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The 4p1000 Initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy

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Abstract:	Climate change adaptation, mitigation and food security may be addressed at the same time by enhancing soil organic carbon (SOC) sequestration through environmentally sound land management practices. This is promoted by the “4 per 1000” (4p1000) Initiative, a multistakeholder platform aiming at increasing SOC storage through sustainable practices. The scientific and technical committee of the initiative (STC) is working to identify indicators, research priorities and region specific practices needed for their implementation. The initiative received its name due to the global importance of soils for climate change, which can be illustrated by a thought experiment showing that an annual growth rate of only 0.4% of the standing global

	SOC stocks would have the potential to counteract the current increase in atmospheric CO2. However, there are numerous barriers to the rise in SOC stocks and while SOC sequestration can contribute to partly offsetting greenhouse gas emissions, its main benefits are related to increased soil quality and climate change adaptation. The aim of this paper is to present the initiative, to discuss critical issues and to show a way forward to its implementation. The Initiative is a multistakeholder plateform, which provides a collaborative space for policy makers, practitioners, scientists and stakeholders to engage in finding solutions. Strong criticism after its launch was related to the poor definition of the Initiative’s numerical target, which was not understood as an aspirational goal. We identify barriers, risks and trade-offs and advocate for collaboration between multiple parties in order to stimulate innovation and to initiate the transition of agricultural systems toward sustainability.

The Editors of AMBIO

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Paris, 20th October 2018

Dear sirs,

I am writing to you as the chair of the scientific and technical comittee (STC) of the 4p1000 initiative (http://4p1000.org). This initiative was founded in 2015 by the French government and has been thriving ever since comprising by 2018 more than 250 partners from 39 countries. The STC is working towards indicators, research and action programs aiming at implementing sustainable agricultural practices to increase soil carbon storage with the aim to mitigate climate change and increase food security.

Please find enclosed a perspective paper for submission to Ambio, which (1) discusses the objectives and controversial issues of the initiative, (2) highlights the potential of the 4p1000 Initiative to provide collaborative space for policy-science-practice interaction and (3) proposes an implementation pathway from policy to action.

Yours Faithfully,

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The 4p1000 Initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy

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Abstract

Climate change adaptation, mitigation and food security may be addressed at the same time by enhancing soil organic carbon (SOC) sequestration through environmentally sound land management practices. This is promoted by the "4 per 1000" (4p1000) Initiative, a multi-stakeholder platform aiming at increasing SOC storage through sustainable practices. The scientific and technical committee of the Initiative (STC) is working to identify indicators, research priorities and region-specific practices needed for their implementation. The Initiative received its name due to the global importance of soils for climate change, which can be illustrated by a thought experiment showing that an annual growth rate of only 0.4% of the standing global SOC stocks would have the potential to counterbalance the current increase in atmospheric CO_2. However, there are numerous barriers to the rise in SOC stocks and while SOC sequestration can contribute to partly offsetting greenhouse gas emissions, its main benefits are related to increased soil quality and climate change adaptation. The Initiative provides a collaborative platform for policy makers, practitioners, scientists and stakeholders to engage in finding solutions. Criticism of the Initiative has been related to the poor definition of its numerical target, which was not understood as an aspirational goal. The objective of this paper is to present the aims of the initiative, to discuss critical issues, and to present challenges for its implementation. We identify barriers, risks and trade-offs and advocate for collaboration between multiple parties in order to stimulate innovation and to initiate the transition of agricultural systems toward sustainability.

Introduction

In recent years, with rising atmospheric CO_2 concentrations, the role of soils in the global carbon cycle has been increasingly acknowledged. As a result and as a supplement to immediate and aggressive emissions reduction, an increase of soil organic carbon (SOC) sequestration has been promoted by scientists and policy makers as a prospective additional opportunity to partly counterbalance increasing atmospheric CO_2 concentrations (e.g. Lal, 2004; https://www.4p1000.org/). The SOC pool of the terrestrial biosphere is estimated to be around 1500 Gt C to a depth of 1 m. Changes of this large pool may affect atmospheric CO_2 concentrations. Consequently, increasing SOC sequestration through environmentally sound agricultural practices has been advocated as an option to remove CO_2 from the atmosphere (Smith et al., 2016).

In 2015, the French government launched the "4 per 1000" (4p1000) Initiative at the 21st Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC) as part of the Lima Paris Action Plan. The Initiative promotes an innovative model for helping to mitigate climate change, through increase in SOC and contributing to climate change adaptation and food security. It is believed that increasing SOC enhances certain soil functions, thereby benefitting agricultural production (Lal, 2004).

As agricultural activities and land use change account for about 25 % of the CO_2, 50 % of the CH_4, and 70 % of the N_2O anthropogenic emissions (Hutchinson et al. 2007), enhanced SOC sequestration could help offset these emissions (Paustian et al., 2016). SOC sequestration could also help to fill the gap between the intended national contributions and the reality to achieve the Paris climate goal (Rumpel et al., 2018).

Moreover, increased SOC sequestration is likely to generate co-benefits helping to achieve several sustainable development goals, in particular those related to reducing hunger (SDG 2), extreme poverty (SDG1, 3), and improving the protection of the environment (SDGs 6, 11, 12, 14, 15) and the global climate (SDG 13) (Soussana et al., 2019). Particularly, the Initiative may have the possibility to contribute to SDG 15.3, by combatting desertification and restoring degraded lands through increasing SOC storage.

