GREENHOUSE GAS REMOVAL
RESEARCH PROGRAMME

UK GGR Research Programme
Policy Brief

Soils Research to deliver Greenhouse Gas Removals and Abatement Technologies (SOILS-R-GGREAT)

Summary

The world's soils have the capacity to store large amounts of carbon but they must be maintained in a healthy state. If soils are managed inappropriately their levels of carbon can decrease and, if left to degrade, they can become sources of CO_2. If we are to successfully deploy soil-based greenhouse gas removal (GGR) we need a better understanding of how different types of soil sequester carbon, what influences their capacity to store carbon and what co-benefits occur from promoting soil carbon sequestration (SCS).

The SOILS-R-GGREAT project has provided important insight into how to assess the potential of soil-based greenhouse gas removal (GGR). By creating new frameworks to identify practices and by developing platforms to monitor effectiveness, the project has helped pave the way to evaluate and incentivise soil-based GGR. Advances in Earth observation and spectral methods are enabling better estimations of soil carbon and the quantification of the impact of different factors, such as extreme climate.

Through new research on global croplands SOILS-R-GGREAT researchers have estimated that arable farming has produced a loss of around 25 Gt carbon relative to the natural state in 1975 but, since that time, there has been an addition of about 4Gt of soil organic carbon (SOC) due to improved agricultural practices. This demonstrates the potential for soil-based GGR.

Alongside agricultural management, approaches such as addition of biochar or enhanced weathering of silicate rocks on soils can improve carbon storage. Researchers from SOILS-R-GGREAT have estimated possible CO_2 sequestration from these two techniques in Sao Paulo State, Brazil (see case studies in annex).

As with other GGR approaches, there is a need to consider potential co-benefits and trade-offs. Based on a mapping of soil carbon sequestration to Nature's Contributions to People and the UN Sustainable Development Goals, researchers have suggested that soil carbon sequestration is a 'no-regrets' GGR option which can be implemented quickly. However, researchers also emphasise that this positive impact cannot be taken for granted and soils must be managed carefully to maintain their carbon storage capacity and to prevent a switch from sinks to sources.

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Recommendations

Monitoring SOC is costly and difficult. New approaches and techniques are making inroads into quantifying and lessening uncertainty but they require further development. In particular, there are gaps in modelling which need to be addressed such as consideration of feedback loops and incorporation of co-benefits and trade-offs. A systematic approach can help to combine on-the-ground data with data from new remote methods such as Earth observation (EO), alongside modelling approaches. SOILS-R-GGREAT project researchers have proposed a framework to do this.

Improving soil carbon sequestration (SCS) through land management appears to bring a number of co-benefits for the environment and society, offering a 'no regrets' option. Research has also demonstrated the vulnerability of soil carbon to climate and land-use change which can switch carbon sinks into sources. If we do commit to the improvement of SCS as a GGR technique then there must be clear plans as to how to maintain carbon storage levels in soil.

Other GGR options such as biochar addition and enhanced weathering of silicate rocks show potential to augment SCS for certain types of crop and land use. More research is needed to demonstrate where these gains could be feasible and to assess local conditions that may affect their performance.

A systematic approach can help to combine on-the-ground data with data from new remote methods such as Earth observation, alongside modelling approaches

1. Introduction

Soils play a key role in the carbon cycle by absorbing carbon from dead plant matter. It is estimated that increasing the carbon content of the world's soils by just 0.4 % each year would remove an amount of CO_2 from the atmosphere equivalent to the fossil-fuel emissions of the European Union in 2008 (around 3–4 Gt) (Chabbi et al., 2017).

Researchers have proposed eight steps to increase soil carbon (Rumpel et al., 2000), which include practices to promote carbon storage, such as protecting peatlands and controlling grazing, alongside practices to reduce carbon loss such as adding crop residues to soil, minimising tillage and promoting agroforestry. These approaches are not one-off solutions, but require maintenance to retain soil carbon sustainably (Sykes et al. 2020).

Monitoring and measurement are essential to the effectiveness of these approaches, but large-scale and long-term monitoring is costly, with challenges around access and technical expertise. New technology, computer modelling and combinations of these techniques can provide cheaper, faster and more accurate measurements but will require verification with data from monitoring stations (Smith, Soussana, et al., 2019).

2. Implementing, measuring and monitoring soil-based GGR

To assess the operationalisation of SCS as a GGR approach, SOILS-R-GGREAT researchers created a framework that categorises practices and summarises barriers and potential incentives towards implementation (see figure 1) (Sykes et al., 2020). By depicting pathways to reduce carbon losses and pathways to increase carbon inputs, the framework can enable the assessment of the impacts of practices to enable soil-based GGR.

2.1 Measurement and indicators

Measurement and monitoring are central to assessing techniques to improve SCS. Advances in Earth observation and remote sensing offer novel possibilities, such as satellite imagery to provide data on vegetation characteristics that can be analysed with automatic procedures and algorithms to assess soil carbon content. New spectral methods that rely on reflectance of light from soil to identify different types of organic compounds are also providing new insight. An example of an application of spectral methods to assess soil carbon in vineyards is described in box 2 on page 10.

