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Current NPP cannot predict future soil organic carbon sequestration potential. Comment on "Photosynthetic limits on carbon sequestration in croplands"

Soil organic carbon (SOC) sequestration is the transfer of CO_2 from the atmosphere into soil organic matter. It, therefore, relies on photosynthesis and plant-derived carbon (C) input, which usually occurs through biomass production. Janzen et al. (2022) reminded us that when calculating SOC sequestration potential, we should recognise the source of C input to the soil as estimated by Net Primary Production (NPP). Indeed, increasing plant biomass production *via* NPP has been discussed as the most important driver of many SOC sequestration strategies (Soussana et al., 2019).

Janzen et al. described a simple back-of-the-envelope calculation to demonstrate the limits of SOC stock increase as defined by the *current* NPP. While such a straightforward approach is reasonable to get a rough guestimate, it is important to recognise that there are limits to such a simplified modelling approach which carries significant uncertainties. In this comment, we discuss the limitations of such an approach and the way forward. Moreover, we show that Janzen et al.'s calculation contains inaccurate assumptions. When these are rectified, their simple model shows that current global cropland soil carbon sequestration rate is within the range of 4 per 1000 of the standing soil C stocks and supports the aspirational goal of the 4 per 1000 initiative.

Janzen et al. (2022) calculated soil C gain (Cg) as a function of global NPP (P), with a portion that is harvested (k_1) and another that is decomposed (expressed as k_2, representing a fraction of added plant C that persists in soil for >5 yrs). In addition, soil C stock (H) is subjected to decomposition at a rate of k_3 (equivalent to 1/mean residence time). This is expressed in Equation [4] of Janzen et al. (2022)):

$$Cg = [P * (1- k_1)*k_2)] - (H * k_3) \tag{1}$$

This model is essentially the same as the classical Hénin and Dupuis (1945) model, which we credit here, commonly expressed as a differential equation:

$$dC/dt = h\ A - k\ C, \tag{2}$$

where dC/dt is the rate of soil C change, which depends on input A, humification factor h, and the decomposition of soil C at a rate constant of k.

Janzen et al. applied this model to global croplands and used estimates of 5.25 ± 0.46 Pg C yr^{-1} as P and 140 ± 14 Pg C as H (the slower, their so-called 'lingering' [>5 year] soil C stocks in the 30 cm soil layer). While they adequately defined the standard deviation of all parameters, Janzen et al. ignored the effect of their error and inaccuracy, which could be large.

1. Assumptions and inaccuracies of the global estimate model

Janzen et al. (2022) calculated soil C gain based on current NPP on cropland. Initiatives such as 4 per 1000 promote a significant shift in management techniques which would increase NPP and induce a significant gain in SOC (and potential CO_2 removal). While Janzen et al. (2022) acknowledge measures such as judicious crop nutrition or cover cropping for NPP increase, the calculation presented by Janzen et al. (2022) should be considered a 'business-as-usual' scenario.

Several large uncertainties are immediately obvious when Janzen et al. estimate a single NPP number for the entire planet:

(1) Estimation of NPP from remote sensing products is subject to large uncertainty. Like any other global estimate, it is a model. Even if the model is robust, it needs to be verified by real-world data. To date, as far as we know, none of the global NPP products has been thoroughly validated worldwide. The global NPP number used by Janzen et al. (2022) was based on a study by Wolf et al. (2015). It was estimated using the statistics of annual harvested biomass of 92 crops for the years 1961–2011 (FAOSTAT) from a harvest area of 1257 Mha, or an average NPP of 4.18 Mg C ha^{-1}. The biomass calculation was carried out using various parameters, e.g., harvest index, shoot-to-root ratios, etc. As a result, global statistical data such as FAOSTAT are known to have considerable errors (Buongiorno, 2018; Liu et al., 2018; See et al., 2015).

(2) Critical to a global NPP estimate is the global cropland area. Cropland area is not a fixed value, rather an estimate based on country statistics or remote-sensing images and thus varies between publications. The NPP values by Wolf et al. (2015) were computed at a coarse resolution of $0.05^\circ \times 0.05^\circ$ (about 5 km × 5 km at the equator), which means that they are only reliable for farm areas greater than 2500 ha (quite large), and would miss lots of small-scale farms in mixed landscapes. Indeed, it is common in some regions for both cropping and pasture phases to be incorporated into rotational sequences, meaning that the apparent locations of cropping systems vary between years. Such fine-grained detail is difficult to extract from country-wide statistics or coarse-resolution remote-sensing products. Nevertheless, the cropland area had been checked using field observations. For example, Ramankutty et al. (2008) demonstrated that the estimated global cropland extent varies by more than 40% between 1220 and 1710 Mha. Another global cropland map had an accuracy of 84% (Fritz et al., 2015).

(3) The simplistic faster (so-called 'ephemeral') and slower (so-called 'lingering') C pools are not based on any evidence. It is important to remind ourselves that soil scientists have moved away from such conceptual pools; and soil carbon forms and persistence are active research areas (Kleber et al., 2021). Additionally, Janzen

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et al. (2022) assume in Eq. (1) that the global cropland C stock and C input are under a steady-state condition. As global SOC stock is not in equilibrium but declining (Stockmann et al., 2015), that approach is conceptually incorrect. The transient-state response is likely to be faster at the beginning than steady-state.

(4) Janzen et al. (2022) used the global C stock in croplands (H) from Table 1 of Zomer et al. (2017), 140.28 Pg C over an area of 16,307,531 km^2 (or 1631 Mha). Zomer et al. (2017) derived the cropland area from Global Land Cover fractional land cover geospatial database at a 1 km grid spacing. The SOC stock data were from SoilGrids 250 (Hengl et al., 2017), known to be highly uncertain (Tifafi et al., 2018). The estimated cropland SOC stock of 86 Mg C ha^{-1} appears to be an inflated value. The back-calculation, assuming a bulk density of 1.3 Mg m^{-3} (30 cm soil layer) would give a SOC mass concentration of 2.2% which is exceptionally high for croplands. This value is highly unlikely for cropland soils (except for Chernozems, Gleysols, and soils in cold regions or Andosols in the humid tropics). The overestimation of SOC stock by Soilgrids has been reported by Mulder et al. (2016) and Tifafi et al. (2018). SOC content for most of the world's cropping areas is around 1–2%, and even lower than 1.1% in many regions of the tropics (Stockmann et al., 2014). Our own recent estimate is 83 Pg C stored in topsoils of cropland area of 1404 Mha, or 59 Mg C ha^{-1} (or average SOC content of 1.37%) (Padarian et al., 2022).

We note that Janzen et al. (2022) made two crucial oversights by not considering a consistent global area of cropland and using an inaccurate C stock estimate. They used global NPP and C stock values calculated from two different sources that show a discrepancy in terms of cropland areas: for NPP, the cropland area by Wolf et al. is 1257 Mha, while for cropland SOC stock, the area by Zomer et al. is 1631 Mha (about 30% higher). If Janzen et al. assumed 140 Pg soil C in the 1257 Mha, that means they took an average SOC stock in cropland of 111 Mg ha^{-1} (or SOC concentration about 2.8%), which is highly exaggerated.

For simplicity of argument, let's assume Janzen et al.'s approach, where the NPP and crop area estimates are assumed to be acceptable, the decomposition parameters are feasible, and Eq. (1) is under a steady-state condition. We just need to correct the discrepancy in SOC stock to a more reasonable estimate. We take the cropland area of Wolf et al.'s NPP estimate (1257 Mha) and again take a bold assumption of a bulk density of 1.3 Mg m^{-3} with an average SOC concentration of 1.5%, giving a SOC stock 73.5 Pg C or 58.5 Mg C ha^{-1}. Then, using Equation (1) of Janzen et al. (2022) (despite all its assumptions and limitations), we can calculate an annual C gain (Cg) of the world's soil (Pg C yr^{-1}) due to the current NPP input:

$$Cg = 5.25 \times ((1 - 0.44) \times 0.15) - (73.5 \times 1/500) = 0.294\,\text{Pg C yr}^{-1}.$$

If we compare the annual C gained in the soil (Cg) with the initial C stock (H): 0.294/73.5 = 0.004 yr^{-1} or 4 per 1000 per year.

Coincidentally the model predicts 4 per 1000 under current NPP input!

To make it a more general equation, we normalise the C stock by area (in Mg C ha^{-1}), and perform the same calculation:

$$Cg = 4.18 \times ((1 - 0.44) \times 0.15) - (58.5 \times 1/500) = 0.234\,\text{Mg C ha}^{-1}\text{yr}^{-1}$$

Similarly, comparing C gain (Cg) 0.234 to initial C stock (H) of 58.5 Mg C ha^{-1}, we have 0.004 yr^{-1} (i.e., 4 per 1000). Interestingly the rate $\sim$ 0.2 Mg C ha^{-1} yr^{-1} is typical of SOC sequestration rates reported for cover cropping, agroforestry or other practices (Poeplau and Don, 2015; Cardinael et al., 2017; Minasny et al., 2017).

Do we believe that 4 per 1000 is the magic number? No, and we are not proving that Janzen et al.'s model validated the 4 per 1000 concept.

Do we believe the calculation is robust and valid for the whole world? No.

Do we think that SOC storage in cropland soils could compensate for all CO_2 emissions from fossil fuels? No. Even if our estimate based on a more realistic global soil C stock produces a slightly higher C sequestration potential, it still accounts for only 2.9% of all global emissions (10 Pg C, (Friedlingstein et al., 2021)).

We believe that (a) there are many uncertainties in this back-of-the-envelope calculation, and (b) the calculation is not robust because the parameters are pragmatically determined, and (c) current NPP estimates cannot be used to estimate future SOC stock storage potential. This latter point cuts both ways: on the one hand, effects of climate change may stall or decrease crop productivity (Hochman et al., 2017); conversely, changes to management that target greater C inputs to soil (e.g., increased cover cropping, agroforestry, etc.) may increase NPP and thus C inputs.

Discussions on global soil carbon sequestration potential consider technologies that would change current practices to increase C inputs to soil and extend to global agricultural lands, which are three to four times the size of croplands, including grasslands and agroforestry systems (See for example, Table 1 of Lal et al., 2018; Table 2 of Soussana et al., 2019). We could speculate further on the potential NPP increase and propagate uncertainties and errors of NPP, cropping and agricultural area, decomposition constants, but that is a futile exercise with a simplistic model. Instead, we propose not being fixated on the number, and discuss the way forward.

2. The way forward

We have moved on in our discussion of the feasibility of soil carbon sequestration to identifying the potential of carbon sequestration in cropland soils. In a recent consensus paper, Amelung et al. (2020) agreed on the importance of increasing C inputs to gain and maintain SOC under climate change. Amelung et al. recommended identifying region-specific opportunities for C sequestration, especially those with large yield gaps and large historic soil organic carbon losses. Soil scientists have already developed robust SOC models for such analysis, and although they use functional C pools, models such as RothC and Century have been tested and applied globally. Global analysis of soil C sequestration potential should be based on a well-calibrated model on gridded NPP, proper climate and soil data, and accounting for all sources of uncertainties. For example, a recent global modelling study on the potential of cover cropping found the median global soil carbon sequestration rates of 0.48 and 0.52 t C ha^{-1} yr^{-1} (Porwollik et al., 2022).

A huge amount of C is stored in global soils and, if released, has the potential to accelerate climate change greatly. Therefore, we agree with Janzen et al.'s aspiration that humans should avoid expanding cultivated land and preserve wetlands, peatlands, and forests. But equally importantly, we also need to restore the SOC in our croplands to increase their capacity to deliver biomass production and other ecosystem and planetary services. As discussed in many papers, human survival is intimately linked to healthy and secure soils, which rely upon functioning biogeochemical cycles underpinned by SOC (Kopittke et al., 2021). Soil scientists should focus their research on understanding factors that control the behaviour and persistence of C in soils so we can increase SOC on many of the agricultural soils and degraded soils, which have lost around half of their SOC since intensive cultivation. Soil carbon is central in regulating soil functioning and is also a solution to increase food production and resilience to climate change (Iizumi and Wagai, 2019).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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