The 4p1000 Initiative mainly focuses on agricultural soils with low levels of SOC due to continuous cultivation and often unsustainable crop intensification practices (Pingali, 2012). The Initiative encourages farm management practices that preserve and build SOC stocks while limiting carbon trade-offs. Adoption of these practices may lead to a transition towards sustainable agricultural production (Tilman et al., 2011; https://futurepolicy.org).

The objectives of this paper are to (1) discuss the aims of the 4p1000 Initiative and controversial issues concerning the Initiative, (2) highlight the potential of the 4p1000 Initiative to provide collaborative platform for policy-science-practice interaction and (3) proposes an implementation pathway from policy to action.

Critiques of the 4p1000 initiative

The 4p1000 initiative was launched based on a thought experiment suggesting that a small increase of the SOC stocks of global soils (4 per 1000 or 0.4% of the standing SOC stock) would remove a significant proportion of CO_2 from the atmosphere, while simultaneously augmenting the capability of agricultural systems to adapt to climate change and to provide food security. The achievability of the Initiative's target of an annual increase in agricultural SOC stocks of 0.4% to a depth of 0.3-0.4 m globally has been intensively discussed and criticized (deVries, 2018; VandenBygaart, 2018).

As a policy goal, a single number, i.e. a quantity of carbon to be stored in soils that appeared to be easily attainable was clear and thus easier to communicate than multiple numbers for different regions or conditions. Articulation of a clear target by prominent promoters of the Initiative including well-respected scientists and policy makers was necessary to ensure inclusion of SOC on the global political agenda (Kong Kam King et al., 2018). The selection of this simplified 4p1000 target for increasing SOC sequestration may be interpreted as analogous to the selection of targets to limit global temperature increase to 2°C or 1.5°C above pre-industrial levels set by the UNFCCC and to targets for Sustainable Development Goals established by the United Nations in 2015. These are broad aspirational goals with much uncertainty about what is achievable, especially in relation to specific geographical locations. The climate science community was faced with similar criticisms when global warming targets were announced. We suggest that some of the controversy regarding the 4p1000 Initiative is attributable to the initial setting of an aspirational target of an annual SOC increase of 0.4% of the standing stock. The initial criticism was related to the suggestion that this could offset *all* fossil fuel emission and that it could therefore be used as an excuse not to drastically reduce CO_2 and other greenhouse gas emissions. This was seen as a complete exaggeration and dangerous. Moreover, the target was interpreted as a strong commitment rather than an aspirational goal. Criticism has also focused on the number, its calculation, significance and achievability. Further, there was ambiguity related to the presentation of the calculation of the quantity of SOC needed to partly offset anthropogenic CO_2 emissions without considering other greenhouse gas emissions (de Vries et al. 2017, Minasny et al. 2018). The initial statements were thus not framed precisely in scientific terms, which made the nature and the role of the target difficult to interpret.

More specific criticisms of the Initiative in relation to biophysical, agronomic and socioeconomic issues are presented in Table 1 and discussed below. These include (1) biophysical limits (demands in terms of water, nutrients and energy), and other barriers such as (2) the trade-off effects, (3) climate change effects and (4) the socioeconomic implications for the agricultural sector, including cultural issues and governance (Baveye et al., 2018; de Vries 2017; van den Bygaaert 2017; White et al., 2018; van Groeningen et al., 2017; Poulton et al., 2018).

Biophysical limits and barriers

Under given constant conditions, SOC stocks will approach an equilibrium level depending on carbon inputs and outputs determined by pedoclimatic conditions, land use and management practices (Fig. 1). Regulation of SOC storage under equilibrium conditions is increasingly ascribed to SOC input (Fujisaki et al., 2018), soil-inherent pedologic characteristics (Barré et al., 2017) and the state of soil development (Schiefer et al., 2018). When land management changes, the equilibrium may be disturbed leading to SOC gain or loss. Following land use change (e.g. agriculture), SOC losses generally occur through increased microbial decomposition rates and through soil erosion (Sandermann et al., 2018). Agricultural practices also often decrease organic matter inputs. For example, in many regions of the world, biomass input into soil is reduced through burning of crop residues (http://www.fao.org/faostat/en/#data/GB), when these could otherwise be used to increase organic carbon inputs. We suggest that improved management practices of agricultural systems are required in order to recycle carbon back to soil. These can be achieved through permanent soil cover, reduced carbon exports (e.g., recycling rather than burning crop residues) or following input of exogenous organic amendments (Chabbi et al., 2017; Chenu et al. 2019).

When management practices leading to increasing SOC stocks are applied, the sequestration rate will decrease as the SOC stock approaches a new equilibrium, beyond which further sequestration will be negligible (Fig. 1; Sommer and Bossio, 2004; Chenu et al. 2019). Modelling has shown that increases in SOC sequestration can continue for 20 years globally (Sommer and Bossio, 2004) and even up to 120 years for specific agricultural practices and pedoclimatic conditions (Poeplau and Don, 2015). However, it is likely that SOC sequestration will not continue indefinitely and that its contribution to mitigating climate warming is time-limited. Permanence of SOC storage will not only depend on the continuity of best management practices but also on the forms of carbon that comprise SOC stocks and stability of pedoclimatic conditions, which may be compromised by climate change. SOC sequestration is only part of the solution to mitigate climate change and must be complemented with other mitigation initiatives that will lead to aggressive and urgent reductions in all greenhouse gas emissions.