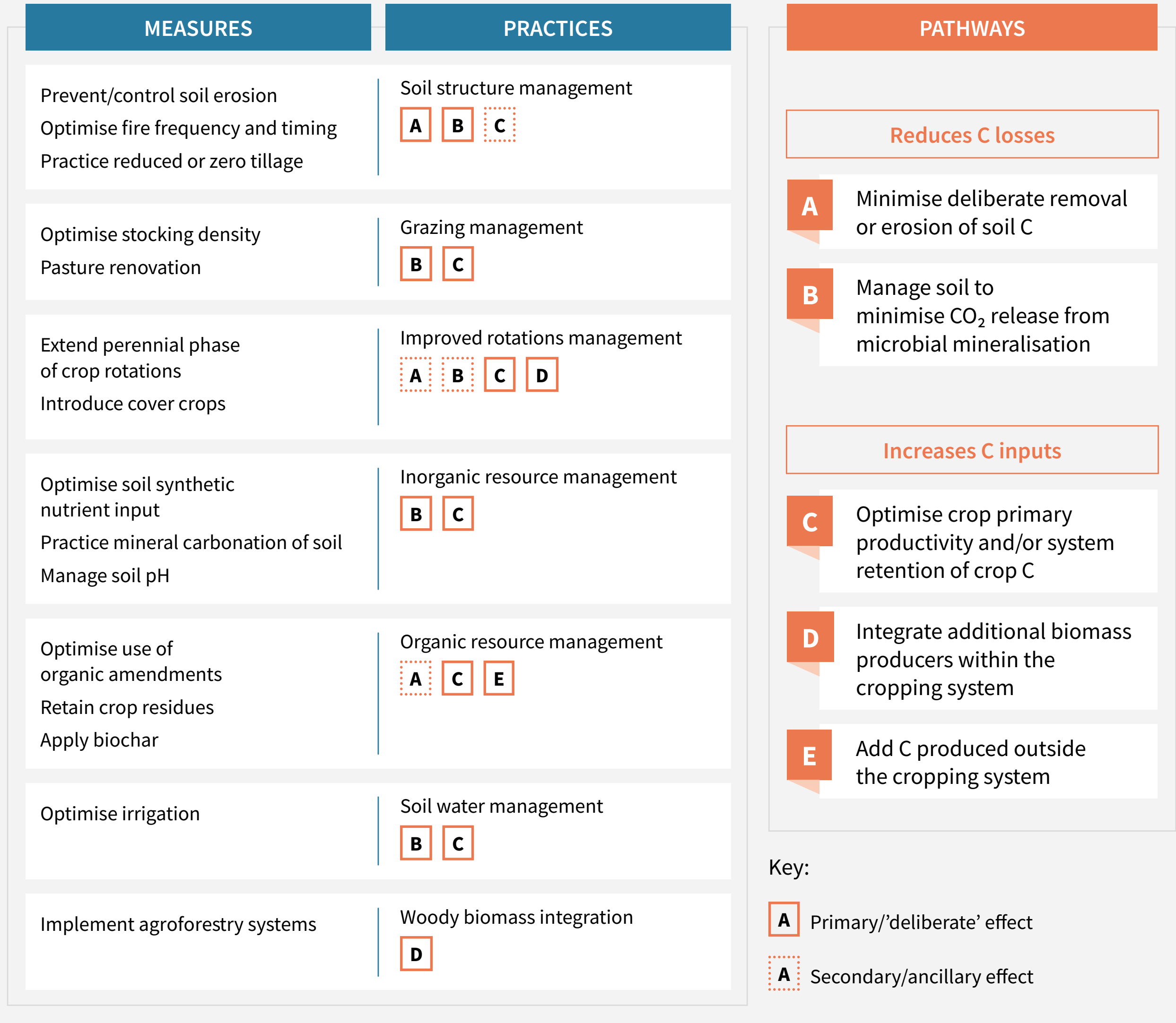


FIGURE 1: **Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology (adapted from Sykes et al., 2020).**

Multi-pool models

BOX 1

Several multi-pool models, such as RothC and ECOSSE have been developed over the last decade to describe responses of soil carbon to land use and climate changes. The ECOSSE (estimation of carbon in organic soils – sequestration and emissions) model uses an approach which describes the soil organic matter (SOM) as different pools of inert organic matter, humus, biomass etc. During the decomposition process, material is exchanged between the pools as described by a specific rate for each pool that depends on temperature, moisture, vegetation cover and soil pH.

2. 2 Modelling and datasets

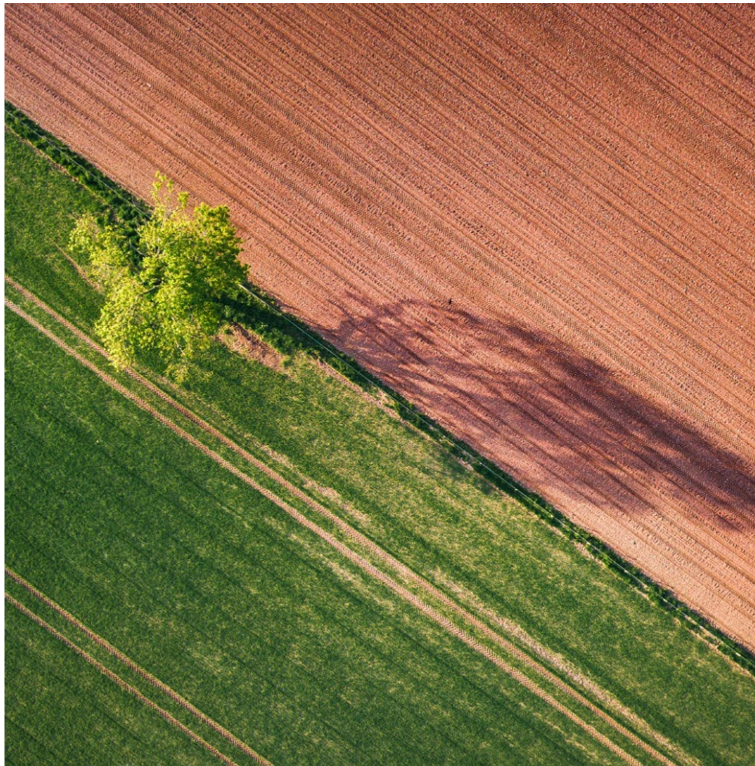
By simulating processes such as photosynthesis and respiration, biogeochemical models estimate levels of SOC. There are many different models that vary in their outputs. SOILS-R-GGREAT researchers ran 23 biogeochemical models over five sites and compared the simulations with experimental data. Most models overestimated or underestimated observed carbon fluxes (Sándor et al., 2020). The ensemble modelling approach adopted in this study performed better than the individual models alone, indicating that it could help upscale projections of carbon fluxes from field scales to larger spatial units.

