Mallard Pass
Solar Farm

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Appendix 12.7: British Society of Soil Science “Soil Carbon” (2021)

SCIENCE NOTE: SOIL CARBON

BRITISH SOCIETY
OF SOIL SCIENCE

Highlights

- There is an urgent need to reduce atmospheric carbon dioxide (CO_2) concentrations.
- Supporting natural and agricultural systems to sequester carbon (C) can help achieve this.
- Many soils have the capacity to sequester C from the atmosphere, however the process is slow, easily-reversible and time-limited.
- The greatest and most rapid soil C gains can be achieved through land use change (e.g. conversion from arable land to grassland or woodland), but this can have implications for food production and the displacement or exporting of emissions.
- Increasing soil organic C contents through sustainable soil management (SSM) practices can improve soil health, the efficiency of food production and the delivery of multiple public goods and services.
- Where financial incentives are developed to encourage SSM practices and sequester C it is essential that funders provide ongoing support to these schemes.
- Given the uncertainties around the amount of additional C that can be sequestered in future, and the ease with which C gains can be lost, it is essential that the carbon stores in existing permanent grasslands, moorlands, peatlands, wetlands and woodlands are protected.

Introduction

Recent reports from the Intergovernmental Panel on Climate Change (IPCC) highlight how human activity is changing the climate in unprecedented and sometimes irreversible ways.

The reports make it clear that action to tackle climate change is an urgent priority. The 26th United Nations Climate Change conference (COP26) is due to take place in Glasgow in November 2021 and is seen as critical for establishing a robust path to future zero or negative emissions of greenhouse gases (GHG's) at a global scale. There is an urgent need to reduce fossil fuel emissions to near zero, while supporting natural systems to sequester and store carbon (C). Soils contain more C than in the atmosphere and vegetation combined and are therefore an essential *carbon store*. Under certain conditions with careful management they can act as an important *carbon sink*.

Increasing the amount of C stored in soil is beneficial from a climate change mitigation perspective, but how much C can be stored in this way?

This science note aims to:

- Set out the importance of C in soils, how it behaves, and the role it plays in supporting soil functions, delivering vital public goods and services, and helping societies adapt to and reduce the rate of climate change.
- Raise awareness of the main issues surrounding soil C and the actions that governments, communities and individuals can take.

Carbon sequestration	Carbon store	Carbon sink	Carbon source
A net transfer of carbon (C) from the atmosphere to land (either into soil or vegetation).	*A medium that stores C. Over a given period of time, the amount of C in the store may be increasing, decreasing or static.*	*Any reservoir or medium that over a given period of time accumulates and stores more C than it loses.*	*Any reservoir or medium that over a given period of time loses more C than it accumulates.*

[redacted]

