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A high-resolution spatially-explicit methodology to assess global soil organic carbon restoration potential

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Abstract
Soil carbon sequestration is high on the policy agenda but understanding of its climate change mitigation potential is limited. The bulk of available research on Soil Organic Carbon (SOC) restoration concentrates on local scales. We made a first high resolution spatially-explicit estimation of the global and regional SOC restoration potential over time transposing this research to a higher scale. We group available soil restoration technologies into 16 restoration categories. Of each category, we determine i) the potential for soil organic carbon (SOC) restoration based on a SOC restoration curve and ii) annual soil loss prevention over the period 2010-2050 derived from WOCAT expert opinion and a literature review. We then determined local suitability of a restoration category considering biome, climate, land use and topography. We used maps of SOC content (30 arc sec) derived from S-World in the natural, current, and continuing production loss scenario to 2050 in natural, agricultural and forestry areas as initial conditions and restoration ceilings. A full-scale SOC Restoration scenario is developed by selecting the most effective restoration technology considering both SOC restoration and soil loss prevention. The Restoration scenario results in a SOC restoration potential of about 15 Gt and prevention of 7 Gt SOC.

Keywords: Soil carbon sequestration; land degradation; sustainable land management; technology applicability limitations; integrated assessment.

Introduction, scope and main objectives

Land degradation poses significant multi-faceted problems to mankind in terms of food and water security, economic development, and wellbeing, and is moreover closely intertwined with other grand challenges: loss of biodiversity and climate change. It is from such a broad perspective on challenges ahead that this study was conceptualised to explore potential options to restore soil organic carbon as one component of land degradation.

Recently, the role of soils and improved soil management in addressing global challenges has gained significant political momentum. The Sustainable Development Goals (SDGs) explicitly mention the urgent need to tackle land degradation, through target 15.3: to "strive towards Land Degradation Neutrality" by 2030. Also, at the UNFCCC COP21 the role of soils in climate change mitigation discussions was significantly upped, including the launch of a new policy initiative (4 per mille) to exploit soil carbon sequestration in agricultural land as a major potential sink. Bonn Challenge pledges from Africa and Latin America to restore 125 million ha of degraded/deforested land point to large scale interventions to improve soil status.

In response to these developments, there is an urgent need for spatial data to guide initiatives on restoration and prevention of land degradation: what practices are available, possible and feasible in each location, and how do they perform? Much research exists on restoration opportunities, but the bulk of it concentrates on local scales. A new approach is therefore much needed that, based on the state of knowledge, enables a global outlook on opportunities and challenges of SOC restoration. Such an approach necessarily combines results from field studies and experimentation with projections.

This paper addresses the following three aims: i) construction of average SOC restoration curves and soil loss reduction rates for different categories of SOC restoration practices, including both SLM practices and reforestation practices; ii) mapping the geographical applicability of each restoration category by application of decision rules per pixel on global map-based local conditions (e.g. biome, climate, land use and topography); and iii) determining a global and spatially-explicit soil carbon sequestration potential up to 2050. It does so by gathering evidence on the velocity of SOC restoration and prevention of SOC losses from SOC restoration practices, grouping restoration practices into categories, considering the applicability limitations of different restoration categories, selecting the most effective restoration categories in each pixel, and finally assessing the aggregated potential for global SOC restoration over all pixels with a restoration potential.

Methodology

We model the global SOC restoration potential in the top 30-cm of soil as a full-scale SOC Restoration scenario by aggregating the effects of the most effective restoration category in each location. The approach is built on the premise that SLM and reforestation practices can affect SOC in two ways:

1. Restoring SOC by improving vegetation cover, productivity, and enhancing soil health, either through amendment of chemical soil fertility (manuring, composting) or altering the physical or biological properties of soils (mostly indirectly).
2. Preventing SOC loss by controlling soil loss by reducing the susceptibility of soils to the impact of rain and wind, e.g. by re-vegetation, soil cover, wind and runoff barriers, and terracing, or by reducing oxidation by decreasing soil disturbance, e.g. through minimum tillage.

Most SLM practices contribute to both effects simultaneously. The extent to which they do so depends on time. However, the shape of the restoration and prevention trend lines is governed by a number of factors:

- Time after investment; A literature survey on results from multi-year and long-term field experiments of restoration options was conducted to construct a SOC restoration curve. This curve provided the basis for SLM category-specific curves.
- SOC restoration potential; S-World input data (Stoorvogel *et al.*, 2017; Stoorvogel *et al.*, under review) provided the potential SOC in soils under natural conditions and optimal agricultural conditions. The S-World methodology generates maps of SOC content under equilibrium conditions, but does not give an indication on the time required to achieve natural or optimal agricultural restoration ceilings. It is important to understand what time is required for restoration to set realistic goals. In this paper this question of restoration speed is addressed. The SOC restoration potential is defined as the difference between current and potential SOC.
- Current levels of soil loss and SOC loss; Schut *et al.* (2015) provide a methodology to establish ongoing trends of NDVI loss over the period 1982-2010. Ten Brink *et al.* (under review) extrapolated these trends towards 2050, corrected for climate change over the period 1982-2010 as a proxy for soil-based production loss (Trend scenario). NDVI losses were translated into SOC losses and diminution of topsoil depth over time due to soil erosion processes using the S-World modelling approach (Stoorvogel *et al.*, 2017). The simulation for 2050 was used in relation to current (2010) topsoil depth to determine annual soil loss over the 40-year interval considering current land use conditions. Top soil loss is considered linearly in this study.