Soils rich in organic matter and carbon behave differently to soils with low levels of organic carbon. To assess the impact of changes in climate and land use on soils that are carbon-rich, multi-pool models simulate the dynamics within and between a set of hypothetical carbon pools (see box 1).

Expansion of croplands is a major source of CO_2 emissions – not only by the removal of natural vegetation but also by the slow depletion of soils from agricultural management

2. 3 Platform for monitoring, reporting and verifying soil-based GGR

Researchers from the SOILS-R-GGREAT project have proposed a platform for monitoring and verifying soil carbon that brings together direct measurement, modelling and experimental data (Smith et al., 2020) (see figure 2). Central to this are benchmark sites where proposed practices, novel assessment methods and projection models could be tested and calibrated. The framework provides a first step towards implementing and incentivising SCS practices.



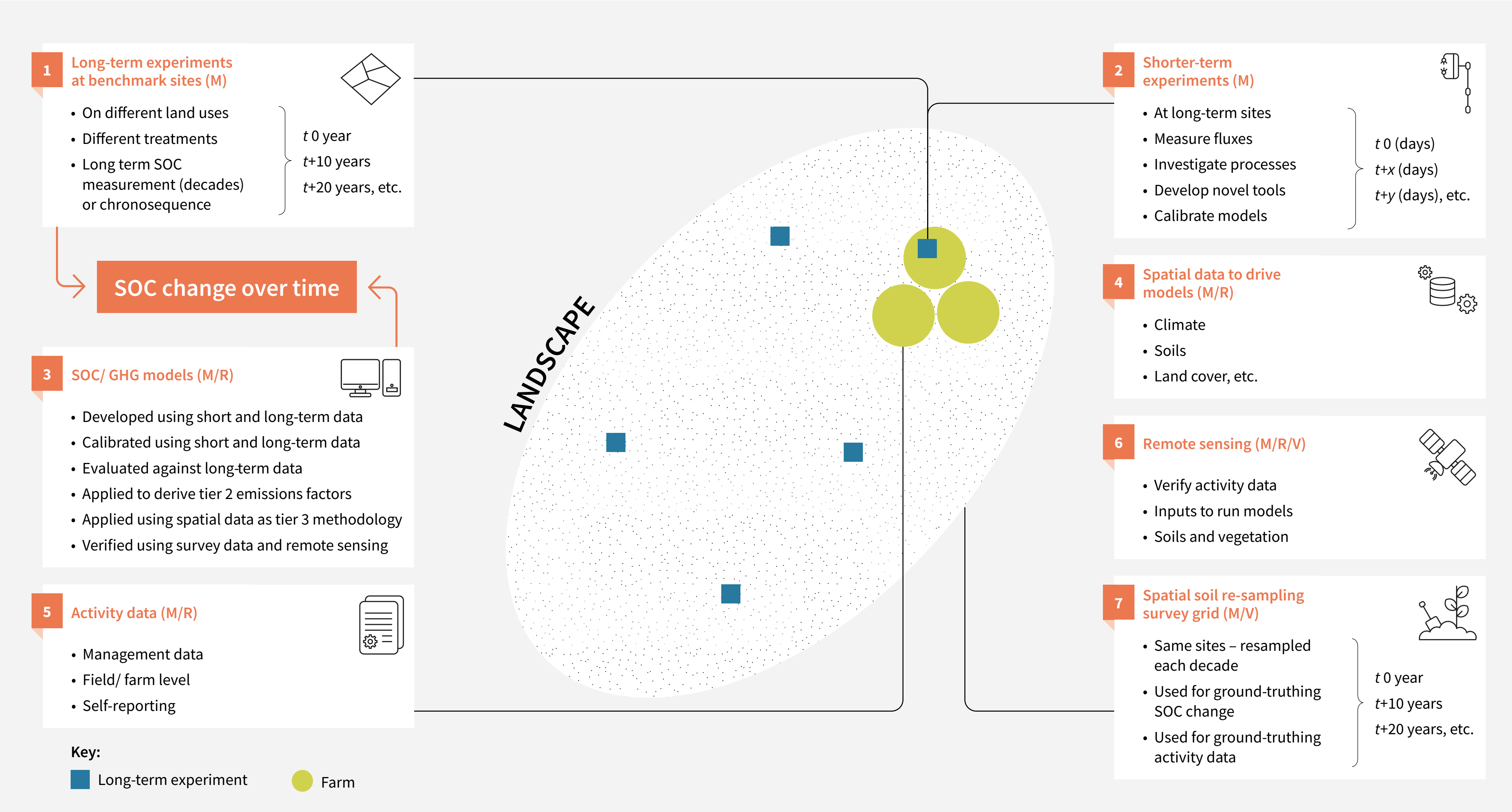


FIGURE 2: **Components of a soil measurement/monitoring, reporting and verification framework, indicating which components contribute to measurement/monitoring (M), reporting (R) or verification (V) (adapted from Smith et al., 2020).**

