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ORIGINAL ARTICLE

Potential Co-benefits and trade-offs between improved soil management, climate change mitigation and agri-food productivity

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Abstract

Maximising resource-use efficiency, productivity and environmental sustainability are all fundamental requirements to raise global food production by ~70 per cent in order to feed a world population of ~9.7 billion people by 2050. Perhaps the most vital resource within our capacity to achieve this goal is our soil. Broadly, the fundamental question concerns whether or not satisfying this production demand will accelerate soil degradation, climate change, and the loss of soil carbon stocks. This paper builds upon the outputs of the UK Charity 'Food & Farming Futures' (chaired by Lord Curry of Kirkharle) virtual workshop held on 23 March 2021, entitled 'Capturing the Potential of Soil'. The event focussed on the link between soil health, primarily soil organic carbon (SOC), and agricultural productivity. Supported with commentaries by Professor Pete Smith (University of Aberdeen and Science Director of the Scottish Climate Change Centre of Expertise) and Professor Steve McGrath (Head of Sustainable Agricultural Sciences at Rothamsted Research), specific focus will be given to the research challenges within the UK's ability to improve soil health and functionality, the implementation priorities that must be held in order to improve soil management by 2050 and what the potential co-benefits could be. These co-benefits were scattered across environmental, economic, social and political issues, yet they may be summarised into six primary co-benefits: developing natural capital, climate change mitigation, carbon trading, improvements in crop yield, animal performance and human health (nutrition). Additionally, the main barriers to improved soil management practices are centred on knowledge exchange-regarding agri-environmental techniques—whilst the most impactful solutions rely on soil monitoring, reporting and verification.

KEYWORDS

agriculture, climate change, environment, food security, soil management, sustainability

1 | INTRODUCTION

As a vital life-support system, the health of our soil is fundamental to the delivery of essential ecosystem services, agricultural productivity (e.g. crop nutrition and animal welfare), food security and environmental welfare [e.g. ecological integrity, conservation, carbon sequestration (balancing), etc.]. Nonetheless, when considering soil health, one may decide to place emphasis upon key physical and chemical indicators of soil health, e.g. pH, organic matter (soil organic carbon), nutrient indices (including micro/macronutrients and trace elements) and porosity. On the other hand, more emphasis may be placed upon soil's role in sustaining and promoting natural capital, ecosystem functionalities including socio-hydrology and, in particular, plant and animal health and overall agricultural productivity (see Doran and Parkin, 1994 and 1997; Kibblewhite et al., 2008 and Bünemann et al., 2018).

Particularly since the green revolution, a time when the world population was ~2.5 billion, at the centre of agriculture's ability to satisfy global food demands has been the predominance of land productivity through the exploitation of natural resources, primarily soils. Soils are fundamental to the production of agricultural and horticultural products, facilitating a myriad of crucial natural services within crop and livestock production systems; such services include plant growth, nutrient cycling and regulation, pest and disease control, carbon sequestration/greenhouse gas (GHG) regulation, habitat for biodiversity, support of microbe health and overall ecosystem prosperity (see Stockdale et al., 2018). Such services have enabled soils to be the source of 98.8% of global food production (Kopittke et al., 2019), whilst in the UK, agricultural production from soils is worth £5.3bn per year (Parliament House of Commons, 2016). Nonetheless, the world's population is projected to increase to ~9.7 billion people in 2050; therefore, feeding this growing population requires raising global food production by ~70 per cent between 2005 and 2050 (Noel, 2016).

Agricultural intensification is likely to lead efforts in satisfying this extra demand. However, further exploitation of soils will raise significant concerns that this may accelerate soil degradation (i.e. loss of soil organic matter and erosion), environmental harm (i.e. loss of genetic diversity and acidification), climate change through the release of GHGs (i.e. nitrous oxide and methane) and the loss of soil carbon stocks—mostly through intensive tillage practices (see Kopittke et al., 2019). For example, according to Reynolds et al. (2013), degradation has led to a loss of 11% in arable topsoil in Britain since the 1970s (i.e. 0.4% loss per year), whilst in 2010, soil degradation in England and Wales was estimated to cost £1.2 billion a year (Lindsay, 2014). Simply put, for Kibblewhite et al., 2008 pg.685), 'the major challenge within sustainable soil management is to conserve ecosystem service delivery whilst optimising agricultural yields'.