The restoration category allocation mechanism and the determination of the speed and effectiveness of SOC restoration and SOC-loss prevention of the different restoration categories is the focal methodology described in this paper. A second methodological advancement is the use of the restoration category allocation mechanism in conjunction with S-World and the Trend scenario to quantify a first spatially-explicit estimation of global SOC restoration potential. The S-World and Trend scenario datasets provide the current best high-resolution spatially distributed current and potential SOC values on which to apply the allocation mechanism.

Results

When the most effective restoration categories are allocated and theoretically implemented over the period 2010-2050, three outcomes are possible per pixel:

1. There is no restoration potential given the current land use.
2. The potential is not reached, restoration will continue
3. The potential level of restoration is reached; further increase of SOC stops.

Figure 1 shows the selected restoration category per pixel. As costs play no role, categories such as multi-faceted intensification dominate densely populated areas. Agroforestry and grazing management are other categories that are frequently selected.

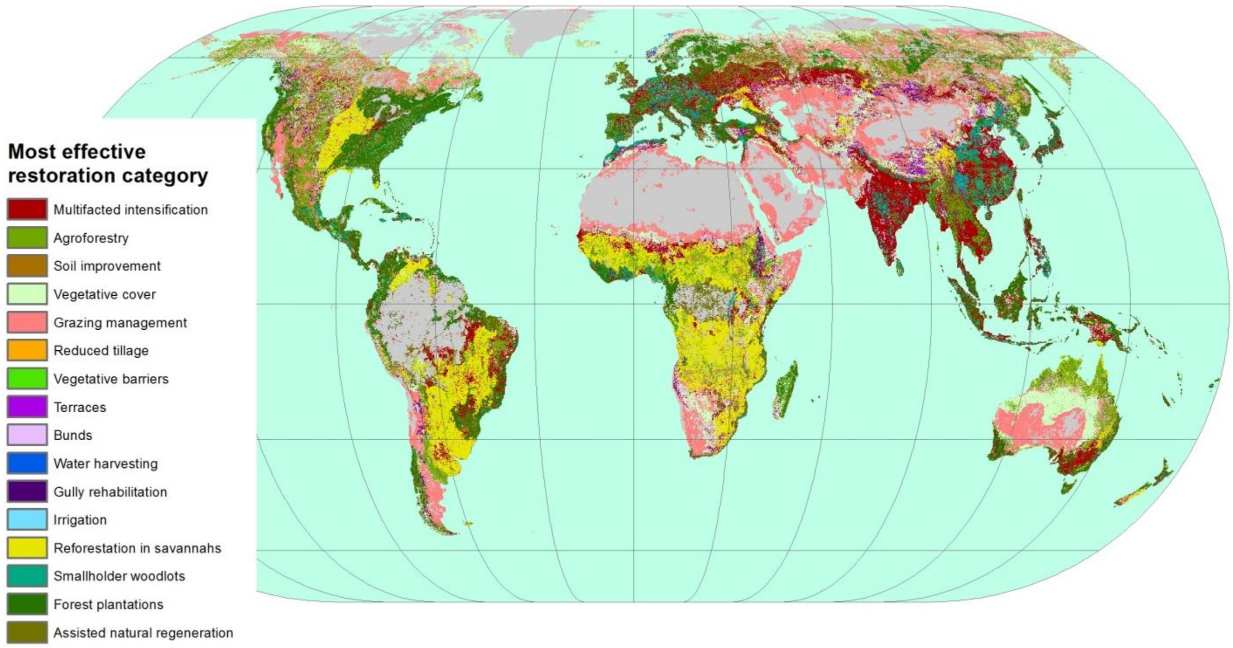

Fig. 1: Most effective restoration technology per location/pixel.

The total global SOC restoration potential of our assessment is 15 Gt. In our assessment, potential SOC restoration was governed by restoration speed and restoration ceilings. Preventable SOC losses by soil loss until 2050 amount to 7 Gt. The total SOC restoration potential is this determined at 22 Gt, spatially distributed as in Figure 2.