SCIENCE NOTE: SOIL CARBON

Figure 1

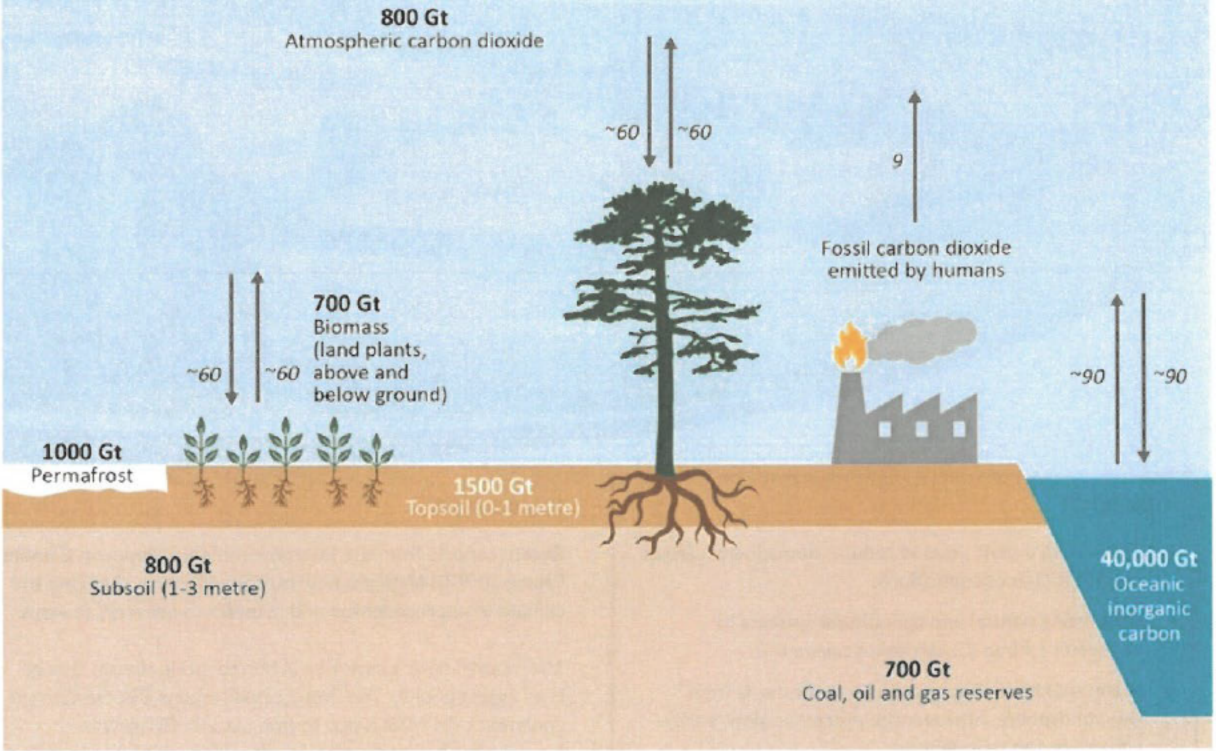

Figure 1: Carbon stocks and flows on land and in the oceans (adapted from Jenkinson, 2010 [1]). The numbers in bold are stocks in Gigatonnes (Gt) C: those in italics are flows in Gt C per year. Topsoil and subsoil stocks exclude peatlands.

What is soil carbon?

C is the fourth most abundant element in the universe by mass after hydrogen, helium and oxygen, and is the primary basis of life on Earth.

The ability of C to form many bonds allows it to form large complex molecules that attach to other elements that are essential to life, such as nitrogen (N), phosphorus (P) and sulphur (S). These bonds also trap energy as a source of fuel for microorganisms.

The soil C stock is around three times that of the atmosphere, at around 2,300 Gt (2.3 trillion tonnes) to three metres depth and 1,500 Gt in the top metre

When plants, animals and microorganisms die and decompose, their remains form organic matter of which about half is C, and on land this combines with weathered minerals from rock (inorganic material) to form soil.

After the world's oceans, soil is the world's largest active C store, holding 80% of terrestrial C, which is almost three times the amount held in the world's atmosphere [2] [Figure 1].

Carbon concentrations are usually smaller in sandy (light) soils and larger in clay (heavy) soils.

Soil organic carbon (SOC) content varies enormously from less than 1% in desert soils to over 50% in peats but is typically less than 5% in most agricultural soils [3].

Deforestation and cultivation can reduce SOC by exposing it to the process of oxidation and conversion to CO_2 which is emitted into the atmosphere. Within soil ecosystems there is a constant exchange of C between SOC and the atmosphere, and these interactions and transformations are part of the global C cycle (Figure 2, page 3).

C is found in soils in two forms:

- **Soil organic carbon (SOC)** – the living and dead components of organisms, including fine plant roots, root exudates, fungi, microbes and decomposing organic matter from plant litter or animal products such as manure.

[redacted]

- **Soil inorganic carbon (SIC)** – chemical compounds such as calcite or chalk (calcium carbonate: $CaCO_3$) [4]. SIC is generally more stable than SOC and accounts for approximately 38% of the total soil C pool. It is much more abundant in the low rainfall regions than in moist, temperate regions of the globe. SIC can also be added to soils in the form of amendments such as rock dust and could be a means of storing more SIC in soils. However, the full cycle and cost-benefit analysis of this emerging technique needs further consideration.