3. Modelling soil carbon at the national and global level

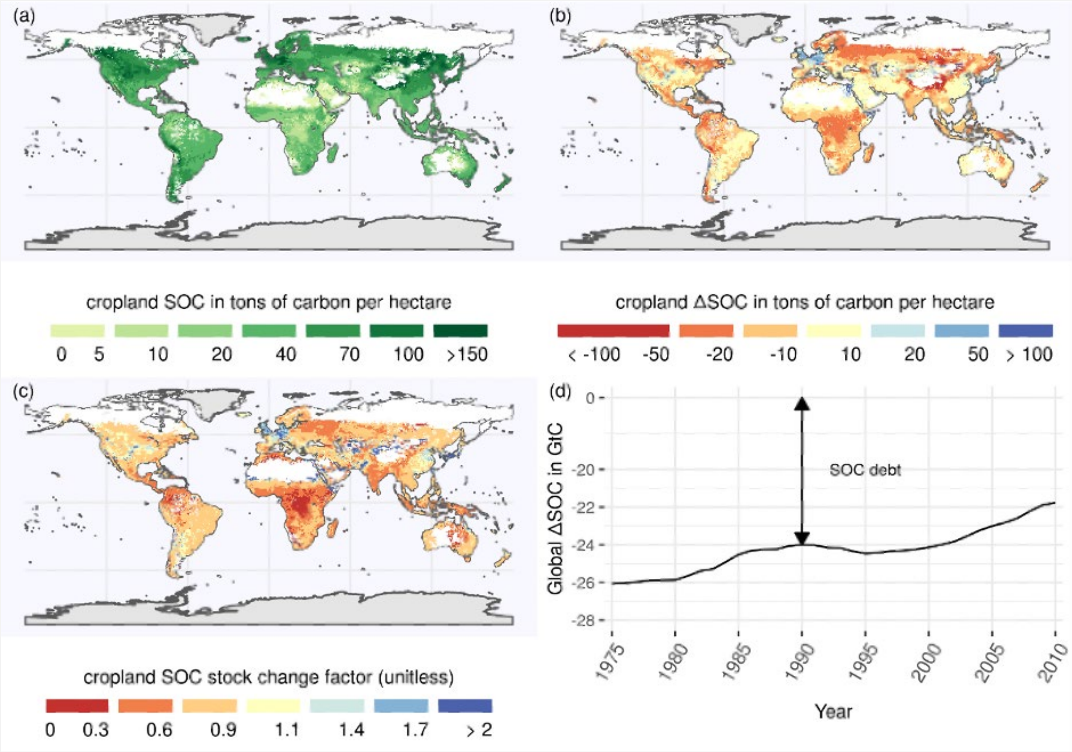
3. 1 Soil organic carbon in croplands

Expansion of croplands is a major source of CO_2 emissions – not only from the removal of natural vegetation but also from the slow depletion of soils from agricultural management. However, models have given little consideration to the management decisions that drive these processes.

3. 1. 1 Impact of past management on SOC in global croplands

New global research has developed a spatially detailed dataset on the impact of agricultural management on croplands that considers different management practices such as return of crop residues, manure application and adoption of irrigation and tillage practices (Karstens et al., 2020). It estimates that due to arable farming, soils have lost around 25 Gt carbon relative to their natural state in 1975. Values range from over 100 tonnes per hectare in northern temperate croplands to less than 5 tonnes per hectare for arid and semi-arid croplands. The spatial detail of the study reveals hotspots of SOC losses and gains (see figure 3).

FIGURE 3: **Distribution of total global SOC stocks for first 30 cm on croplands (Karstens et al., 2020).**



From 1975 to 2010, there was a decrease in SOC debt by about 15% reducing the loss from 25 Gt to 22 Gt carbon. This was due to improved management on existing croplands partly compensating for the depletion of SOC stocks on newly converted soils. One of the most influential management practices is the return of crop residues to the soil. According to researchers, the following practices could further improve SOC:

- Circular flow from food supply chains back to soils through waste composting or excreta recycling
- Soil carbon sequestration techniques such as transformation of carbon into more recalcitrant biochar
- Reducing share of residue burning and improved manure recycling
- Cultivation of cover crops and agroforestry

As highly complex ecosystems with varying combinations of grazing, cutting, re-seeding and fertiliser application, the quantification of carbon stored in grassland soil is challenging

3. 1. 2 Predictions of the impact of future cropland expansion on soil carbon

Projections of future land use often include expansion of cropland in response to changes in climate and food demand. Researchers from SOILS-R-GGREAT have explored this by comparing different socioeconomic scenarios across three models (Molotoks et al., 2020).

The research showed variation on estimates of carbon losses, but with a clear implication that future cropland expansion will have significant negative impacts on carbon storage, with as much as 46 Gt projected to be lost before 2050.

3. 2 Soil organic carbon in grasslands

Grasslands can act as a source or sink for atmospheric CO_2. As highly complex ecosystems with varying combinations of grazing, cutting, re-seeding and fertiliser application, the quantification of carbon stored in grassland soil is challenging. Any carbon sequestration from grasslands is time-limited, reversible and can be outweighed by emissions from grazing systems (Godde et al., 2020).

