**Supplementary Information to:**

# Towards a global scale soil climate mitigation strategy

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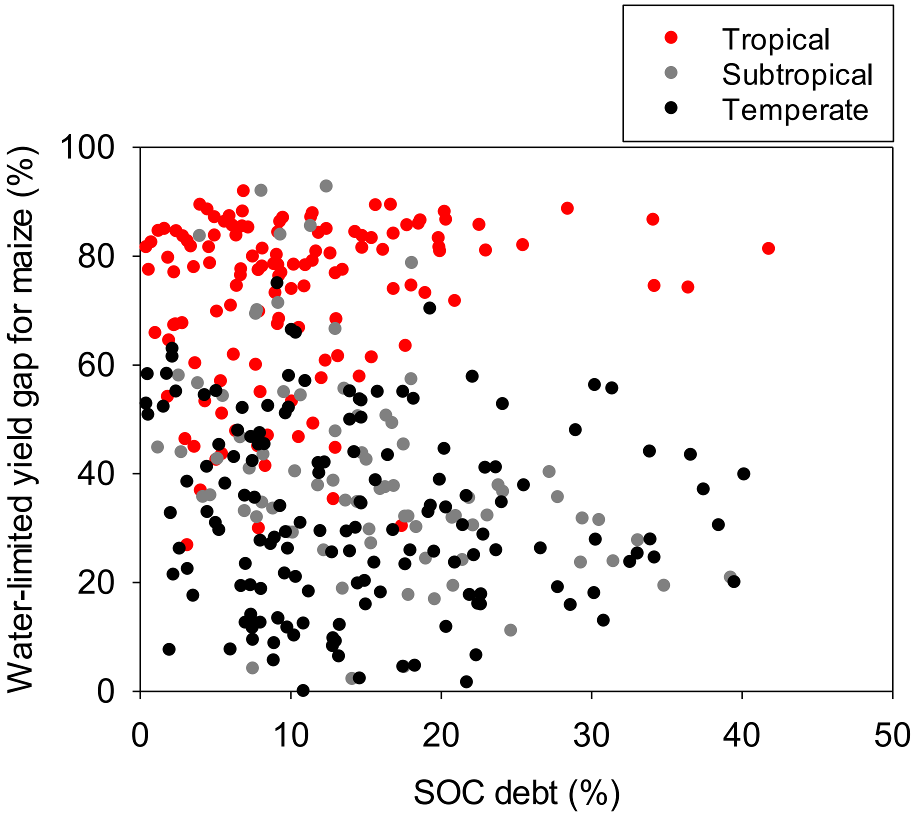
Supplementary Figure 1

The relationship between yield gap (www.yieldgap.org) and soil C debt (data extracted from [1]) show significant variations for given C debts but no overall straight correlation, because other biogeophysical constraints rather than only SOC are limiting yields.




For each station where yieldgap.org [2; 3] has estimated potential yields and extracted actual regional yields for rainfed maize (n = 424), we extracted the soil organic carbon debt for those locations [4]. For illustration, sites were assigned to tropical climates at latitudes reaching 23.5°N or S; "subtropical" indicates sites with latitudes between 23.6 and 40°C at the Northern and Southern hemisphere, respectively.

Each station location is representative of an agronomical important unique climate x soil zone within a country. The mean size of this climate x soil zone is 93 km2 (25th - 75th quartiles = 12 - 103 $km^2$). The SOC debt was calculated at a roughly comparable resolution of 10 x 10 km.

Yield gap was calculated as: YG (%) = 100 x (YP - YA) / YP,

where YP (yield potential) was calculated using an appropriate crop simulation model assuming unlimited water and nutrients. Actual yield (YA) was the 10-year average of reported yields in that region for farmers following typical district practice.

Water-limited yield gap: YWG (%) = 100 x (YW - YA) / YW,

where YW (water limited yield potential) was calculated using a crop simulation model using actual rainfall at each station.

Supplementary Table 1.