SIC is predominantly controlled by the weathering of C-based rock minerals (mostly underlying chalk and limestone in the UK) and it can essentially be considered to be a fixed constant for most temperate zone soils, notwithstanding the application of lime and other carbonate-containing mineral amendments in agriculture. For this reason, it is SOC that is the more dynamic fraction, being more responsive to management, and it is SOC that is the focus of this scientific note.

Soil organic carbon (SOC) levels can be increased (or decreased) through changes in management, although it normally takes years to decades to bring about measurable change. Where SOC stocks are currently large e.g. under old grassland or forest, it is important to keep them and not lose them through changing land use. Long-term historical loss of SOC, (particularly in arable soils) offers a potential route for future C storage increases.

Soil carbon stocks and flows

Carbon dioxide (CO_2) in the air is absorbed by plants through photosynthesis, creating biomass that is eventually deposited on or in soil as wood, leaf litter, root exudates and root material [Figure 1, page 2]. In well-aerated soils, most of the C in this plant debris is converted back to CO_2 by the activities of soil organisms (fungi, bacteria, etc.) through soil respiration, but a fraction is retained in soil and becomes stabilised to varying degrees. In temperate climates about one third of plant C entering soil is still present after one year. Integrated with the cycling of C is the cycling of important plant nutrients, which enhances soil fertility. As organic matter enters the soil, the soil organisms process it to mineralise the key nutrients into forms that are available to plants [5].

Soil conditions vary and in more extreme environments (such as very acidic, dry or wet) soil C turnover is reduced. For example, in waterlogged soils, with very low oxygen levels, decomposition is slow to non-existent and peat forms along with other 'saturated soil' (anaerobic) decomposition products, including methane (CH_4), an important GHG [2]. Where these conditions are maintained for centuries, such as on upland bogs and lowland fens, peat accumulates over time. However, if these peats are drained, allowing air to enter, microbial respiration is reactivated and the peat C is emitted as CO_2 at rates in excess of 30 t CO_2/ha/yr [6], although it will take many decades to lose all this stored C.

Plants also respire all the time (Figure 2) and use the sugar produced through photosynthesis to drive their metabolism in

Figure 2

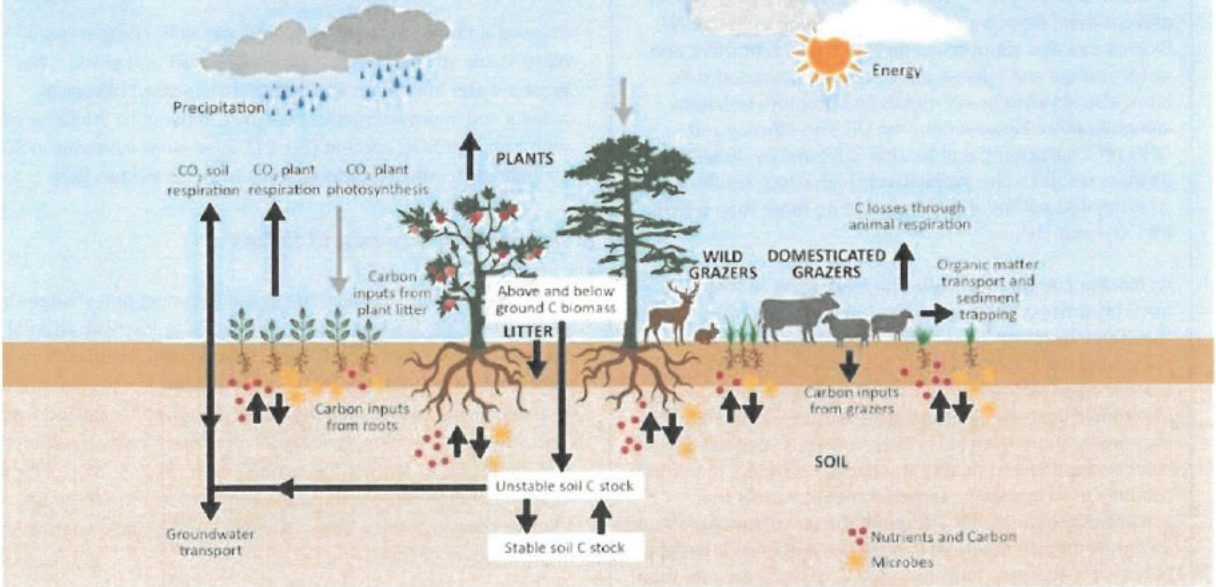

Figure 2: A simplified representation of the carbon cycle in terrestrial ecosystems (adapted from Garnett *et al.*, 2017 [7]).

a process known as plant respiration. In stable ecosystems, and in many agricultural systems, which have not changed for decades, photosynthesis and plant/microbial respiration are in balance, with the overall effect on atmospheric CO_2 being zero.

However within these systems, in addition to respiration, C is removed through harvested crops and livestock products, and also through animal respiration and fermentation from ruminating cattle, sheep, goats and domesticated deer; and in addition to photosynthesis, C is returned to the land as crop residues, livestock manure (Figure 1), human sewage and food waste. Organic C can also be added to soils as biochar, a stable form of C that is a category of charcoal (See Biochar box). If the rate of C input is greater than the rate of decomposition, then the amount of C in the soil increases. The opposite is true where the rate of decomposition exceeds C input [5].

Humans have therefore had an important influence on the C cycle through the burning of fossil fuels (Figure 1), breeding of domesticated livestock on a large scale and replacing natural ecosystems with agricultural and urban land. All these activities have altered the balance of the *natural* C cycle to such an extent that in many agricultural systems the amount of plant and microbial respiration (due to a combination of bare soils and cultivation) exceeds the amount of photosynthesis, resulting in a gradual depletion of SOC. However, this depletion can be reversed through land use change and sustainable soil management (SSM) practices [8].

Biochar

Biochar is the organic and inorganic C remains of organic material that has been heated in the absence of air (oxygen) to produce a form of charcoal. This heating or *pyrolysis* can prevent the C from degrading and returning to the air [9]. Biochar can also support soil fertility through nutrient and water storage and release, particularly in degraded soils. It can also stabilise heavy metals and promote pollutant immobilization. However, for the UK, the efficacy and GHG removal potential of biochar is limited by domestic biomass resource and prohibitively high costs, resulting in an estimated potential for biochar of no more than 6 to 41 Mt CO_2/year [10].

As biochar composition varies depending on source material, processing, local climate and soil type, the timeframe over which biochar-C remains sequestered in the soil is uncertain. There is also a lack of long-term data, e.g. biochar crop yield response field experiments provide only four to five years of data, and glasshouse experiments are necessarily short-term [11]. Therefore, it is suggested that biochar should meet quality standards, be closely monitored and only used in specific targeted circumstances that maximise its benefits [9]. Although the use of biochar should be tightly regulated, where it is applied with care it has the potential to increase long-term soil C, at a greater rate than any other treatment or management technique [12].

Soil carbon functions [13]

There are many reasons why we should be concerned about protecting or increasing the stock of C within soils [14, 15]. SOC has a profound influence on soil properties and functions that affect the production of food and fibre. It also impacts on the functions that soils perform for the wider environment such as regulating the flow and quality of water, providing clean air, filtering pollutants and contaminants, and supporting biodiversity. All functions which are often termed 'soil ecosystem services' (SES) are reliant on the turnover of SOC and are closely related to 'soil health' [15,16,17].

Soil organic C is an essential component of soil structure, function and soil life

SOC is the energy supply that enables soil organisms to carry out their functions in a healthy soil. Together with soil microorganisms, SOC is a key factor in the formation and stabilisation of soil structure – the system of aggregates (units of sand, silt and clay particles bound together) and the surrounding pore network (containing air and water) [18]. SOC can interact with soil particles (notably clay) to form small aggregates through various chemical and biological processes. The processing by soil microorganisms of organic matter that enters the soil from leaf litter or from roots produces substances which act as a glue (glomalin) to combine smaller aggregates into larger aggregates, making the aggregates more stable and resistant to external forces such as raindrop impact and cultivation [19]. The greater resilience of soil aggregates also stabilises the soil pore network, allowing the soil to carry out its functions of retaining water for plants, transmitting water down to the groundwater and, in the topsoil, allowing plant roots to grow without restriction and to access nutrients.