3. 2. 1 Impacts of grazing density and fertilisation

Biogeochemical models address many complex interactions in grasslands that affect carbon levels but, as with croplands, they vary considerably in their outputs. SOILS-R-GGREAT researchers have conducted an ensemble modelling exercise with eight biogeochemical models at five grassland sites (France, New Zealand, Switzerland, United Kingdom and US) and compared their projections under a range of reductions in the density of grazing animals and levels of fertilisation (Sándor et al., 2018). Modelling results indicated that if the numbers of grazing animals and the amounts of fertiliser are reduced from current business-as-usual levels then there may be a shift towards a carbon sink depending on complex processes by which carbon is fixed in the soil and potentially released. The study confirms that grasslands could be exploited for greenhouse gas removal in beef and dairy production with a reduction in fertiliser use and grazing, but this could only partly compensate for methane emissions from the cattle.

3. 2. 2 Combining Earth observation data with biogeochemical models

Biogeochemical models are generally calibrated and applied at a few intensively studied sites, with limited scalability. Earth observation (EO) produces high-resolution data that is retrieved frequently and can provide a proxy on the state of grassland canopies. The expansion of EO missions and advances in remote sensing have increased the amount and resolution of spatial data on grasslands.

Researchers from SOILS-R-GGREAT have investigated the potential of model-data fusion (MDF) to provide robust near-real time analyses of managed grasslands in England, Wales and Scotland (Myrgiotis et al., 2021). By combining EO data and biogeochemical modelling, they estimated the grassland soil carbon balance from 2017 to 2020, and examined the role of management and the impact of climate abnormalities (summer 2018 was an extreme drought).

The approach estimated that in 2017 and 2018 grassland ecosystems were, on average, carbon sinks, but these were reduced significantly by the 2018 summer drought, with a 9-fold increase in the number of fields that were carbon sources in 2018 compared to 2017, showing that extreme weather can convert grassland carbon sinks to sources.

3. 3 Soil organic carbon in perennial crops

Perennials are defined as plants that live more than two years and include fruits and nut crops, beverage crops, oil crops or short rotation coppices and perennial grasses such as sugarcane, switchgrass and Miscanthus. They produce more plant residues than annual crops and this extra organic matter returns to the soil. The Food and Agriculture Organisation (FAO) of the United Nations has suggested the "perennialization" of agricultural lands could mitigate climate change, as well as enhancing food security and the delivery of ecosystem services. However, there is a lack of evidence about the capacity of perennial crops to store SOC (Ledo et al., 2019).

3. 3. 1 What is the SOC potential of switching to perennials?

SOILS-R-GGREAT researchers have used a global and harmonised dataset of SOC dynamics in perennial crops (Ledo et al., 2020) to explore global changes in stocks after a transition to perennials from other land uses. Results show that a change from annual to perennial crops induces a SOC gain (Ledo et al., 2020). The increase in SOC is especially marked in woody crops, with average gains of up to 0.1 Mg per hectare, but this gain was not linear: the increase in SOC was larger during the initial years after conversion to perennials, after which there was a steady decline in SOC accumulation rate.

Management of vineyards and SOC

BOX 2

Vineyards are perennials and constitute one of the most widespread agricultural production systems in several European countries. They are managed with a broad range of practices.

Researchers have conducted an analysis of global field studies to assess the response of SOC stocks in vineyards to different practices (Payen et al., 2021), such as biochar addition, returning pruning residues to the soil, no-tillage, cover cropping and combinations of these practices. The highest SOC sequestration rate (11.06 Mg CO_2-eq per hectare per year) was achieved under a combination of adding organic matter and no tillage.

Using spectral analyses to create models of soil organic carbon, researchers have also shown that growing grasses and legumes in vineyards improves levels of soil carbon (Ball et al., 2020), indicating that this approach could further enhance SOC in vineyards.

Spectral analysis is a novel approach (see section 2) and this study demonstrates its potential as a valuable method to quantify short term management impacts.

There are a range of soil management practices that affect the levels of organic carbon. Many of these are agricultural practices, whilst others are GGR options applying novel materials to soils

4. Other GGR options that work in synergy with soil carbon sequestration

There are a range of soil management practices that affect the levels of organic carbon. Many of these are agricultural practices (Sykes et al. 2020), whilst others are GGR options applying novel materials to soils. Two examples are the addition of biochar to soils and addition of silicate rock dust to soils (enhanced weathering).

4. 1 Addition of biochar

Biochar is a charcoal-like substance made by burning biomass through a controlled process in a container with very little oxygen. Biochar production is carbon-negative, as the unstable carbon in decaying plants is converted into a stable form of carbon that is stored for potentially hundreds or thousands of years. Biochar also contributes to the mitigation of climate change by enriching soils and reducing the need for chemical fertilisers, which in turn lowers greenhouse gas emissions (see annex for case study).

4. 2 Carbonation and enhanced weathering

Enhanced reactive weathering (ERW) is defined as the process by which CO_2 is sequestered from the atmosphere through the dissolution of calcium and magnesium-rich silicate rocks on the surface of the land. Natural rock weathering is a slow process whilst enhanced weathering involves crushing rock into smaller pieces, thereby increasing its reactive surface and promoting its dissolution and CO_2 capture. By adding silicate rocks to soil and promoting ERW, it is possible to increase its carbon storage in soil (see annex for case study).

As with other GGR approaches, ERW will need scaling to be effective. To assess this for croplands, researchers have modelled the potential contribution of ERW compared to business-as-usual in different nations over five decades (Beerling et al., 2020). Researchers estimated an aggregate global removal of 25–100 Gt CO_2 from ERW, which is similar to that of other GGR strategies. Financial costs are comparable to estimates summarised for bioenergy with carbon capture and storage (BECCS), direct air capture with storage and biochar addition.