Several authors have raised concerns about the nutrients needed for increasing SOC sequestration (de Vries, 2017; van Groeningen et al., 2017). In mineral soils, nutrients are needed to achieve increases in SOC sequestration because they (1) increase plant production and therefore carbon input into soil (Ladha et al., 2011) and (2) build up stable (mineral associated) SOC (Kirkby et al., 2014). In particular, estimates of the amounts of nitrogen and phosphorus required to increase SOC stocks on agricultural land globally were deemed unrealistic (van Groeningen et al., 2017; de Vries, 2017). The nutrient cost of SOC sequestration may be addressed by (1) optimising nutrient management through improved farm management practices (Ditzler et al., 2018), (2) incorporating spatially- differentiated SOC sequestration strategies into precision agriculture and (3) using green manure legumes instead of mineral fertilisers (Soussana et al., 2017). Use of exogenous amendments in the form of farm manure and compost may be part of improved nutrient management practices while additionally contributing to increasing SOC stocks (Diacono and Montemurro, 2010). However, their local application could result in major carbon and nutrient transfers from other locations with no net increase in SOC sequestration, and possible increases in other greenhouse gas emissions (Powlson et al., 2011; Poulton et al. 2018). Exceptions are where the biomass would otherwise be burned or deposited into landfills. In this context, the recycling of organic wastes from domestic activities and urban areas as organic fertilisers is an opportunity to transfer organic carbon in ways that enhance SOC storage, ameliorate the nutrient content of soils and close nitrogen and phosphorus cycles at regional scales (Chabbi et al., 2017; Minasny et al., 2018; Nath et al., 2018). Use of amendments containing organic carbon in thermally stable forms, (biochar), while being a practical way of recycling organic wastes, may avoid inputs of nitrogen and phosphorus to form SOC because of their low concentrations of both elements. Peatland restoration is another option for sequestering SOC with minimal nitrogen inputs due to the high carbon to nitrogen ratios of peatland plants (Leifeld and Menichietti, 2018).

Important biophysical issues that possibly limit SOC storage potential are related to the (1) inherent capacity of soil to store carbon in a stable form, (2) longevity of the additional stored carbon, (3) reversibility if C retaining practices are not maintained and (4) scarcity of crop residues or other biomass and nutrient inputs for soil amendment. We acknowledge these limitations, but suggest that there are many possibilities for improving nutrient and organic residue management at farm, region and national scales, which could be exploited to maintain and if possible increase SOC stocks and improve soil quality. As concluded by van Groeningen et al. (2017), a spatially diversified strategy is needed for climate change mitigation from agricultural soils. Research to develop new innovative technologies is also required.

Socioeconomic barriers

The feasibility of SOC increases will depend on the abilities of farmers to implement changes to management practices as driven by their equipment, skills, operational and economic constraints. Farmers are likely to implement management changes only if there are clear co-benefits, in terms of yields and long-term economic profitability. Some authors have suggested that the achievement of 0.4% SOC increase will not be feasible since farmers are unlikely to adopt new management practices given the low trading price of carbon and more profitable alternative uses of carbon-rich materials (White et al., 2018; Poulton et al., 2018). However, the trading price of carbon is likely to increase with increasing focus on climate change mitigation and adaptation policies providing strong incentives for farmers (Frank et al., 2017). Adoption of novel practices or systems may also require cultural adaptation, as new practices present risks for farmers, when there is insufficient support from farm advisors or where there are vested interests. Smallholder farmers in developing countries may be less interested in change because they are more vulnerable to impacts on food security and community well-being (Lal, 2018). In some developing countries, gender inequality, social exclusion, lack of land rights and/or tenure security, and lack of education impede the adoption of new practices, compounded by the lack of financial resources (Nath et al., 2018; Corbeels et al., 2019). However, there are documented ways to overcome these constraints in at least some locations (Pan et al., 2017). Support for information exchange, finance and capacity building can also enable farmers to adopt more innovative practices. One example is the adoption of biochar technology which, despite being a promising option to improve soil quality and increase SOC stocks (Marousek et al., 2017), remains unknown to many framers and uneconomic to implement due to high demand for organic residues from other sectors and high transportation costs.

Risks and trade-offs

Emissions of greenhouse gases and water use

Non-CO_2 greenhouse gas emissions with a much higher global warming potential may limit the climate change mitigation potential of SOC sequestration. These include N_2O emissions following mineral fertilisation, CH_4 and N_2O emissions from ruminant livestock and CH_4 and N_2O emissions from rice production systems. Practices promoted by the 4p1000 Initiative need to take them into account to ensure that net greenhouse emissions do not exceed the offset benefit from increased SOC sequestration. The trade-off effects between greenhouse gas emissions and SOC sequestration may be dynamic. For example, if fertiliser applications are not reduced, increases in SOC sequestration may no longer offset N_2O emissions when the system is approaching a new equilibrium for SOC storage (Lugato et al., 2018). These dynamic processes need to be evaluated carefully, and should be considered when actions to increase SOC stocks are undertaken.