Examples for site prioritization considering SOC sequestration potential, yield gap and soil degradation status. Note that this Table is meant as an example for priority setting, which may change with quantification of co-benefits from, e.g., biodiversity, water storage and ecosystem resilience.

| Options | SOC sequestration | Yield Gap | Soil degradation | Priority |
|---|---|---|---|---|
| 1 | + | + | + | Very high |
| 2 | + | + | - | High |
| 3 | + | - | + | High |
| 4 | - | + | + | Moderate |
| 5 | + | - | - | Moderate |
| 6 | - | + | - | Low |
| 7 | - | - | + | Low |
| 8 | - | - | - | Low/None |

Different major Reference Soil Groups (RSG) provide an important though yet underused guide to hotspots where SOC sequestration will be the most efficient. A RSG as defined by World Reference Base for soil resources (WRB) is based on specific and unique combinations of soil characteristics and properties that are relevant for both yield and carbon storage, such as cation exchange capacity, pH, texture, water holding capacity, and hardpans. This is more than the assessment of individual soil parameters, which may not all be available in maps, particularly not for the subsoil, and which alone do not determine how a particular soil may degrade or should be managed. The soil units within the RSG, on the other hand, can help to derive important yield and C-sequestration limiting factors, i.e. improved soil maps could help to steer possible large-scale management support, which would then need to be refined locally. Examples for such soil-specific means refer to Box 1 (main paper):

i) *Fertilizer and organic residue management* with high chance of improving soil fertility, e.g., by adding biomass C to SOC-poor soils (e.g. Arenosols), nutrients to nutrient-poor soils (e.g., Acrisols, Ferralsols, Lixisols), organic residues and gypsum to sodic soils (e.g., [5; 6]) and simply by adding nutrients in "unfertilized" soils [7; 8].

ii) *Liming* is commonly needed to adjust soil pH and thus to maintain high yields and crop residue return, in addition to potential positive effects on faunal activity and soil structure [9] and reducing $N_2O$ emissions [10]. As reviewed by [9], positive effects of liming on SOC sequestration are not yet observed globally but reported for certain soil orders, like the acidic Ferralsols and Andosols with potential Al toxicity and some acidified sites in central Europe. Increasing soil pH may particularly enhance crop yields in regions where low pH constrains crop production, which is estimated to occur at 179 million hectares of arable land [11], being about 12% of the total crop land area. It is specifically relevant in non-calcareous soils with a low buffer capacity (CEC) that are receiving high N fertilizer rates, being the case in large parts of China [12; 13].

iii) *Biochar amendments* add persistent C to soil, aiming at both sequestering C and improving yields (e.g., [14]). Intriguingly, mere biochar additions showed variable effects on yields of some productive soils in humid climates [15; 16]. Biochar amendments resulted in positive effects on soils when they were combined with inorganic fertilizers and organic manure additions irrespective of climate [17], in sandy and clayey soils with needs to improve aggregate formation [18; 19], and in some impressive improvements of the fertility of soils with pronounced anion exchange capacity benefiting from additional cation exchange by oxidized biochar surfaces (e.g., Ferralsols, Acrisols; [20; 21]). Biochar also helped to mitigate other greenhouse gas emissions, such as methane [22] and nitrous oxide [23] as well as to reduce ammonia emissions [24], thus helping to improve N use efficiency [25] at higher overall nutrient demands needed for yield gap closures.

iv) *Soil tillage*, e.g., adoption of reduced tillage or no-till options combined with mulching, particularly on Vertisols with potentially large C sequestration potentials due to elevated clay contents [26], and high C soils prone to erosion and benefiting from increased water storage under intensive cropping, like Kastanozems, Chernozems, Phaeozems [27]. These practices are also promising many soils in the tropics and subtropics like Acrisols and Ferralsols since they generally benefit from organically stored nutrients and in case of surface mulch also from lower soil temperatures, eventually allowing double or triple cropping, for instance. Much more radical methods like soil inversion, flipping or clay devolving may be needed to increase soil productivity and SOC levels in Durisols and other hardpan sites, like in Australia and New Zealand [28; 29], whereas soft methods like traditional subsoil composting can be beneficial for vulnerable sandy soils in arid climates [30; 31].

v) *Altered land-use systems*, e.g., use of precision farming and new field arrangements (e.g., multiple cropping systems) on abundant soil orders like fertile Luvisols with Cambisol associations and thus heterogeneous properties in the landscape, or even the combination of different management systems, such as of paddy management with duck, fish and rice-shrimp farming, for instance, on Fluvisols [32; 33; 34].

vi) *Water management*, e.g., protecting hotspots like peatlands [35] or any other managed organic soils may already positively affect future projections of net C effluxes. The same applies to the protection of carbon stock in mineral soils with high water tables (Gleysols, Stagnosols, Planosols; [36; 37; 38]. Protecting these soils from C losses may be achieved by flooding, or, simply, by avoiding ploughing and keeping them under grass or forest. In soils where water is limited or where yields are impaired by salts, adapted *irrigation* measured may be required.