Soil-based GGR is attractive, not only because of its potential to remove CO_2 but because initiatives to increase soil carbon can bring biodiversity improvements, ecosystem resilience, climate change adaptability and food security

5. Socio-cultural-economic impacts of soil-based GGR

As well as sequestrating CO_2, soil-based GGR methods have several other impacts on soils and ecosystems, as well as economic and social repercussions (Sykes et al. 2020).

5. 1 Ability to deliver ecosystem services and sustainability

Soil-based GGR is attractive, not only because of its potential to remove CO_2 but because initiatives to increase soil carbon can bring biodiversity improvements, ecosystem resilience, climate change adaptability and food security. However, concerns have been raised about the true value of these nature-based climate solutions and their effect on other mitigation strategies (Anderson et al., 2019). There are also questions around the certainty of their impact on climate change and the length of time it takes (Qin et al., 2021).

Researchers have assessed the impacts of land-based GGR options on ecosystem services and sustainable development by mapping the functions they provide onto the achievement of the 18 Nature's Contributions to People (NCPs) and 17 United Nations Sustainable Development Goals (SDGs) (see box 3) (Smith, Adams, et al., 2019).

BOX 3

Nature's Contributions to People and Sustainable Development Goals

Both SDGs and NCPs reflect attention to interconnected relationships between people and ecosystems. NCPs are both positive and negative contributions of living nature to the quality of life of people. SDGs recognise that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all the while tackling climate change and working to preserve our oceans and forests.

The assessment indicated that soil carbon sequestration along with wetland restoration exclusively deliver positive impacts, whereas afforestation, BECCS and addition of biochar could negatively impact some NCPs and SDGs, particularly when implemented at scale due to land competition. The researchers suggested that the 'no regrets' options, such as improving SCS, could be implemented quickly whilst others require large-scale demonstration to establish monitoring methods for adverse outcomes and risk management plans.

Positive impact cannot be taken for granted and soils must be managed carefully to maintain their health

Research specifically investigating soil-derived NCPs (Smith et al. 2021) has confirmed the role of soil in underpinning all SDGs (see figure 4). Although soil can contribute positively to sustainable development, when it is poorly managed, degraded or polluted, it can also contribute negatively to both NCPs and SDGs.