One critical issue, not yet addressed, is the effect of SOC sequestration on the water balance of (agro-) ecosystems. For example, Jackson et al. (2005) showed that C sequestration in woody biomass reduced water availability for consumption because of increased water loss from the evaporation of intercepted rainfall. In many agricultural systems, irrigation is used to enhance productivity with variable impacts on SOC sequestration (Trost et al. 2013). Especially under arid conditions, water is needed for (1) additional biomass production and thus carbon release into soils (2) microbial activity to transform plant litter compounds into refractory SOC, and (3) compensation of water loss in plants, due to high evapotranspiration, as water is needed for photosynthesis. On the other hand, improvements in soil structure when increasing soil organic matter content have positive effects on soil water retention and infiltration (Pittelkow et al., 2015). These interrelationships need to be considered as well as the fact that water shortage following climate change may put at risk SOC in systems with permanent waterlogging (exp. Paddy rice)

Avoiding emissions from SOC-rich soils

SOC-rich soils and organic soils are among the most fertile sites but some are heavily exploited for agricultural production, often at the expense of maintaining SOC stocks, leading to large releases of CO_2 to the atmosphere (Leifeld and Menichetti, 2018). Globally, peatlands occupy only 3% of land area but are estimated to store about 600 Gt of SOC. This corresponds to around 20% of SOC stored in the first 30 centimetres of soils globally (Scharlemann et al., 2014). Natural peatlands are characterised by continuous waterlogging, limiting organic matter decomposition because of low oxygen supply. For this reason, avoiding further drainage of intact peatland soils should be a priority. Many of these soils are under agricultural management and major contributors to greenhouse gas emissions. A recent analysis showed that degraded peatlands globally store ~80.8 Gt of soil C with emissions dominantly from tropical regions of ~1.91 (range 0.31–3.38) Gt CO_2-eq. yr^{-1} (Leifeld and Menichetti, 2018). The authors also showed that the global greenhouse gas emissions estimated from cultivated peatlands may completely offset the SOC sequestration potential of mineral soils. Therefore, in humid regions, careful management of water-logging may be required to ensure that losses from the large amounts of SOC stored in peatland soils are minimised.

The 4p1000 Initiative as a collaborative platform for policy-science-practice interactions

Increasing terrestrial biosphere carbon sinks could contribute to achieving the ambitious climate change mitigation target of limiting the increase in global average temperature to well below 2 °C above pre-industrial levels by offsetting emissions. The use of bioenergy with carbon capture and storage (BECCS), biochar and SOC sequestration have been presented as possibilities (IPCC, 2006). It is apparent that SOC sequestration is the most viable option because it (1) has been tested, (2) is feasible at large spatial scales, (3) does not constrain the use of land and (4) provides potential co-benefits to meet other SDGs (Smith, 2016). The 4p1000 Initiative attracted attention because it addresses many social issues related to agriculture that impact widely on communities and integrates engagement from many disciplines and sectors. The Initiative addresses global issues to mitigate greenhouse gas emissions and food security and, at the same time, local issues to improve soil quality and agricultural production. However, this broad application also leads to difficulties in engaging adoption to implement the necessary actions. While there are already other initiatives to promote SOC sequestration and improve soil quality, such as the Global Soil Partnership, the 4p1000 Initiative provides a platform to encourage interactions among scientists, policy makers and practitioners (farmers, NGOs, funders…). This tripartite collaboration is important to ensure that policy decisions are based on credible research and that scientific findings are implemented to meet local needs. The biggest challenge to the success of the 4p1000 Initiative is to stimulate collaboration across the breadth of collaborators to agree on actions and their implementation to achieve the target of the Initiative. It should serve as a catalyst to enhance information exchange and collaboration, leading to joint actions by a wide range of stakeholders.

The way forward

The controversy resulting from the initial articulation of the goal of the Initiative has been helpful to promote scientific rigour and policy debate to formulate action. After successful engagement with stakeholders, and elaboration of criteria to assess management actions by the Scientific and Technical Committee of the Initiative (Fig. 2), the next challenge is to build on tripartite engagement between policy makers, scientists and practitioners to promote implementation of best practices. To support the implementation, the 4p1000 Initiative must provide linkages with action plans, contributions and agricultural development projects at national scales. Progress was made at COP of the UNFCCC in Bonn in 2017, where discussion of agriculture and the role of soil carbon stocks were included for the first time in the Koronivia Decision on joint work of the subsidiary body for scientific and technological advice (SBSTA) and the subsidiary body for implementation (SBI) (UNFCCC, 2018). Eight steps for achieving increased SOC sequestration were recently presented. These include protection of existing SOC stocks, e.g. in organic soils, promotion of C uptake through new practices and regulations, monitoring, reporting and verifying impact through advanced analytical techniques and data harmonisation. New strategies need to be tested and communities must be involved. Further, education, identification and coordination of policies as well as provision of financial support to help farmers, who use sustainable SOC improving practices is required (Rumpel et al., 2018). To increase public awareness about the necessity to increase SOC stocks, the Initiative promotes SOC sequestration to a wide audience, including farmers and land managers, agricultural suppliers of resources, other contributors to the supply chain, central and local governments, urban waste managers, and consumers, etc. The 4p1000 Initiative will take advantage of existing online tools and create an interactive platform to support exchange between multiple partners with different roles and from different geographical regions and cultures. It is essential to communicate success stories of increasing SOC sequestration in different pedoclimatic conditions and different agricultural management systems. Moreover, further investment in research and the development of innovative technologies will be needed to provide stronger support for the 4p1000 Initiative. In addition, the Scientific and Technical Committee of the Initiative established a research programme (STC, 2017a). This programme comprises four pillars: (1) Estimation of the SOC storage potential, (2) Development of management practices, (3) Definition of the enabling environment and (4) Monitoring, reporting and verification. Within each of these pillars, key knowledge gaps have been identified and these need to be promoted to engage activities by research organisations and promote investment in these areas. To initiate implementation of C sequestering options that are relevant to local conditions and embrace farmer knowledge along with research findings, innovative learning networks linking farmers, technical assistance organisations, scientists and policy makers are also required. This can be achieved by establishing living labs and networks of demonstration farms to better communicate successful management practices based on rigorous research findings. The 4p1000 Initiative, as an international multi-participant programme, will facilitate adoption of the best management practices and innovative technologies by providing information and promoting international collaboration at all levels (Lal, 2019; Rumpel et al., 2018).