This paper builds upon the outputs of the UK Charity 'Food & Farming Futures' (chaired by Lord Curry of Kirkharle) virtual workshop held on 23 March 2021, entitled 'Capturing the Potential of Soil'. The event focussed on the link between soil health, primarily soil organic carbon (SOC), and agricultural productivity. Specifically, using the UK as an exemplar, this paper scrutinises the research challenges that are facing government (especially within developed nations) as they aim to improve soil health and maximise productivity, the implementation priorities that must be centralised and what the potential co-benefits, barriers and solutions to improve soil management could be.

2 | RESEARCH CHALLENGES

Within the UK, cropland soils are depleted in SOC (Smith et al., 2007). One primary driver of this depletion has been changes in land use. For example, a meta-analysis by Guo and Gifford (2002) demonstrated that land-use change from native forest to crop results in a ~40% reduction in SOC concentrations whilst pasture to crop results in ~60% reduction of SOC—primarily because of increased soil tillage and reduced carbon inputs when changing to arable farming. An article by Paustian et al. (2016) presented a decision tree for cropland GHG mitigating practices. Such decisions included, for example, land-use changes, wherein 'the most productive mitigation option for degraded or marginal lands is conversion to perennial vegetation' (Paustian et al., 2016 pg. 50). Moreover, a range of managerial changes were also provided, in the form of making recommendations on key practices to reverse soil degradation or improve GHG mitigation potential. These include reducing tillage intensity: implementing residue retention, increasing N2-fixing legumes, multispecies swards, and improving timing and placement of nutrient applications using enhanced fertiliser application techniques. These management changes are regularly implemented in various parts of the world to increase soil organic carbon levels, as outlined in case studies provided by the FAO's 'Recarbonizing Global Soils (RECSOIL)' programme in six volumes (FAO, 2021).

Looking specifically at the mitigation potential of soils, carbon sequestration through SOC offers significant GHG mitigation potential. SOC is found within soil organic matter, which is a measure of all living organisms and decomposing material (microbial biomass and microbial activity). Loveland and Webb (2003) reported that an SOC of 2% was equivalent to ca. 3.4% soil organic matter—this was thought to be the critical level at below which soil properties are undermined—but this single value does not hold across all soil types and climatic conditions. Insufficient levels of SOC severely decreases the mitigation potential of soils. In relation to soil type, a front-runner in sequestration potential (due to elevated levels of soil organic matter) is peatlands. In the UK, peatlands store around 3 billion tonnes of carbon but are emitting an estimated 23 million tonnes of carbon dioxide equivalent (CO2e) annually (5% UK emissions) as a result of drainage and degradation (Stafford et al., 2021).

Overall, an estimated 9.8 billion tonnes of carbon are stored in Britain's soils (Parliament House of Commons, 2016). In 2013, GHG emissions from UK soils were 22.29 million metric tonnes of CO2 equivalent (MtCO2e). In contrast, GHG removal by UK soils from the atmosphere (carbon sequestration) amounted to 15.5 MtCO2e in the same year. This means that the net emissions from UK soils were 6.75 MtCO2e (UK soil carbon balance) in 2013—1.45% of the UK's total emissions (see Parliament House of Commons, 2016). The sequestration potential of peatlands is central to this balance, storing around 40% of soil carbon—sequestering carbon 100 times faster than it is emitted (Parliament House of Commons, 2016).

Globally, with improved soil management, particularly increasing SOC levels, global sequestration potential of SOC is equivalent to ~1.3 Gt Ceq/year. This sequestration is equivalent to around 5–10% of annual global GHG emissions. A variety of management practices exist to help reach this target, for example, the restoration of histosols (peatland restoration), grazing land management, cropland management and biochar application (Hardy et al., 2019). Seminatural land has the highest concentrations of SOC, primarily because (1) it is not disturbed or ploughed and includes rough grazing land/grazing land and (2) the semi natural land includes peaty soils—a larger carbon stock. Importantly, increasing SOC stocks not only enhances climate change mitigation but also improves the productivity of agri-food; globally, increasing SOC by 1 MgC/ha may result in a yield increase of 100–300 kg/ha/Mg C for maize—and a potential increase of 30–50 million tonnes of food production per year in developing countries.