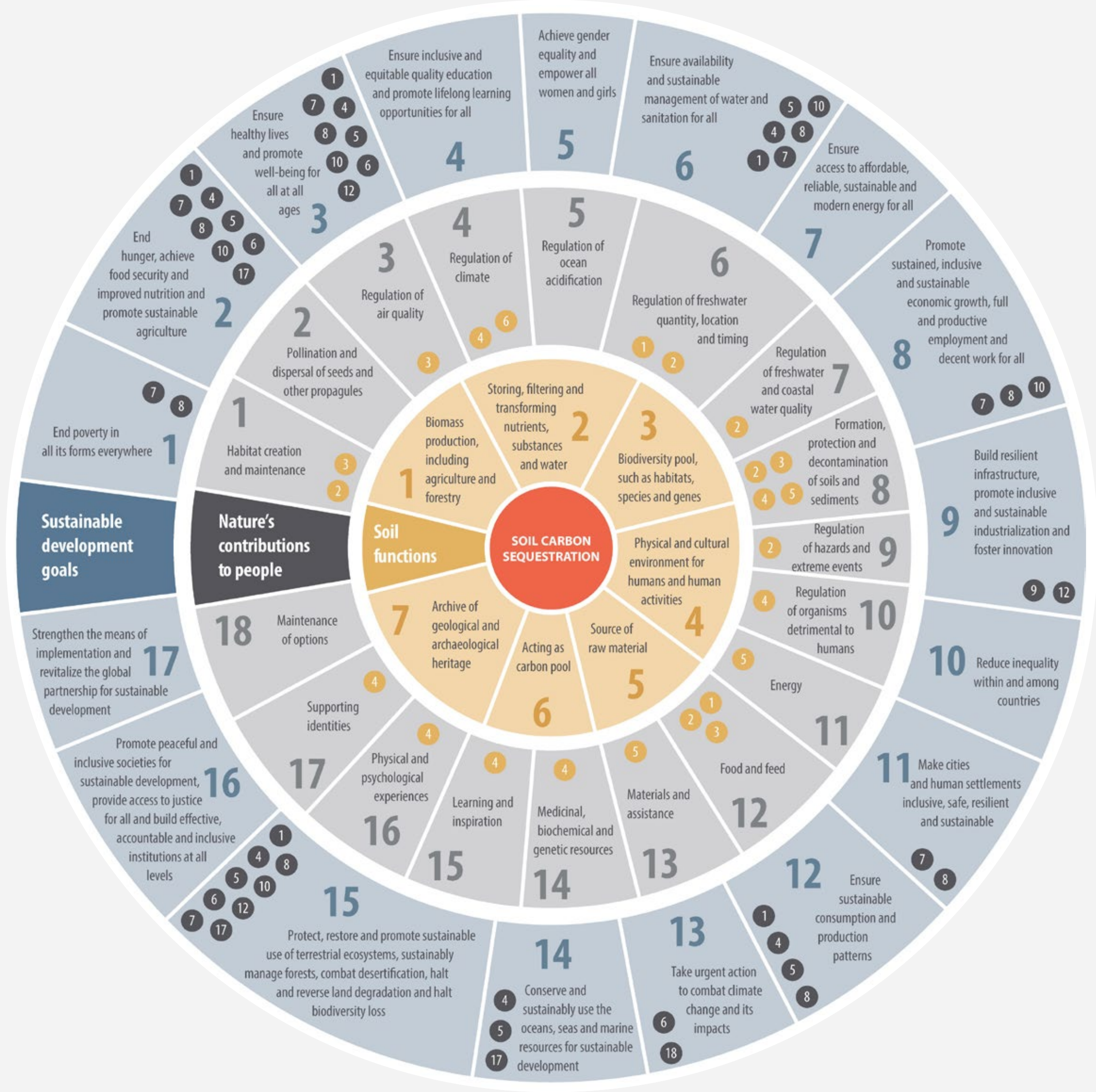


FIGURE 4: **Summary of impact of soil carbon sequestration on soil functions, on NCPs and on the UN SDGs, showing the impact of each function on each NCP and the contribution of the NCPs on each SDG (Smith, et al., 2019).**

Positive impact cannot be taken for granted and soils must be managed carefully to maintain their health. Researchers (Smith et al. 2021) recommend the following:

- protect healthy soils from conversion and degradation
- manage soils to protect and enhance soil biodiversity, health and sustainability and to prevent degradation through approaches such as maintaining ground cover, reducing disturbance and maintaining soil organic matter
- restore degraded soils to full health through options such as reduction in grazing, revegetation and maintaining soil organic matter

Since soil is integral to agricultural systems, soil carbon sequestration measures will also impact the agroecosystem as a whole, and this impact may directly affect the wider social and economic systems (Sykes et al. 2020). For example, implementation of enhanced weathering is likely to increase demand for crushed rock and may reduce demand for fertiliser, which could change system labour demands. Similarly, biochar will create demand for its raw materials and system labour requirements may also change, particularly if biochar is produced on-site. Perennial system establishment is likely to reduce arable outputs, and increase those outputs derived from the perennial crops.

Enhancing synergies and reducing trade-offs is an important aspect of policy formation to help decision-makers choose more effective or, at least, more benign options (Henderson et al., 2022), but co-effects vary with the soil carbon sequestration measures and geographical locations. Many of the co-benefits will not happen automatically and will depend on institutional and enabling conditions for success (see box 4). Future research on implementation successes and failures of these options is needed to inform policy (McElwee et al., 2020).

Enhancing synergies and reducing trade-offs is an important aspect of policy formation to help decision-makers choose more effective or at least more benign options, but co-effects vary with the soil carbon sequestration measures and geographical locations

Rewarding soil carbon sequestration

BOX 4

There are various options for incentivisation systems that consider environmental co-benefits and trade-offs of soil carbon sequestration (Henderson et al., 2022):

- Stacking credits – farmers receive multiple credit revenues for a practice that delivers multiple environmental benefits. This increases farmers incentives for changing to more sustainable practices, but it can be questionable whether environmental co-benefits can be considered additional.
- In contrast, allowing the sale of credits only to one primary market eliminates non-additionality but can prevent adoption of multi-benefit practices.
- An alternative to both is to use a financial additionality criterion to decide which practices are eligible for the sale of credits to multiple markets.

Next steps

Further work is needed to develop and validate new measurement techniques such as Earth observation and spectral monitoring. These could provide an effective and feasible way to monitor soil carbon for soil-based GGR.

Although there has been a great deal of effort to consolidate soil data-sets, they are still uncoordinated and some geographical areas lack case studies, such as in Africa, South America and Oceania. If we are going to rely on soil-based GGR at a global level there will need to be wider and more systematic data coverage.

Monitoring, reporting and verification (MRV) has a core set of elements in terms of observed data, modelled data and data from new measurement techniques. To make progress in soil-based GGR, we must try to establish systematic ways to ensure these elements are integrated into MRV approaches.

Research has demonstrated the vulnerability of carbon stored in soil. To manage it as a GGR technique, we should try to establish a better and more detailed understanding of the triggers and thresholds that are influential in when soil-based carbon sinks become sources.

Questions for the next generation of research projects to address

BOX 5

- How can we estimate levels of SOC more effectively and with more certainty?
- What techniques work to manage and enhance SOC and where are these feasible to implement?
- How can we monitor SOC and incentivise ways to ensure long-term sustainable carbon storage?
- What conditions cause soil carbon sinks to become sources and how can we predict when this might happen?

Annex – Technologies to enhance soil carbon

CASE STUDY 1

Carbon storage using biochar from sugarcane residues in Brazil

Sugarcane is the world's largest crop by production quantity, with 1.8 billion tonnes of cane being produced globally per annum in more than 90 countries. After harvesting, large amounts of biomass are left on the fields which could be made into biochar. Researchers from SOILS-R-GGREAT have used modelling to explore the potential for carbon sequestration with sugarcane biochar in Sao Paulo, Brazil. The results show a potential increase in soil carbon stocks by 2.35 tonnes carbon per hectare per year at application rates of 4.2 tonnes of biochar per hectare per year. Scaling up to the level of the state, this would be 50 Mt of CO_2 per year, which is equivalent to removing 31% of emissions attributed to the state in 2016 (Lefebvre et al., 2020).

To enable a more accurate analysis in the context of wider environmental impact, researchers used a life cycle assessment (LCA) approach to investigate the emissions associated with a change from the combustion of sugarcane residues in a combined heat and power (CHP) plant to the pyrolysis of these residues for biochar production and field application. The research showed that if sugarcane residues were made into biochar and distributed rather than burnt in a CHP system there could be a net carbon abatement of 6.3 ± 0.5 t CO_2eq per hectare. Applied to Sao Paulo State, this could lead to the sequestration of 36 Mt CO_2eq per year or 23% of the State's greenhouse gas emissions in 2016 (Lefebvre et al., 2021).