Conclusions

The '4 per 1000' Initiative aims to increase carbon storage in agricultural soils and therefore contributes to mitigating climate change, adapting to climate change and increasing food security (http://www.4p1000.org). The Initiative has potential as an international multi-disciplinary platform combining a recommended research programme with a multi-stakeholder action plan to link scientific research and action. It aims to communicate and promote management actions to increase SOC sequestration through implementation of sustainable development practices. The main strength of the Initiative is that it provides a collaborative space for engagement and discussion between contributors (scientists, practitioners, NGOs, private sector and policy makers) from different educational and cultural backgrounds. With its simple message, the Initiative encourages widespread participation and adoption by many partners. Recent clarification of the initial message has strengthened the rationale for the Initiative. It is clear that SOC sequestration has the potential to offset greenhouse gas emissions to contribute to aggressive, large-scale, urgent reductions in greenhouse gas emissions, as well as to improving food security and climate change adaptation. However, the potential of soils to sequester SOC is limited by biophysical, socioeconomic and political barriers. These need to be overcome by region specific actions and the development and implementation of innovative technologies. While SOC sequestration can make a significant contribution to climate change mitigation, the more certain and principal benefits, especially those on degraded land, will be improvements in soil quality, contributing to food security and agricultural systems that are more resilient to climate change. To achieve this, priorities will need to be decided to ensure that actions are focused on sites and conditions where opportunities to increase soil carbon stocks are most likely to be successful. We conclude that the 4p1000 Initiative is likely to facilitate findings from site-specific studies, practical experiences and model predictions to be incorporated into future policy actions to encourage long-term adoption and implementation of sustainable development strategies.

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Table 1: Classification of the criticisms of the 4 per 1000 Initiative's target and explanation and proposed actions to respond to the criticisms.

Criticism	Articles	Proposed explanation and action	Associated research needs
Poor calculation of target			
Inconsistent inputs for calculation	de Vries 2017	Consistent communication and clear explanation of calculations	na
Global emissions number only reflect CO_2, not CH_4 and N_20, so the calculation of the offset is too low	De Vries 2017; Baveye 2017	Explanation of calculations: only anthropogenic CO_2 emissions are targeted in the calculation of the Initiative, not all anthropogenic greenhouse gas emissions, Actions: non CO_2 GHG emissions should not be increased	na
Biophysical			
C storage is limited. Storage reaches an equilibrium value and the rate of storage starts to decrease once storage is initiated, so the potential for sequestering carbon sequestered will decrease rapidly over time.	White et al. 2017 ;Baveye et al. 2017 ; Schiefer et al. 2018	Even additional storage over a few decades would help mitigate CO_2 emissions. Predictions must account for these dynamics	Assessments of the local/regional/national C stocks and C storage potential considering time limits
Non-permanence of SOC storage	Baveye et al. 2017 ; Poulton et al. 2018	Encourage the maintenance of best management practices.	Vulnerability of SOC stocks
4p1000 per year (rate of sequestration over time) is not feasible quantitatively: estimates are too high globally but also locally	de Vries 2017; White et al. 2017	Even an additional storage, less that 4‰ would contribute to mitigate CO_2 emissions. Large variability of SOC storage rates depending on pedoclimatic conditions and management options implemented	Assessments of the local/regional/national C stocks and C storage potential, using long term observations and experimental farm plots
Insufficient biomass available	Poulton et al. 2018	Implementation has to be spatially differentiated. Promote recycling and valuation of waste v (circular economy).	SOC storage potential of organic wastes.
Insufficient nitrogen and phosphorus available	van Groeningen 2017; White et al. 2017; Baveye et al 1017	Where possible, N-use efficiency needs to be improved. Implementation has to be spatially differentiated. Avoid use of synthetic or mined fertilisers by alternative practices (e.g., mycorrhizae, legumes, Plant Growth Promoting Rhizobacteria, rotations, waste management and circular economy)	Effects of nitrogen fertiliser on SOC storage in grasslands (has been better studied in cropland). Global estimation of the nitrogen fixing potential of agroecosystems. Development of new fertilisation strategies.