It should be noted that management options are usually combined to maintain or improve soil fertility. The above-mentioned list is thus meant to illustrate that due to specific properties of different soil groups, different options to manage the soil have different potentials to close yield gaps and therewith to sequester C in the different soil groups. An exemplary first comprehensive guide to soil group-specific management options can be found in the appendix / lecture notes on the World Soil Reference Base [6], which can help policy makers in defining regional management potentials, but certainly require refinement on the ground, then also considering other factors such as length of cultivation, existing SOM levels, production system, farmer income or availability of inputs. Acrisols and Ferralsols, frequently found in the tropics and subtropics, for instance, require liming, are usually limited in P (same as Andosols), basic cations, and also N, and benefit from water storage and low surface temperatures with, e.g., surface mulch. Also, biochar shows most promises for such soil groups, as well as agroforestry, depending on the prevailing climatic conditions. Carbon sequestration in Vertisols must guarantee rooting when the soils have excess water when wet or when they are hard when dry, sometimes requiring specific bed and furrow management. Temperate soils like Luvisols, Chernozems and Phaeozems instead rather require adapted fertilization, maintenance liming, and reduced tillage protecting them from erosion. Arenosols lack soil aggregates and can thus not benefit from measures to improve soil structure, but may benefit from sprinkler irrigation as commonly prone to drought. Similarly, calcareous soils do not require liming but may need, e.g., furrow irrigation.

Any additional nutrient input has to be done with care in order to avoid additional nitrous oxide release as greenhouse gas, if not reduced by temporary microbial N immobilization or nitrification inhibitors, the evaluation of the latter being beyond the scope of this study. Also, the rewetting soil in intensively used agricultural areas must be done with care to prevent excess formation of $N_2O$ and $CH_4$, but to improve the full greenhouse gas balance of the system.

New ways to increase soil carbon contents may evolve, e.g., by using new plant cultivars that store more carbon in soil [39], or by growing algae on waste water-streams for C sequestration and organic fertilizer production [40; 41]. There is also a need for larger-scaled and more open, holistic crop rotations that include ley farming to enhance soil C storage and prevent its losses [42]. However, the success of such measures depends on site conditions and is thus region-specific.

As outlined in the main manuscript, main scientific tasks are now to: (1) Foster the establishment of a regionally relevant soil information system that contains localized information on soil group, degradation status, and yield gap. (2) Establish finely resolved maps showing C sequestration potentials in these regions and as related to yields in order to identify priorities and to define support schemes. (3) Improve predictive models for soil C sequestration as a function of site-specific nutrient requirements and management options in order to allocate resources effectively and to reduce risks when investing in C storage. (4) Develop sophisticated predictive models that include complete full life-cycle assessments of all greenhouse gas emissions on farm. These models are at best extended by closing remaining gaps in terrestrial C modelling, such as erosion-induced transport of SOC, fate of inorganic C, or the global black carbon cycle (see nice-to-have criteria). (5) Create regional and national scale maps of soil carbon sequestration potential. (6) Account for possible ‘leakage’ in carbon market terms, i.e. the transfers of organic amendments to a region from another, where it would also help to sequester C. (7) Provide a broad set of incentives and policy options to address the diverse, region-specific social and economic challenges in implementing C sequestration measures.

Additionally, we identified six nice-to have options:

i) *A-priori assessment of C sequestration potentials*: Estimates of SOC storage and SOC stabilization potential in agricultural soils at the regional to global scale need to be improved [43; 44]. Recently, first global estimates for C sequestration potentials have been provided for the terrestrial biosphere [45], although this requires further validation on regional numbers for the included measures and systems. With respect to agricultural soils, the resolution of such estimates is not fine enough to inform farmers on the optimization of SOC management at the local scale. One of the main reasons is the complexity of historic land use and management [46; 47]. In addition, past land may have left legacy effects on future SOC stock development irrespective of current land-use decisions [1]. As a result, declining SOC stocks despite current SOC conservational management may be observed [48; 49; 50]. Therefore, the development of scenario maps is critical for future SOC stock changes, based on historical data, underpinned with uncertainty ranges, and at best linkable with other similar joint efforts like global yield gap assessment.

ii) *Quantitative estimates on the persistence of sequestered SOC*: How stable is newly sequestered SOC remains a key valid criticism of SOC sequestration efforts. Only parts of the added labile Carbon are stabilized, e.g., via sorptive interactions of formerly dissolved organic C with mineral phases [51; 52; 53]. Another significant portion of additional biomass C input are sequestered in labile pools, because the whole process is controlled by C saturation [54; 55].