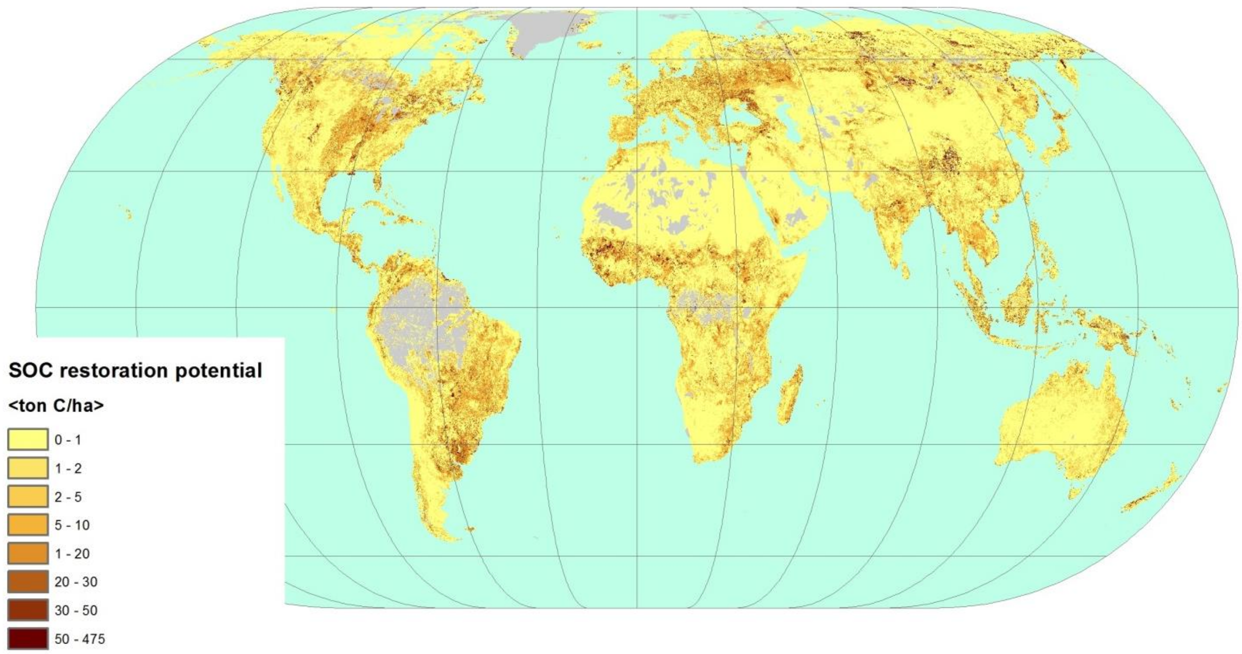

Fig. 2: Soil organic carbon restoration potential until 2050.

Discussion

Smith *et al.* (2008) produced a global estimate of the potential of the agricultural sector to mitigate greenhouse gas emissions, including an assessment of global SOC restoration (maximum of 1.44 Gt year^{-1}). However, they did not consider applicability limitations of individual practices and assumed similar potentials across climatic zones, whereas current soil status was not considered. Sommer and Bossio (2014) estimated the carbon benefits of a highly ambitious but realistically-phased global C sequestration effort in agricultural and grazing land. Their phasing strategy paid due attention to a gradual decline of sequestration potential as soils approach the local equilibrium SOC content. In their approach, a peak SOC accumulation of 1.37 Gt year^{-1} is reached after ~20 years with a total C sequestration potential of 30-64 Gt over a 87-year period. Admunsen *et al.* (2015) build on the work of Smith *et al.* and project a total global effect of restoration of 16.4 Gt to be realized (and exhausted) by 2050. Paustian *et al.* (2016), also elaborating on Smith *et al.* (2008), estimate the total potential contribution of a wider set of soil management practices to be 2.18 Gt C year^{-1}.

There is generally a lack of data on the state of degradation of global soils, but even more so a study that points out the potential for different restoration practices. While other studies have already presented estimates of the global SOC restoration potential (Smith *et al.*, 2008; Sommer and Bossio, 2014), to our knowledge none has jointly considered the restoration of historical and prevention of ongoing losses, its spatial distribution, and related effective restoration categories. Most degraded areas can be restored, but the extent to which is often limited if the same land use is to continue. Hence productivity impacts of SOC restoration should be considered strategically.

The '4‰ Initiative' launched by the French Government, aiming stocking 4‰ SOC every year into cropland and grassland soils (Smith, 2008; IPCC, 2014) to counter balance 3.5 Gt C of the annual fossil fuels seems out of reach when considering our results.

Conclusions

In this paper, we presented a first, high resolution (30 arc second) and spatial-explicit assessment of the global SOC restoration potential. Considering 16 restoration categories covering both SLM and reforestation practices, we defined a theoretical full-scale Restoration scenario assuming instant implementation of the most effective restoration category in each pixel. The potential SOC restoration potential, considering both restoration of historical and prevention of ongoing SOC losses, amounts to 22 Gt. Comparing our results to findings by others, the potential contribution of SOC restoration to climate change mitigation is low, mainly governed by SOC ceilings associated to current land use.