Need for comprehensive greenhouse gas accounting (i.e. include non-CO_2 emissions such as N_2O, CH_4)	White et al.2017; Baveye et al. 2017	A net greenhouse gas balance must be provided for all projects. Avoid or adapt SOC storage strategies in situations with high risk (e.g., inhibitors, liming, timing nitrogen additions, slow release fertilisers, paddy water management)	Conditions conducive to N_2O emissions (nature of organic matter, pH, soil structure)
Not accounting for climate change (temperature increase)	Baveye et al. 2017	Reinforces the need for the Initiative	Temperature sensitivity estimates have been based mostly on disturbed soil and laboratory incubations. Perform more *in situ* measurements
Enhanced mineralisation on addition of easily decomposable carbon (priming effect) could release more CO_2	Baveye et al. 2017	Measure changes in SOC storage rates under field conditions, integrate enhanced priming effect if any	Modelling and experiments to quantify and reduce priming effects
Not all carbon is organic; inorganic carbon could release large amounts of CO_2 with temperature rise or microbial activity	Baveye et al. 2017	Inorganic C dynamics must be accounted for in climate change modelling	Model temperature and microbial activity to assess climate impacts of inorganic carbon in soils
Better measurement and monitoring are needed to implement the initiative	White et al.2017	Use best available methods for measurement and activity . Improve and disseminate measurement guidelines.	Developing high through-put and low cost methods to monitor changes in SOC stocks
Many soils are already well managed therefore presenting limited opportunities to increase SOC storage		Concerns only certain regions; the majority of agricultural soils is not managed sustainably	Maintain best management practices; Identify most promising sites;
Socio-economic			
Farmers will not be able to adopt practices due to social and institutional and economic constraints (costs, need for continuous financial incentives)	White et al.2017; Poulton et al. 2018; Baveye et al. 2017	Address first farm sustainability (SOC storage is likely to also lead to success in sustainable production). Demonstrate the benefits of soil carbon and related incentives. Identify whether benefits outweigh costs. Capacity building. Develop policies.	Quantify the benefits of SOC increase on productivity and resilience, so that a monetary value can be attributed to SOC increases. Show levels of sequestration possible based on different carbon costs.
Political			
The 4p1000 is proposed to avoid making any changes in community lifestyle	White et al.2017	A strategy reducing the fossil fuel consumption of communities is out of scope for the Initiative but the Initiative contributes to the much broader Paris agreement of the UNFCCC	na

Overall credibility of the soil science community is weakened	Baveye et al. 2017	Even additional storage of less that 4‰ would help mitigate CO_2 emissions. The 4p1000 Initiative is an aspirational target to contribute to climate change mitigation	Improve estimates of SOC sequestration potential at the local to the global scale

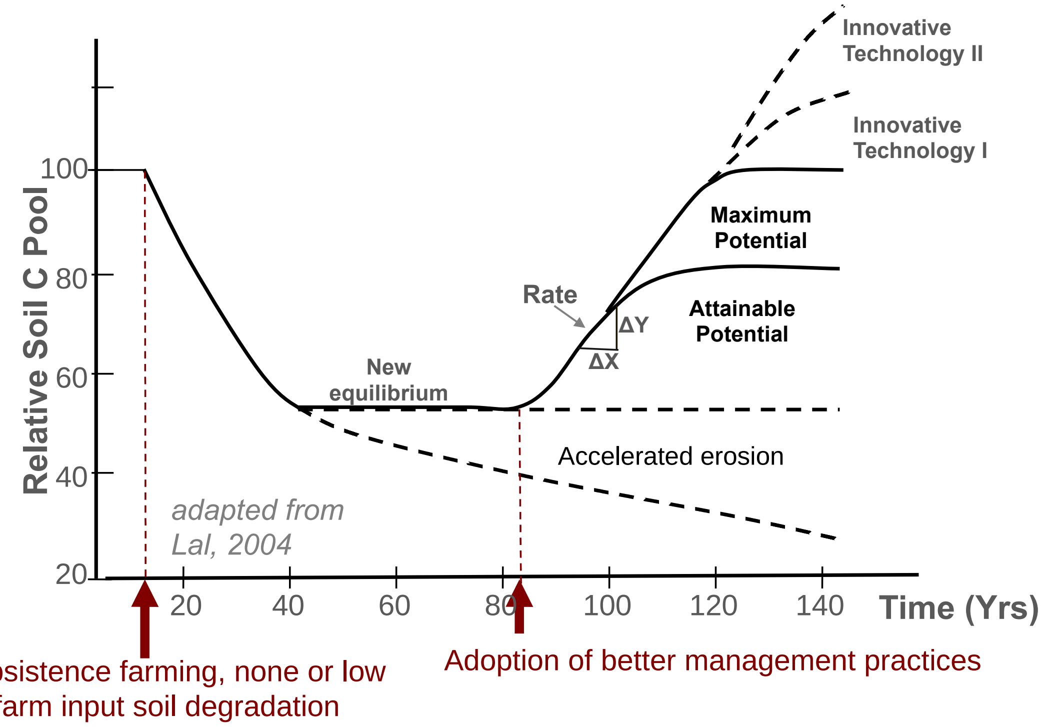

Fig. 1. SOC trajectories after adoption of improved management practices, adapted from Lal (2004)