CASE STUDY 2

Enhanced reactive weathering (ERW) in Brazil

A more detailed understanding is needed of the environmental costs and impacts linked to this soil-based GGR technology. SOILS-R-GGREAT researchers used Sao Paulo State (Brazil) as a case study, because it has the Parana flood basalts with an existing network of basalt quarries close to a large amount of agricultural land on which rock dust could be applied (Lefebvre et al., 2019).

Their assessment included the emissions associated with the rock extraction, comminution, transport and application through a life cycle assessment (LCA) approach. Considering the state's sequestration potential, the study shows that the application of crushed basalt at 1 tonne per hectare on all its 12 million hectares could capture in total 1.3 to 2.4 Mt CO_2eq through carbonation and enhanced weathering, respectively.

Analysis of each process stage shows that transportation of the material greatly reduces the sequestration potential. The weathering of basalt rock on soils improves crop growth and soil fertility and the subsequent decrease in fertiliser and pesticide use would contribute to a reduction of the carbon footprint. These benefits are specific to soil, climate and plants, and further research is needed to ascertain these potential co-benefits.

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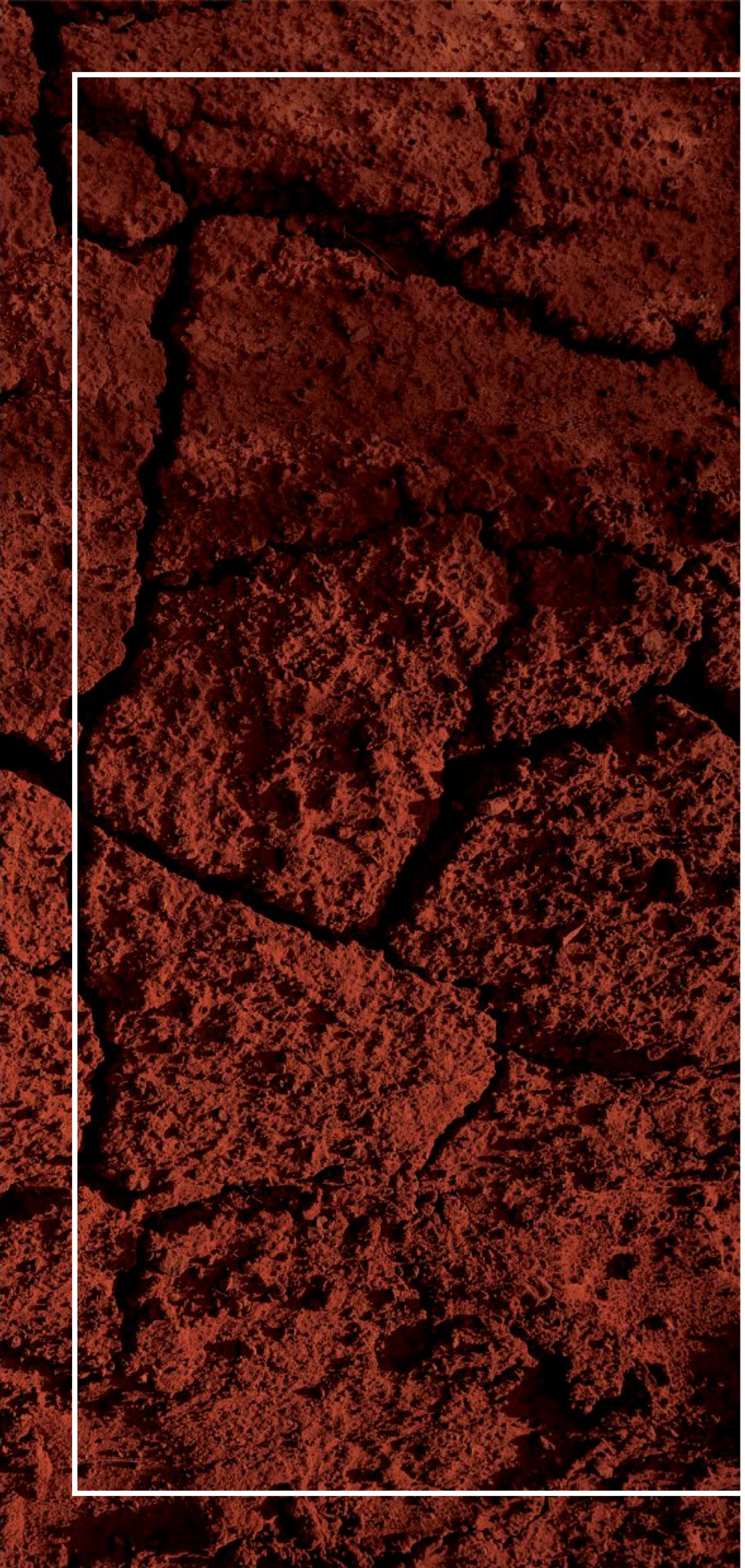
About the programme »



About the programme

The Greenhouse Gas Removal research programme aims to improve our knowledge of the options for removing carbon dioxide and other greenhouse gases from the atmosphere. Through eleven component research projects it addresses the environmental, technical, economic, governance and wider societal aspects of such approaches on a national level and in an international context to inform implementation of climate policy pathways that include large scale removal of carbon dioxide.

The Soils Research to deliver Greenhouse Gas Removals and Abatement Technologies (SOILS-R-GGREAT) project is one of eleven components. This policy brief was created in collaboration with Professor Pete Smith.

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