Unless C is added in stable forms such as biochar [14], a significant and still unknown fraction may be readily lost upon disturbance, and it will respond differently to unhalted climate change. The response reactions are likely non-linearly related to OM input [4]. Meyer et al. [56] reported that the response of soil C to warming exhibits significant regional variation. To provide reasonable numbers of longer-term C sequestration potentials, it is important to be able to relate potential C storage to potential C response reactions. Thus, it is essential to couple projections on future C storage to the valuing of its vulnerability to climate and management change.

iii) *Evaluation of subsoil storage options for additional C*: Up to 75% of total soil nutrient and carbon stocks may be stored below the plough layer [57; 58; 59], this has not yet even been considered in the 4p1000 initiative. Subsoils usually comprise old radiocarbon ages [60; 61; 62]. Nevertheless, additions of labile C and nutrients promoted mineralization of subsoil C [63; 64], which is also vulnerable upon land-use change [48; 59; 65]. Efforts to sequester C also in the subsoil by converting arable soil into, e.g., grasslands have been successful [66], but not always [67]. A promising alternative might be the direct residue placement into deeper soil, which may even support yield increases [68].

iv) *Gaps in terrestrial C cycle*: Despite recent advances in soil C turnover modelling, the coupling of these models to reduce current uncertainties in global C modelling still warrants further attention. Examples for such gaps are erosion-induced transport of soil carbon: With 36 Gt of sediments transported annually by world rivers, the fate of erosion-induced transport of SOC (along with complete accounting of $CO_2$, $CH_4$ and $N_2O$) must be considered in the global carbon budget [69; 70; 71]. Other examples relate to the modelling of the global cycle of black carbon and the incomplete residues of burning [62; 72; 73; 74]. Additionally, the impact of management on soil inorganic C (SIC) is not yet part of 4p1000, but globally, about one-third of total C is SIC [75]. Routine liming is recommended to sustain agricultural productivity, a typical rate is 4t $CaCO_3$ $ha^{-1}$ in 3 years. This means that up to 360 kg SIC may be released as $CO_2$ per year, which can be larger as the potential C sequestration by no-tillage agriculture, for instance (324 kg C $ha^{-1}$ $yr^{-1}$; [27]). Under paddy management, losses of SIC from parent material even exceeded the amount of SOC sequestered [65]. Gaps do also exist in incorporating organic matter dynamics of peatlands, both natural and drained, into modeling the terrestrial C cycle. Although models for natural Northern Peatlands exist [76]; dynamic modeling of greenhouse gases for managed peatlands is in its infancy. This is a major barrier towards implementing mitigation strategies given the often-observed radiative trade-offs between avoided $CO_2$ and accelerated $CH_4$ [77]. Also, the fate of $CO_2$ in soil is not yet clear, since large parts of $CO_2$ produced in the soil may not be immediately released to atmosphere but leached and thus at least temporarily stored in the regolith, amounting to c.0.1 Gt C annually [78].

v) *Harmonized analytical tools:* There is no method available to directly quantify the SOC sequestration potential in the field. Physical soil fractionation carried out to identify pools of different SOC stability and turnover time must still be adapted to the range of stabilization mechanisms that control SOC cycling in different major reference soil groups, e.g., as reflected in the different role of Fe and Al (hydr)oxides and phyllosilicates in the sequestering SOC in the tropics and temperate climate, respectively. Yet, such analytical procedures may provide early indicators of management impacts on SOC and may help to initialize and parameterize the underlying SOC models [79; 80; 81; 82]. To use these models for putting climate mitigation activities on the ground, however, there is still a need to combine them with longitudinal, long-term experiments, which allow full joint socio-economical and biophysical assessment.

vi) *Monitoring*: to convey farmers of the 4p1000 initiative, it must be a success story that is communicable via regional case studies within a global network approach [83]. For this purpose, there exists a need for well-coordinated large-scale monitoring studies at farm scale and rural areas for filling many of the data gaps in all regions, particularly in those currently underrepresented in global assessments. The monitoring should be specific for the different major soil groups and climatic regions. This monitoring system should likely also involve satellite imaging and spectroscopic soil C assessments [84; 85; 86; 87; 88], however, it should also be accompanied by on the ground surveys to obtain more hard data on the potential role of C sequestration for a range of other ecosystem services, such as biodiversity, water retention, and societal benefits in terms of improved livelihoods. The design of this global monitoring system and registry must be rigorous, verifiably and transparent, and at best underpinned by long-term experiments that include evaluation of social-economical and anthropological information.

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