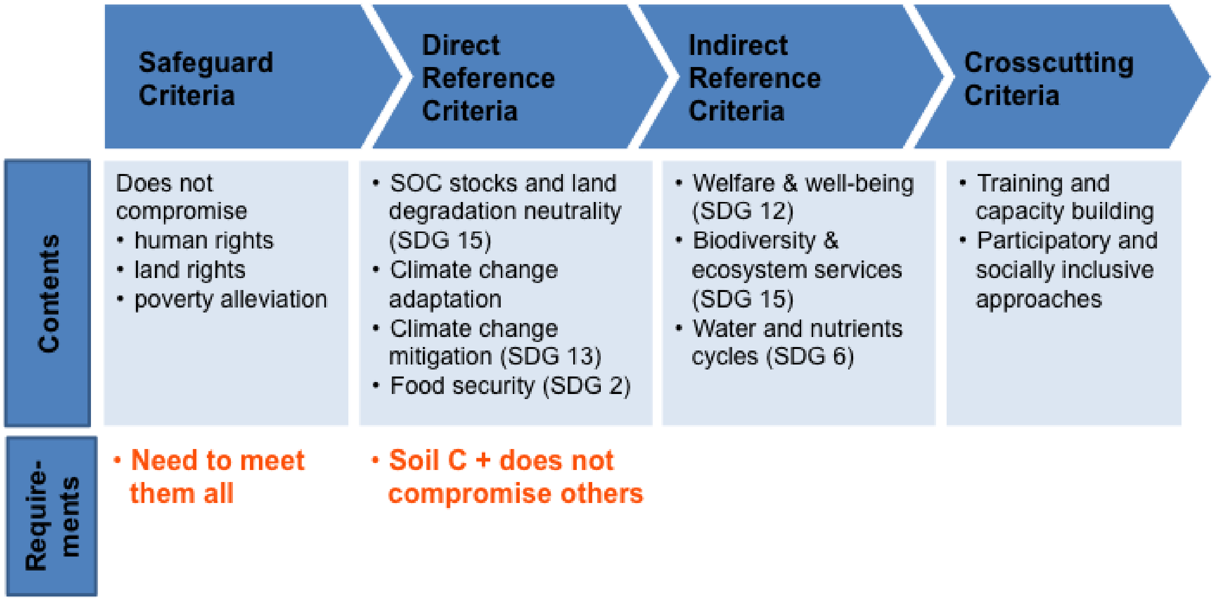

Fig.2: Criteria that need to be met by management actions implemented under the 4p1000 Initiative (STC, 2017b)

Dear Dr. Söderström and Dr Andren,

Thank you very much for your mail with the evaluation of our manuscript. The comments of the editor and the reviewers were addressed carefully and the manuscript improved considerably as a result. We thank the editor and the reviewers for their time and effort and hope that the paper is now acceptable for publication. All changes on the manuscript are marked in yellow. In particular the following has been done :

This Perspective ms concerns the 4p1000 initiative, founded in 2015 by the French government – now with more than 250 partners from 39 countries. In the Abstract it is a bit unclear what this means, but the cover letter states that: "The STC is working towards indicators, research and action programs aiming at developping (sic!) and implementing sustainable agricultural practices to increase soil carbon storage with the aim to mitigate climate change and increase food security." "which (1) discusses controversially (sic!) the objectives of the initiative, (2) highlights the potential of the 4p1000 Initiative to provide collaborative space for policy-science-practice interaction and (3) proposes an implementation pathway from policy to action." The first question is if this a scientifically important initiative (including applications and 'saving the world')? The second question is if this is for Ambio? It can be argued that there are numerous more or less ephemeral collaborative efforts – leading to some travel, some scientific sightseeing and some documents of minor value. However, this is a very crucial subject in mitigation, and the ms deals with the issues and criticism that have been put forward. Clearly, thorough thought is behind this. The second question – is this for Ambio? – can be answered positively.

Thank you for this apprehension.

A Perspective article can be used to present global cooperation – and it contains a review on soil C sequestration as well as (perhaps too many) different scientific schools on what really happens in the soil… Both reviewers are positive and recommend Minor revisions. Rev. 1 Points out the misleading title, and a too detailed review with individual papers instead of meta-analyses. Also, the reviewer has concerns about the old argument on stabilizing factors and saturation etc.. Rev. 2 wants more discussion on the 'policy-practice interactions for SOC sequestration' promised in the title. Here I will step in as an additional reviewer, having worked in this field some years (www.oandren.com). This is more a review of the subject than "stimulating policy-science-practice interactions" and the title should reflect this. But see below. The Abstract and cover letter should be revised – the definition of what 4p1000 and STC is should be in the Abstract.

Ok, we included the definition of what 4p1000 and the STC is in the abstract, changed the title and revised the cover letter.

Table 1 is excellent – addressing criticism openly is good science. However, the solutions in the Table to 'Insufficient nitrogen and phosphorus available' are unrealistic.

Ok, we reformulated.

The present human population as well as soil C levels are dependent on 'synthetic' and 'mined' fertilizers – N fixation etc. has its uses but in modern agriculture that has good yields fertilizers are necessary – organic is a green dream. Note also that manure is a product that is very wasteful concerning efficiency in energy as well as nutrient losses – ammonia etc. Also, green manuring will lead to N leaching as well as N2O emissions etc.

We should all go vegan (not that I like this) to save the world. Plants need nutrients – we have long ago - green revolution etc. – passed the point of no return - we need fertilizers. Ambio is not a soil science journal, and the 'quarrel' on 'saturation' etc. is way too detailed.

Ok, we removed discussion on saturation.

There was and is so much misunderstanding here. Saturation is the wrong word for 'in balance'. The gradual increase in soil C after increasing inputs that gradually reaches a new 'steady-state' has so often been interpreted as 'saturation'. This is wrong; if you add more C per year, a new steady-state will be reached after some time – perhaps decades or centuries. Some clay soils can physically protect C, but also these soils can exceed 'saturation'. Just bring on more manure! Probably most fractions will decompose faster than 'physically protected' but the soil is not 'saturated'. In Sweden there are sandy soils with very high C content without 'protective capacity' – probably due to previous inputs of heather vegetation. The discussion above (I am guilty) is exactly what should be deleted from the ms – the reader is interested in the big picture – not soil science infighting… Therefore, the Chapter 'Biophysical limits and barriers' should be shortened considerably.

Ok, this has been done.

The assumption here that resistant fractions are 'stabilized' is misleading. As said above, even a sandy soil can have stable fractions (in the extreme case biochar) that have nothing to do with soil properties – they are products of microbial activity or even compounds that were in the original plant. Use the term stable, resistant or refractory!

Ok, we use these terms.