In general therefore, a soil with a greater SOC content has a more stable structure, is less prone to runoff and erosion, has greater water infiltration and retention, increased biological activity and improved nutrient supply compared to the same soil with a smaller SOC content [20, 21]. Even small increases in SOC can markedly influence and improve these properties [22].

Soil carbon stores and fluxes

SOC is a key component of the global C budget and changes in stocks have implications for the mitigation or intensification of climate change. The largest stocks of soil C are found in non-agricultural soils with a peaty surface horizon (e.g. semi-natural grasslands, moorlands and wetlands), woodlands, peatlands, and uncultivated long-term agricultural permanent pasture, where it is important to protect the existing C stores [23, 24, 25]. Soil C sequestration represents an important mitigation route for climate change and is achieved largely by stabilisation rather than turnover of SOC.

Although soils used for arable agriculture (annually cultivated) typically have smaller SOC contents than grassland or woodland soils, they are potentially more amenable to alteration through direct management interventions. Soil C stocks can be increased by either increasing inputs (e.g. crop residues, cover crops, use of organic materials, inclusion of grass leys in arable rotations) or decreasing losses (i.e. reducing oxidative losses to CO_2, or particulate and dissolved organic content), via improved management such as reduced intensity tillage [26]. Significant long-term land use change (e.g. conversion of arable land to grassland or woodland) has by far the biggest impact on SOC, but is unrealistic on a large scale because of the continued need to meet food security challenges.

More practical approaches could be the inclusion of grass leys into arable rotations (i.e. arable soils being under grass for several years in a crop rotation). This may result in a more sustainable system with healthier soil, although the cycling of C will result in some GHG emissions, and the whole rotation crop productivity is decreased since there is no human-edible crop during ley years. Integrating livestock may displace some human edible crop production, emit more CH_4 (if ruminant livestock numbers are not reduced elsewhere), and the change in soil C stocks is small compared with that of land use change.

Since changes to soil C occur over periods of many years, the financial benefits of soil C sequestration are normally based on modelled future soil C levels. Such models need to be relevant to individual soil types, land use and climate, and need to be accurately baselined through field measurements.

Nevertheless, relatively small changes in C stock per unit area in arable agricultural soils may translate into substantial stock increases at the national or regional scale [27, 28]. There has been much discussion of the possibility of mitigating climate change through soil C sequestration [27]. However, changes in SOC are generally slow to occur and, because of the large background C in soils and the inherent variation, it is difficult to measure accurately.

Moreover, the process of soil C sequestration is often misunderstood, and can lead to an overestimation of the climate change mitigation achievable by using this route [28]. This is primarily because the quantity of C that can be stored in any soil is finite. After a positive change in management practice, soil C levels increase (or decrease) towards an equilibrium value (after 20-100 years or more) that is characteristic of the 'new' land use, management system and climate [21]. The relatively large annual rate of soil C accumulation in the early years after a major change in land use or management (such as a change from a conventional cultivated arable rotation to a reduced tillage system incorporating grass leys and cover cropping) cannot be maintained indefinitely and the annual rate of increase will decline (eventually to zero) as the soil approaches its new equilibrium. The use of organic amendments in arable agriculture, such as composts and manures, is a practice that can increase SOC, but the supply is finite and there are costs incurred with such practices. It is therefore unlikely that the initial rate of increase in soil C following a change in land use /management practice will be sustained over the longer term (>20 years), as the new equilibrium level is reached.

When increased over time through altered management, soil C concentrations will reach an equilibrium state beyond which, no further increases are (naturally) possible.

Beneficial soil management approaches need to be continued beyond the equilibrium point to prevent returns to prior low C status.

In addition, C sequestration is reversible. Maintaining a soil at an increased soil C level, due to a change in management practice, is dependent on continuing that practice indefinitely. Indeed, soil C is lost more rapidly than it accumulates [29]. Also, to increase soil C levels, inputs of other elements such as nitrogen (N) and phosphorus (P) are needed. [30] The soil C, N and P cycles are intimately linked, and increasing soil C may affect the release of diffuse water pollutants (nitrate-NO_3 & phosphate-P) and GHGs considerably more potent than CO_2 (e.g. nitrous oxide (N_2O) & CH_4).

In other words, there is a risk of 'pollution swapping' where the reduction of one form of pollution increases another. Land use changes such as reafforestation and wetland creation may also result in deforestation and cultivation elsewhere to grow the food that is not produced in the C sequestration project (i.e. displacement) [31].

Despite these risks and limitations, there is scope for soil C sequestration to contribute to climate change mitigation, particularly on low C, degraded landscapes. It is equally important that this C sequestration is allied with retention of existing SOC stocks in non-agricultural and long-term permanent pasture soils. Maintaining or enhancing SOC levels can deliver a range of benefits not only for climate change mitigation, but also for soil quality and functioning which can make soils more resilient to the impacts of climate change (e.g. ability to cope with extreme events such as droughts and floods) and other global change factors [32].

Measurement, Monitoring, Reporting, Verification (MRV) and Valuing

Sequestering additional C in agricultural soils is attracting interest from governments and industry as a way to meet climate change objectives and is leading to the development of schemes to pay farmers to adopt SSM practices. Such soil-focussed schemes do not yet exist in the UK, but equivalents have been running

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in Australia and Canada for a number of years [33] and the European Commission's Carbon Farming Initiative is due in 2021. The Australian Emission Reductions Fund (ERF) and Carbon Farming Initiative encourage the adoption of a number of land management strategies that result in either the reduction of GHG emissions or the sequestration of atmospheric CO_2, while the Conservation Cropping Protocol in Canada provides payment for no-till cropping [34].

Any financial mechanism based on soil C status needs to include mechanisms to accommodate situations where soil C:

- has declined over an agreed sequestration period
- has increased (relative to other soils of a similar type) prior to an agreed sequestration period.

Setting up robust monitoring, reporting and verification (MRV) platforms for soil C is very challenging, due not just to variations in how changes in soil C are influenced by climate, land use and management in different agro-climatic regions, but also because it can be difficult to determine the baseline soil C content against which to judge (and pay for) the success of any sequestration initiatives [35]. The potential for future land management changes to cause captured C to be re-released from soils also means that monitoring has to be robust for the lifetime of any payment scheme.

Existing MRV protocols for soil C credits take different approaches to quantifying soil C and net removals of GHGs from the atmosphere. Some rely on soil sampling, some combine sampling with process-based modelling, while others rely on combinations of modelling and remote sensing [35]. Differences in the way protocols and C markets estimate sequestration make it difficult to be confident that climate benefits have actually been achieved – but the costs associated with direct measurement of soil C make it impractical as a long-term monitoring option [2], meaning that models and remote sensing become essential once a ground-truthed soil C baseline has been established. Ground truthing needs to take account of the high degree of variability between soil C contents even where soils are apparently similar across a field. An alternative is to simply link specific management practices to mean C sequestration potential within a set of given contexts.

Soil C sequestration provides a useful tool in global efforts to tackle GHG emissions, but the slow rate of change, the relatively small amounts that can be sequestered (e.g., in 2010 it was calculated that even the most extreme land use change scenarios in Great Britain would account for only c. 2% of national GHG emissions [36]), and the ease of reversibility in soil C gains present significant challenges with respect to measurement, monitoring and verification [5]. Stakeholders must be aware that a focus on soil C can have unintended consequences and should not be perceived as a 'quick fix'.

Conclusions and recommendations

Climate Change is arguably the greatest challenge facing humanity and efforts are underway globally to reduce GHG emissions and to capture those that continue to be emitted.

The counterbalancing need, on the one hand, to remove C from the atmosphere and, on the other, to add C to soils, presents an obvious confluence. Soils are a significant reservoir of C, but land use changes over centuries have resulted in a proportion of that C being lost from many soils. Although present in both organic and inorganic forms, it is SOC and (more specifically) soil organic matter that is critical to the functioning and resilience of soils in countries such as the UK. This is why addressing historic C losses provides clear potential for improving soil quality and for future C sequestration in soils, which is leading to the development of monetised soil C sequestration schemes that can be built into governmental or corporate strategies to offset residual GHG emissions.

Increasing the SOC of degraded soils can significantly improve productivity and resilience, and SSM techniques such as reduced intensity tillage, residue management to maintain ground cover, the use of cover crops, and the application of bulky organic manures (e.g. compost) are commonly used to achieve this. Changing SOC concentrations with such techniques can however take decades, and gains can be rapidly reversed in the event of further land management changes. Further, increases in soil C will not continue indefinitely; rather C concentrations will reach new equilibria, which can themselves only be maintained by continuation of the favourable management practices. Equilibrium concentrations of C will vary depending on soil type, land use and climatic conditions. It is possible that in some circumstances the natural SOC store can be augmented to some extent through use of basalt minerals or biochar, which offer potential for longer term inorganic or organic C storage - but the whole life cycle C costs of such techniques need to be considered with care before genuine sequestration benefit can be claimed. The source and chemical characteristics of biochars and rock dusts can also be problematic from both regulatory and environmental perspectives.

In the UK context, it is essential that historic SOC declines are addressed if soils are to function effectively, improving their resilience to increased temperatures, increased intensity of rainfall events and other inevitable effects of climate change. However, this essential requirement creates significant potential for abuse at a time when governments, corporations and individuals are increasingly keen to offset their C emissions through sequestration initiatives.

Although this Science Note is based on a UK perspective, we recognise that the same issues apply internationally and there is a need for action on a global scale.

[redacted]

Based on the available scientific evidence, we recommend that:

- The C stores in existing permanent grasslands, moorlands, peatlands, wetlands and woodlands are protected.
- SSM practices are more widely adopted to increase SOC, to help mitigate existing GHG emissions, to improve soil health and resilience, and to protect and enhance the multiple public goods and services provided by soil.
- Where financial incentives are developed to encourage SSM practices it is essential that funders provide ongoing support to these schemes. This recommendation applies equally to any scheme claiming C sequestration in soils.
- Soil C concentrations should be periodically monitored. While modelling can be used to estimate future C stocks in specific soils, it is essential that these estimates are validated through soil testing at a network of representative field sites.
- Sequestering C in soils and vegetation, although important, must not distract from the urgent need to reduce CO2 emissions from the burning of fossil fuels. Failure to address the latter will render the former irrelevant.
- Attempts to overcome natural soil C equilibria through application of materials such as rock dust or biochar must consider the whole life C costs of such practices as well as ensuring that they do not impact negatively on soil quality through pH change, chemical contamination or other undesirable characteristics.

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[redacted]

Bibliography

[1] Jenkinson, D. S. (2010) *Climate change - a brief introduction for scientists and engineers or anyone else who has to do something about it*. Rothamsted Research. [redacted]

[2] Keenor, S. G *et al.*, (2021) Evidence synthesis: Capturing a soil carbon economy. *Royal Society Open Science*, 8(4) [redacted]

[3] IUSS Working Group WRB (2015) *World Reference Base for Soil Resources 2014 (update 2015) International soil classification system for naming soils and creating legends for soil maps*. World Soil Resources Reports No. 106. FAO, Rome

[4] World Bank. (2021) *Soil Organic Carbon MRV Sourcebook for Agricultural Landscapes* World Bank, Washington, DC [redacted]

[5] Yeluripati, J *et al.*, (2018) *Payment for carbon sequestration in soils: A scoping study* ResearchGate [redacted]

[6] Evans C. *et al.*, (2016) *Lowland peat systems in England and Wales - evaluating greenhouse gas fluxes and carbon balances* (DEFRA Project SP1210) http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=17584

[7] Garnett, T. *et al.*, (2017) *Grazed and Confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question – and what it all means for greenhouse gas emissions* FCRN, University of Oxford [redacted]

[8] UN FAO (2017) *Voluntary Guidelines for Sustainable Soil Management* [redacted]

[9] Sohi, S (2012) Carbon Storage with Benefits. *Science* 338 [redacted]

[10] Royal Society (2018) *Greenhouse GAS Removals* [redacted]

[11] Abiven, S. *et al.*, (2014) Biochar by design. *Nature Geoscience*: Volume 7 May 2014