Further to this 'win-win' output, improving soil management may also result in an enhanced array of ecosystem services—all positively linked to the UN Sustainable Development Goals (SDGs). Smith et al. (2021) outlined a plethora of such benefits, linking them to SDGs via a network of ecological, economic and social subthemes, for example, soil as a natural carbon pool, regulating air quality and ocean acidification, contributing positively to all SDGs. Despite the scale of these potential benefits, one may argue that no service offered by soils has more contemporary value than GHG mitigation, primarily through carbon sequestration via SOC. However, it is important to note that SOC has significant sequestration potential soon after a management change, but this declines over time until it reaches saturation after 10–100 years, and most importantly, soil carbon storage is reversible and highly sensitive to poor management.

Given that changes in soil carbon are relatively small relative to large carbon stocks, and because soil carbon levels change slowly, in order to fully harness the potential of soil carbon sequestration, strong monitoring, reporting and verification (MRV) protocols are required (Smith et al., 2020), including direct measurement, modelling, soil survey data, long-term experimental field trials, remote sensing and statistical activity data to capture management changes. Models of soil carbon turnover can be developed, calibrated and evaluated with data from long-term experiments, flux measurements and other *in situ* observations. Well-tested models, driven by spatial datasets of climate, soil characteristics, land use and land management, can be used to complement in-field measurements and to project likely changes in soil organic carbon content in the future after a management change. Farm survey data can be used to define management practices, and the model outputs can be verified by direct measurement and remote sensing. By using all of these data and information streams together, soil MRV can be made more accurate and affordable (Smith et al., 2020).

3 | IMPLEMENTATION PRIORITIES

In response to these challenges, there are multiple implementation priorities that government (especially within developed nations) must hold in order to improve soil management to maximise production and ecosystem delivery by 2050. However, it must first be noted that most soil properties change quite slowly; therefore, sustainable global soil management is dependent on a number of key conditions: (1) evidence and prediction of what really works; (2) models that are truly predictive of outcomes; (3) agreed standards and certification for MRV and (4) what is a 'good level' of SOC for a particular situation.

Building upon the major challenge of maintaining and improving SOC, a key priority for the UK, for example, particularly at the farm level, is raising SOC concentrations in cropland soils. Building upon research by Poulton et al. (2018), who analysed SOC increases in 16 long-term experiments in the southeast of the UK, a profile of strategies that can effectively improve SOC stocks can be developed. According to Poulton et al. (2018), the two strategies that increased SOC the most within the topsoil were applications of farmyard manures (35 t/ha to soils with <2.5% org C) and sewage sludge (sludge compost), with farmyard manures delivering SOC increases of 18‰ and 43‰ per year (23 cm depth) during the first 20 years. The positive impact of such strategies on SOC stocks was followed by increased applications of compost, ley-arable, green manures, straw and nitrogen fertiliser, with the latter an example of a strategy that improves productivity, farm economic performance and carbon sequestration. However, as Poulton et al. (2018) pointed out, there are concerns around the permanence and additionality of the SOC that is sequestered. Inputs of organic carbon (OC) need to be sustained to maintain higher SOC levels, and the OC sources used must not be simply from one part of the land to another, i.e. they must be additional to what is in the system originally. Poulton et al. (2018) also pointed out that in many systems, the organic residues such as straw and others may already be returned to soils, and that such residues are in short supply.

In addition, one must appreciate that there is a scarcity of evidence within this area. Further research is required to address how much carbon, and for how long, is required to achieve such changes in SOC levels in a range of soils and situations, including climate and previous management. To assess the potential for implementing SOC increase, the following needs to be known: the current (baseline) SOC, the soil type, whether SOC concentrations are close to an equilibrium, and the co-benefits. Hijbeek et al. (2017) used meta-analysis to quantify the additional yield effect due to organic inputs for arable crops in Europe, the research found that although surprisingly there were no significant impacts of increased organic inputs on crop yields across all sites, there were significances among spring-sown crops and crops that are very sensitive to soil physical conditions: potatoes (mean yield increase 7.0% ±4.9 – 95% c.i.) and maize (mean yield effect of 4.0% ± 3.7 – 95% c.i.). Relatively small increases in SOC rather than large ones may in fact be beneficial for some crops, through improving the soil structure and general soil health (Poulton et al., 2018).

