

3. Crop fertilisation above recommendations enhances soil carbon stocks

Fertilization over recommendations was experimented in very few experiments but appeared to refill SOM stocks in all cases. Poeplau et al. (2016) at long-term experiments in Sweeden that started from 1962 showed that doubling recommended rates of P and K caused decline, while for N only resulted in increase, while doubling the combination (NPK) yielded a 50% increase in soil organic carbon stocks (from 2 to 3 tons ha^{-1} or 19 kg C ha^{-1} yr^{-1} or 0.96% yr^{-1}). These positive effects could be explained by increase in net primary production. Such a positive impact of fertilization above the recommended rate on SOM levels was further confirmed under different environments worldwide by the meta-study by Liu et al. (2023) who additionally pointed out that SOM gains follow a nonlinear correlation with fertilizer amounts. It was also confirmed with addition of organic fertilizers. Indeed, at the long-term experiment of Rothamsted, farm-yard manure has been applied for 100 years at a rate of 35 tons ha^{-1} yr^{-1}. Considering a nutrient content of 7 kg N, 4 kg P_2O_5, 11 kg K_2O per ton of manure, the spreading of 35 tons of manure per hectare and per year would correspond to 245 ha^{-1} yr^{-1} N, 140 ha^{-1} yr^{-1} P, 385 ha^{-1} yr^{-1} K_2O, which is well-above the recommendation rate of 160-200 kg N ha^{-1} yr^{-1}; 30-35 kg P ha^{-1} yr^{-1}. Such a rate, enhanced organic carbon stocks from 40 to 80 tons C ha^{-1} over 100 years (i.e. 400 kg ha^{-1} yr^{-1} or 0.01% yr^{-1}).

The existing literature also indicates that mineral fertilization above recommendations in conjunction to organic carbon addition as manure or straw proved to enhance the rate of SOM

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building (Liu et al., 2023), while over-fertilization with animal manure slurries, such as pig slurry, proved to significantly decrease SOM (Chikuvire et al., 2019).

4. Crop fertilization programs miss to consider nutrient needs for crop residue decomposition

Kirkby et al. (2014) showed that wheat straw to be converted by soil bacteria into SOM requires larger amount of nutrients than available in the soil and that decomposition of old SOM occurs to release the key nutrients (also called "priming", Fontaine et al., 2007). The rate of SOM decay could for instance reach 1.17 to 2.37% of SOM stocks as estimated by Lenka et al (2019) after wheat residue addition in a Luvisol. To avoid "priming" and to favour SOM building through the process of wheat straw decomposition, Kirkby et al. (2014) estimated that 5 kg of N, 2 kg of P and 1.4 kg of S should be readily available in the soil per ton of wheat straw. However, these nutrients are largely missing in soils after harvest since fertilization programs aim at letting no nutrient left into soils. For winter wheat, average of 23 kg of nitrogen (N), 10 kg of phosphorus (P_2O_5), 20 kg of potassium (K_2O), 5 kg of magnesium (MgO) and 5 kg calcium (CaO) are required to produce a ton of grain and the corresponding secondary crop (straw) (Czuba 1996). Considering a production of 7 tons of wheat grain per hectare (world average), the recommended fertilization would be 161 kg of N, 70kg P_2O_5, 140kg K_2O. Following Kirkby et al. (2014), an additional 25 kg N, 10 kg P_2O_5, 100 kg K_2O per hectare per year, would be required, resulting in a total nutrient need per ha of 186 kg N, 80 kg P_2O_5, 240 kg K_2O, in order to avoid priming during the decomposition after harvest of wheat straw (world average of 5 tons ha^{-1} yr^{-1}). Current fertilization thus induces a nutrient gap from 12.5% for P, 13% for N to 42% for K_2O.

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5. What way forward for reversing SOM losses and promoting sustainable agriculture

The present paper reviews the evidences on crop fertilization impact on soil organic matter (SOM) levels, and points to decreasing SOM levels when soils are fertilized below recommendations but increasing SOM levels when fertilization is performed above recommendations. The decrease in SOM levels under low fertilization could be explained by nutrient mining as suggested by authors such as Smaling et al (1993). In their study of 23 African countries, Smaling et al (1993) demonstrated that more nutrients are exported from soils each year than added. SOM is the main reservoir of soil nutrients and nutrient mining occurs through the decomposition of SOM by bacteria, which are solicited by crops (e.g. Kallenbach *et al*., 2016), which in turn decreases SOM levels and further crop productivity. In addition, we point here that the less soils are fertilized the higher is the loss in SOM.

Suppressing nutrient mining in soils due to both the export of agricultural products and to crop residue decomposition thus appears to be a credible solution to halt SOM losses from croplands. The mining due to the difference between nutrients exported by agricultural products and added to soils was estimated for example in Africa to amount 22 kg ha^{-1} yr^{-1} N, 2.5 kg ha^{-1} yr^{-1} P, 15 kg ha^{-1} yr^{-1} K (Stoorvogel et al, 1993). Nutrient mining also occurs during the process of crop residue decomposition and was estimated here to be as high as 25 kg ha^{-1} yr^{-1} N, 10 kg ha^{-1} yr^{-1} P, 100 kg ha^{-1} yr^{-1}. Moreover, to avoid any nutrient mining, even under adequate fertilization rate, one should make sure that soil nutrients are available in the soil in a stochiometric way and when plants and bacteria need them, i.e. at all stages of the cropping cycle and during the whole duration of decomposition of crop residues. Further research is thus required not only to estimate the current nutrients gaps to be filled for existing crops and agro-ecosystems worldwide, but also to better estimate the dynamics of nutrient requirements in soils, nutrient

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availability, and potential environmental pollution from the nutrients and then nutrient application requirements over time.

A possibility to improve the nutrient balance into soils and thus to lessen SOM losses due to mining is to favor natural nutrients inputs of for instance N by legume cover crops (despite cover crops per see having not shown a frank tendency to enhance SOM levels, Chaplot and Smith, 2023) and to promote zero tillage (also not showing direct increase in SOM stocks, e.g. Baker et al 1997) to limit nutrients losses by soil erosion.

The building of SOM proved to be enhanced when excess N, P, K fertilization occurs in conjunction to C inputs to soils such as through manure, straw or cover-cropping (Mukumbareza et al 2015; Mukumbareza et al 2016). This indicates that not only should practitioners seek stoichiometry between the different nutrients but also between these and the amount of fresh organic C available in the soil for SOM building.

Finally, one probably needs to make sure that all crop macro and also micro-nutrients are not in short supply in the soil as any limitation in these might induce SOM decomposition.

In a context where the two of the most promising land management practices that are zero tillage and cover cropping alone did not yield the expected benefits for SOM stock building (Baker et al, 1997; Chaplot and Smith, 2003), a complete overhaul of fertilization plans (both in quantity, quality and dynamics) together with inputs to soils of fresh C is more than ever required to halt and reverse the current soil degradation process and to switch from an agriculture that mines soils in most parts of the world to sustainable agriculture. More is to be done on the level and stoichiometry of nutrients and C addition to maximize SOM building while limiting environmental impacts such as those associated to nutrient leaching.

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Author contribution

Both authors equally contributed to literature search and manuscript conceptualization and writing

Competing interests

The authors declare that they have no conflict of interest.

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