[12] Joseph, S. *et al.*, (2021) How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar *GCB-Bioenergy* In press. [redacted]

[13] Keesstra, S. D. *et al.*, (2016) The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals *SOIL* 2: 2 111-128

[14] Powlson, D.S. *et al.*, (2012) The Potential to increase Soil Carbon Stocks through Reduced Tillage or Organic Material Additions in England and Wales: a Case Study *Agriculture Ecosystems Environment* 146(1): 23-33

[15] Lal, R. (2016) Soil health and carbon management *Food and Energy Security* 5(4):212-222

[16] Janzen, H.H. (2006) The soil carbon dilemma: Shall we hoard it or use it? *Soil Biology and Biochemistry* 38(3):419-424

[17] Smith, P. *et al.*, (2021) The role of soils in delivering Nature's Contributions to People. *Philosophical Transactions of the Royal Society. B 376*: 20200169. [redacted]

[18] Tisdall, J.M. & Oades, J.M. (1982) Organic matter and water-stable aggregates in soils. *Journal of Soil Science* 33: 141-163. [redacted]

[19] Redmile-Gordon, M. *et al.*, (2020) Soil organic carbon, extracellular polymeric substances (EPS), and soil structural stability as affected by previous and current land-use. *Geoderma* 363:114143. [redacted]

[20] Bhogal, A. *et al.*, (2018) Improvements in the Quality of Agricultural Soils Following Organic Matter Additions Depend on Both the Quantity and Quality of the Materials Applied. *Frontiers in Sustainable Food Systems, Waste Management in Agroecosystems* 19 April 2018 [redacted]

[21] Johnston, A. E. *et al.*, (2009) Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes *Advances in Agronomy* 101:1-57

[22] Watts, C. W. *et al.*, (2006) The role of clay, organic carbon and long-term management on mouldboard plough draught measured on the Broadbalk wheat experiment at Rothamsted *Soil Use and Management* 22(4):334-341

[23] Jobbágy, E.G., Jackson, R.B. (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, 10:423-436. [redacted]

[24] Gregory, A.S. *et al.*, (2014) An assessment of subsoil organic carbon stocks in England and Wales. *Soil Use and Management*, 30:10-22. [redacted]

[25] Chapman, S. J. *et al.*, (2013) Comparison of soil carbon stocks in Scottish soils between 1978 and 2009. *European Journal of Soil Science*, 64: 455-465. [redacted]

[26] Poulton, P. R. *et al.*, (2018) Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom *Global Change Biology* 24(6):2563–2584

[27] Smith, P. *et al.*, (2008) Greenhouse gas mitigation in agriculture *Philosophical Transactions of the Royal Society B: Biological Sciences* 363(1492): 789-813

[28] Smith, P. *et al.*, (2000) Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture *Global Change Biology* 6(5):525-539

[29] Powlson, D. S. *et al.*, (2011) Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false *European Journal of Soil Science* 62(1):42-55

[30] Davies C. A. *et al.*, (2021) The importance of nitrogen for net carbon sequestration when considering natural climate solutions *Global Change Biology* 27(2): 218-219. [redacted] Epub 2020 Oct 30. PMID: 33124108

[31] Smith, P. (2012) Soils and climate change. *Current Opinion in Environmental Sustainability* 4: 539–544. [redacted]

[32] Rillig M. C. *et al.*, (2019) The role of multiple global change factors in driving soil functions and microbial biodiversity. *Science*. 2019 Nov 15;366(6467):886-890. [redacted] PMID: 31727838; PMCID: PMC6941939.

[33] Environmental Defense Fund, & Woodwell Climate Research Center (2021) *Agricultural Soil Carbon Credits* [redacted]

[34] Paustian, K. *et al.*, (2019) Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. *Carbon Management* 10(6):567-587 [redacted]

[35] Smith, P. *et al.*, (2020) How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology* 26(1): 219–241 [redacted]

[36] Smith, P. *et al.*, (2010) Consequences of feasible future agricultural land-use change on soil organic carbon stocks and greenhouse gas emissions in Great Britain *Soil Use and Management* 26:4 381-398 [redacted]

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