Line 136: "It is well established that there is an upper limit to SOC sequestration in soils." This is extremely misleading! I do not understand what this means – is this an idea that soils have a 'protective capacity' and you cannot maintain any higher C levels? So if I add manure every year it will go poof into the air – including the perhaps 10% very resistant compounds in the manure? Instead discuss equilibria, steady-state values etc. Cut out most of line 136-154 and why not ask a modeler about more or less stable fractions in most models.

Ok, most of the discussion related to saturation, protective capacity of soil etc. was removed and replaced by a discussion on equilibria and steady state.

Line 294- Good discussion on tradeoffs.   In conclusion, this can be published in Ambio after a major revision. Besides dealing with the comments above and by the reviewers it would be preferable if the ms was shortened by at least 30%. There are too many references and too many general statements. Focus on why, and what 4p100 is and want to achieve, and only paint a simple picture of what happens in the soil. You do not understand this wholly, and neither do I! The Perspective is not a review, and more than usually aimed at semi-laymen. Or women.

Ok, thank you for these helpful remarks. We carefully addressed those, in particular through shortening the MS (from 5200 word to 3774), removed references (from 90 to 42), general statements and specialised discussion on soil processes.

Reviewer #1: GENERAL COMMENTS: This is an interesting and well-written review on the 4p1000 initiative including a detailed discussion of critical points of the initiative as well as a (shorter) section on future challenges to implement the initiative. As the main part of the manuscript is related to critical points of the initiative raised by the soil science community, the title ("stimulating policy-practice interactions…") is somehow misleading. The paper provides a thorough overview on the initiative, its limitations and major challenges for implementation and is thus a valuable contribution.

Thank you for this appreciation. We changed the title according to better reflect the content of our perspective.

After a revision in terms of following minor points it is acceptable for publication. L108-115: There are thousands of studies on C sequestration by various practices (mainly agricultural management) and numerous meta-analyses, why did you refer to these single observations? I suggest at least include some of the most prominent meta-analyses.

This paragraph was removed from the manuscript in order to shorten the manuscript.

L148-150: I would not say that recent work of McNally et al. 2017 and others have generally challenged the concept of minerals as primary regulator of SOC stabilization, they further gained insight into the properties of the fine fraction that determine the SOC stabilization capacity. Moreover, the "Hassink concept" may be not valid in e.g. allophanic soils, but this does not mean that it does not work in other soils.

Ok, the paragraph discussing these aspects was removed according to the suggestions of the editor.

Table1: What I am missing in this table is the fact that in many regions/countries (e.g. Central Europe), a large proportion of (agricultural) soils is already managed in a "good" way (e.g. soils under organic farming), so there may be limited potential to build up SOC by improved management.

Ok, this aspect was integrated into the table.

MANDATORY TO ANSWER QUESTION 1 TO 4 1. Does the subject of the manuscript fall within the scope of Ambio? (exploring the link between anthropogenic activities and the environment; especially encouraged are multi- or interdisciplinary submissions with explicit management or policy recommendations). Yes Comment: 2. Is it comprehensible not only to specialists but also to scientists in other fields and interested laymen? Yes Comment: 3. Is this a new and original contribution? No, is a Review Comment: 4. Are the results of sufficiently high impact and global relevance for publication in Ambio? Is the manuscript set in an international context and does it demonstrate how it builds on previous work on the subject? Yes Comment:

Reviewer #3: GENERAL COMMENTS: In this review the 4 per 1000 initiative is presented with a focus on critical points as well as a discussion of its practical implementation. From my point of view such a critical discussion is highly needed in order to make a step forward towards practical implementation of the initiative. However, I miss a more concrete discussion in which way "policy-practice interactions for SOC sequestration" could be stimulated as promised in the title.

The title was changed. Additionally, a more concrete discussion on policy-practice interactions was added.

After a revision in terms of this point the manuscript should become acceptable. MANDATORY TO ANSWER QUESTION 1 TO 4 1. Does the subject of the manuscript fall within the scope of Ambio? (exploring the link between anthropogenic activities and the environment; especially encouraged are multi- or interdisciplinary submissions with explicit management or policy recommendations). Yes Comment: 2. Is it comprehensible not only to specialists but also to scientists in other fields and interested laymen? Yes Comment: 3. Is this a new and original contribution? Yes Comment: 4. Are the results of sufficiently high impact and global relevance for publication in Ambio? Is the manuscript set in an international context and does it demonstrate how it builds on previous work on the subject? Yes Comment: OPTIONAL TO ANSWER QUESTION 5 to 15 5. Are the interpretations and conclusions sound, justified by the data and consistent with the objectives? Yes Comment: 6. Does the title of the manuscript clearly reflect its contents? Will it catch the reader's attention? Yes Comment: 7. Is the abstract sufficiently informative, especially when read in isolation? Yes Comment: 8. Is the statement of objectives of the manuscript adequate and appropriate in view of the subject matter? Yes Comment: 9. Are the methods correctly described and sufficiently informative to allow replication of the research? Yes Comment: 10. Is the rigour of the statistics applied in this paper satisfactory? [Please indicate to us if you feel you are not sufficiently proficient in statistics to judge this aspect of the paper yourself] Yes/No Comment:not relevant 11. Is the organization satisfactory and are the results clearly presented? Yes Comment: 12. Are the figures and tables all necessary and are the captions adequate and informative? Yes Comment: 13. Are the references adequate for the subject and the length of the manuscript? Yes Comment: 14. Is the quality of the English satisfactory? Yes Comment: 15. Is the length of the paper appropriate to the content and/or can you suggest changes, brief additions or deletions (words, phrases) that will increase the value of this manuscript for an international audience? Yes Comment: