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PERSPECTIVE

SOIL ORGANIC CARBON SEQUESTRATION MATTERS BUT IS NO PANACEA FOR CARBON-NEUTRAL AGRICULTURE

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The idea of a carbon-neutral agriculture is appealing and overwhelming at the same time. It is appealing because agriculture may and has to contribute to decreasing the influence of humans on the climate system through a drastic decrease of the net emissions of carbon dioxide, methane and nitrous oxide from agriculture to the atmosphere. It is overwhelming, when looking at the many large and diffuse emission sources, which are often intimately associated with current food production practices, and which are not easy to control. Thus far, essentially all emissions of these greenhouse gasses will increase, mainly in response to the increasing global food demand and the lack of suitable incentives to reduce them[1]. The main emission sources are enteric fermentation by ruminants, manure management, synthetic fertilizers, rice cultivation, deforestation and draining/burning organic soils. Reducing emissions from these sources will be painful and will require incentives and targeted joined actions. An important role in the strive for carbon-neutral agriculture has been reserved for carbon sequestration in soils, at least in the intermediate term[2]. The idea is to increase the storage of atmospheric CO_2 in soil as soil organic carbon (SOC), and thereby to compensate for (some of) the emissions that cannot be reduced so easily in the short-term. However, the question is how much emissions can SOC sequestration compensate and what benefits of SOC sequestration can be realized by farmers in China.

Yang Haishun[3] was the first to report in the English literature on the control and management of SOC contents of the topsoil (0–20 cm) of the winter wheat-summer maize double cropping system of the North China Plain (NCP)[3,4]. Yang summarized the available experimental data and made simulations of SOC contents for various scenarios, using a simple mathematical model. The model was extensively calibrated and validated, using data not only from China but also from international literature. More than 25 years later, it is still informative to read these insightful publications; the context has changed but their insights on the management of the SOC content of arable land have not changed substantially. Maintaining and improving soil quality, and crop productivity were the main objectives 25 years ago whereas SOC sequestration is now also considered as a strategy to mitigate and adapt to climate change. The most important statements and insights of Yang's study are summarized in these six points:

1. Accumulation of SOC in soil follows basic rules; it is the result of C inputs and C outputs. The inputs depend primarily on primary production and the fraction of the primary production that is added to soil. The output is difficult to control, as the mineralization rate of SOC is largely determined by soil and environmental factors. It is generally assumed that the output increases proportionally with the SOC content and quality (i.e., the relative age of the organic material). These assumptions were extensively tested, using experimental data, and resulted in a simple, robust model[3].

2. Mean soil organic matter (SOM) content was low (10–20 g·kg^{-1}; equivalent to an SOC content of about 5–10 g·kg^{-1}) on the NCP during the early 1990s[3]. The main C inputs originated from plant roots and stubble. Straw and other crop residues were mainly used as biofuel, animal feed and as litter in animal housing, while excess straw and crop residues were largely burned in the open air. Manure was mainly applied to vegetables fields (and not to cereals).

3. Three C input scenarios for cropland were explored over a time span of 50 years, i.e., (1) only roots and stubble; (2) as (1) plus return of one third of the straw produced *in situ*; (3) as (2) plus farmyard manure made with another one third of the straw, both for situations of average cereal yields (7.5 t·ha^{-1}·yr^{-1} at that time) and high yields (15 t·ha^{-1}·yr^{-1}, i.e., the sum of wheat and maize grains), and for initial SOM contents of 5, 10 and 20 g·kg^{-1}. The results indicate that an initial SOM content of 20 g·kg^{-1} could only be maintained in scenarios 2 and 3 with high yields; the SOM content dropped from 20 to between 15 and 19 g·kg^{-1} in scenario 1, and especially for situations with average yields. Importantly, SOM increased in the three scenarios when the initial SOM content was 5 and 10 g·kg^{-1}. Increases were the largest in scenario 3 with an initial SOM content of 5 g·kg^{-1}. However, increases were maximally 8 g·kg^{-1} over a time span of 50 years[4].

4. SOM content can be maintained at about 10 g·kg^{-1} when crop yields are low, and at about 15 g·kg^{-1} when yields are high in scenario 1, in which roots and stubble are the only organic C inputs. In scenario 3, steady-state SOM contents were about 5 g·kg^{-1} higher than in scenario 1[4].

5. The absolute annual change in SOM content is related to the difference between the initial and final SOM contents. Thus, annual changes in SOM content decrease over time, sharply at first and more slowly at later stages. Initial changes in SOM content may be as large as 0.2–0.5 g·kg^{-1}·yr^{-1}, but later changes are $\leqslant$ 0.1 g·kg^{-1}·yr^{-1}, after a change in C input[3,4]. Such small changes cannot be quantified easily in experimental studies, especially when considering spatial variation.

6. The fraction of SOM mineralized annually can be considered as a measure of SOM quality. Newly formed SOM has a larger fraction of SOM mineralized than existing (old) SOM, and consequently SOM quality improves with increasing proportions of newly formed SOM in the total SOM. Therefore, SOM quality rises from scenario 1 to 3 as well as with increasing cereal yields. This has implications also for the mineralization of nitrogen; the annual release of N from SOM will increase more than proportionally compared to the increase in SOM content[4]. However, background N_2O emissions also increase with an increase in SOM quantity and quality[5], thereby providing a negative feedback in the strive for carbon-neutral agriculture.

How do these results and insights relate to more recent published findings? The mean SOC content in the topsoil (0–20 cm) on the NCP has increased by an average of 9.4 Mg·ha^{-1} C between 1980 and 2010[6], which translates to an average mean sequestration rate of 0.31 Mg·yr^{-1} C and an overall increase of the mean SOM content by 6.2 g·kg^{-1}. This mean increase in SOM content is in line with the increases in SOM content simulated by Yang and Janssen[4] for scenarios 2 and 3, for the situation with high cereal yields. Indeed, the increases in SOC content during the period 1980–2030 were ascribed to increases in crop yields and to increases in straw return to soil[6]. The increasing availability of cheap fossil energy sources and fertilizers in the 1980s increased crop yields and decreased the use of straw as biofuel[4]. More straw became available to add to the soil, but large amounts were burned in the open air, because of shortage of appropriate machines and labor to incorporate the straw in the soil. Though series of bans on straw burning have been implemented from 1999 onwards, straw burning is still occurring on the NCP[7]. This suggests that there is further potential to increase SOC sequestration on the NCP.

An additional C sequestration of 5.1 Mg·ha^{-1} C in the subsoil (20–40 cm) was observed[5]; this quantity translates to an average mean sequestration rate of 0.17 Mg·ha^{-1}·yr^{-1} C. Yang[3] and Yang and Janssen[4] did not consider the subsoil. It is reasonable to expect that the amounts of roots in the subsoil also increase when crop yields increase, but the mean SOC sequestration in the subsoil estimated by Han et al.[6] is surprisingly large given the fact that the mass of wheat and maize roots increases less than proportionally with increasing crop yield, and decreases exponentially with depth. Also, manure, straw and other crop residues are added to the topsoil and not to the subsoil. Evidently, this finding of Han et al.[6] warrants a further investigation.

No-tillage agriculture is sometimes also seen as a way to help store SOC in soil, through slowing down the organic matter mineralization rate[8]. However, no-tillage is mainly practiced to reduce fuel (and machine and labor) costs, and this is the main reason why no-tillage can make a substantial contribution to carbon-neutral agriculture. It has also been implemented on the NCP, but it contributes to subsoil compaction and thereby decreases wheat and straw yields[9].

No-tillage also reduces the risk of erosion and the depth distribution of SOC in soil, but most studies now indicate that it is not a measure that helps to increase SOC sequestration by reducing the rate of mineralization and thereby the C output from soil[10].

Yang[3] and Yang and Janssen[4] did not consider the additional C input of manure derived from imported animal feed. Animal production has greatly increased in China; the production is partly based on alfalfa, maize and soybean imported from abroad[11]. Consequently, this practice provides an opportunity to add carbon to cropland of the NCP from external sources. Manure contains a large portion (20%–50%, depending on feed quality) of the C in the animal feed, but a significant fraction of this manure C is respired during storage and treatment, another fraction ends up in landfill and rivers, and the remaining, currently undefined, fraction is applied to soil and contributes to SOC accumulation[12]. This suggests that manure C derived from imported animal feed is not a main source of C input in soil, but further studies are needed to confirm this. Compost derived from household waste may also contribute to SOC sequestration, but this contribution is also uncertain, and thus warrants further study.

In conclusion, total primary production and the fraction of the biomass produced that enters the soil are the main factors controlling SOC sequestration, as stated more than 25 years ago[3,4]. The importance of primary production for global SOC sequestration was recently reiterated and elucidated by Janzen et al.[13]. They concluded that it is likely that some 0.14 $\mathrm{Pg \cdot yr^{-1}}$ C could be stored as SOC in global cropland (equivalent to an average of 0.1 $\mathrm{Mg \cdot ha^{-1} \cdot yr^{-1}}$ C), which is only 2.7% of the annual global net primary production of 5.25 Pg C (above and below ground). A slightly higher global SOC sequestration (0.28–0.43 $\mathrm{Pg \cdot yr^{-1}}$ C; which translates to an average of 0.2–0.3 $\mathrm{Mg \cdot ha^{-1} \cdot yr^{-1}}$ C) was estimated by Lessmann et al.[8]. Nevertheless, the estimates of global SOC sequestration in cropland have fallen over recent years by a factor of almost 10; several earlier estimates were too optimistic[14]. This does not exclude the possibility that SOC sequestration is above the global average of 0.1–0.3 $\mathrm{Mg \cdot ha^{-1} \cdot yr^{-1}}$ C in some regions.

The total greenhouse gas emissions from Chinese agriculture (crop and animal production) was about 1600 $\mathrm{Tg \cdot yr^{-1}}$ CO_2-equivalents between 2010 and 2017[15], which translates to an average of about 8 $\mathrm{Mg \cdot ha^{-1} \cdot yr^{-1}}$ CO_2-equivalents and 2.2 $\mathrm{Mg \cdot ha^{-1} \cdot yr^{-1}}$ C. This indicates that the relatively high SOC sequestration rates on the NCP (0.31 + 0.17 = 0.48 $\mathrm{Mg \cdot ha^{-1} \cdot yr^{-1}}$ C) measured by Han et al.[6] cover an average of only 20% of the total greenhouse gas emissions from Chinese agriculture, when expressed per unit area of land. Thus, SOC sequestration may deliver a significant contribution to a carbon-neutral agriculture, but it should not be viewed as a potentially major contributor to reducing net C emissions from agriculture. Efforts in the strive for carbon-neutral agriculture have to be focused on a drastic decrease of the net emissions of CO_2, CH_4 and N_2O from agricultural sources, and on increasing renewable energy production.

What about the farmers and other stakeholders? These seem to have been overlooked or neglected so far in the strive for carbon-neutral agriculture and SOC sequestration. We all know that farmers have to make a living from farming activities, but few use this as starting point for the analysis. What is the business model for farmers in carbon-neutral agriculture and SOC sequestration? How can farmers be rewarded for the efforts they provide to society in carbon-neutral agriculture and by SOC sequestration?

Agriculture provides a number of functions to society, but mostly we reward farmers only for the food, feed and fiber they deliver. We generally reward farmers for the primary productivity function of the land. Why should citizens not pay for other functions of the land that farmers manage, including (1) carbon sequestration and regulation of greenhouse gases, (2) provision and cycling of nutrients, (3) protection and provisioning of functional and intrinsic biodiversity, and (4) water storage, purification and regulation? Some may rightly argue that many farmers do a poor job in managing these functions. Perhaps this is true, but farmers are also not paid for it.

My hypothesis is that sustainability-driven business models are key to carbon-neutral agriculture. Sustainability-driven business models are a panacea also to green agriculture in my view. The implications of this hypothesis is that the businesses of farmers and other stakeholders should be considered as the starting point for the transition to carbon-neutral and green agriculture. The required business models are sustainability-driven, because farmers are rewarded for those functions that society demands, and that have impact on the environment and society. Thus farmers have to be rewarded not only for the food, feed and fiber they deliver, but also for SOC sequestration, greenhouse gas mitigation, protection and provisioning of functional and intrinsic biodiversity, nutrient cycling, water storage, purification and regulation, and landscape maintenance.

Setting-up such sustainability-driven business models will be a joined effort of farmers, policy makers, scientists and other actors in the food production-consumption chain. Pilots could be established first at regional levels. Let us find out whether sustainability-driven business models are a panacea to carbon-neutral agriculture.

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