When aiming to establish a good level of SOC, the SOC to clay ratio is often used in research. Prout et al. (2020) used this ratio to assess SOC concentrations across 3,809 sites using data from the National Soil Inventory of England and Wales—with thresholds of 1/8, 1/10 and 1/13 (SOC/clay) indicating the boundaries between 'very good', 'good', 'moderate' and 'degraded' levels of structural condition. Whilst variables such as land use, soil type, annual precipitation and soil pH explained significant variance in SOC/clay ratio, using this scale, the research revealed that 38.2, 6.6 and 5.6% of arable, grassland and woodland sites, respectively, were degraded—with most of these degraded soils found in eastern and southern areas (see Prout et al., 2020). Ultimately, the optimum SOC can be a challenge, as it depends on how different soil functions are valued (FAO, 2017). Additionally, it is noteworthy that there is no 'critical threshold' of SOC, although a ratio of 1:10 SOC/clay is widely considered "good" but more could be "better". But at higher ratios, the SOC present tends to be less well protected and is more susceptible to losses (reversal of SOC gains).

Despite the above, there are limitations regarding the standards for monitoring, reporting and validating levels of SOC; current knowledge remains limited regarding SOC baselines and changes, the detection of vulnerable hot spots for SOC losses and the situations that provide the greatest opportunities for SOC gains under both climate and land management changes. There is no agreement in SOC monitoring schemes, and this may already lead to carbon credits that are not at all comparable (Oldfield et al., 2021). Ideally, to resolve these challenges, an assessment of the mitigation potential of agricultural practices at both local and national levels is required, using common protocols, coupled with the implementation of mitigation options in an emission trading/market mechanism.

Importantly, solutions are conditional on accurate and quantifiable techniques. Indeed, a report by the FAO introduced an international approach for measuring and modelling SOC stocks from grasslands and rangelands—placing emphasis on carbon sequestration gains/losses within livestock supply chains (FAO, 2019). The report outlined a wide range of conditions that need to be fulfilled in order to gain a thorough understanding of SOC stocks and changes. For example, a soil sampling strategy should encompass the following features: allow for climate, soil type, hydrology, topography, land use, management and land-use history; minimum measurement requirements, a sampling depth of at least 30 cm; changes in soil bulk density as SOC increases need to be accounted for and all samples georeferenced. For repeated measurements, sampling should typically occur at least 4 to 5 years apart because soil carbon changes slowly in most situations.

In summary, many of the practices are already known but now need rapid implementation, which requires change in the way agricultural soils are managed, and in farm businesses. Research is needed in the area of soil information and assessment, to produce information upon which management decisions can be made accessible and affordable to farms. The priorities for implementation of current knowledge and future innovations in agricultural systems need to be based around sustainable soil management principles (FAO, 2017) but also depend heavily on parallel policy and socio-economic factors to support implementation. In general, these now come under the wide banner of 'regenerative agriculture', and the following activities urgently need to be funded and promoted:

1. Protecting and increasing existing carbon stores in permanent grasslands, moorlands, wetlands and woodlands
2. Minimizing soil disturbance by avoiding mechanical tillage through adoption of conservation tillage and no-till systems. Enhancing and maintaining a protective organic cover on the soil surface using cover crops and crop residues.
3. Enhancing crop nutrition through balanced measures that include crop rotations with N-fixing crops, judicious use of organic and inorganic fertilisers, and targeted amendments such as lime to address specific soil chemical conditions such as high acidity, which limit primary production in some regions.

These apply worldwide but will need urgent efforts to attain because of the largely fractured nature of the farming industry, especially in developing counties with many smallholder farmers. In the UK, this will be promoted through new policies that include 'payments for public goods' to farmers (UK Government, 2020).

4 | POTENTIAL CO-BENEFITS, BARRIERS AND SOLUTIONS

Thus far, focus has been placed on the range of challenges and the subsequent priorities the UK must tackle and implement to maximise productivity and ecosystem delivery through improved soil management by 2050. Yet, if this is done successfully, the plethora of potential co-benefits may be categorised into the three primary dimensions of sustainability (Figure 1 for an illustration of benefits from a soil management wide range of practices, whilst Table 1 focusses on practices increasing SOC). Firstly, a surplus of environmental and ecological benefits must be acknowledged including reducing soil nutrient deficiencies, improved nutrient cycling (geological and biological processes), erosion reduction, improvements in biodiversity and species conservation. For example, looking specifically at SOC, gains in microbial community structure and increasing oxidation by methane-oxidising bacteria (Tveit et al., 2019) are associated with building SOC. In addition, there would also be improvements in water regulation, minimization of pollutions and soil contamination, whilst improving SOC concentrations reduces supplementary inputs required to sustain/improve productivity, e.g. artificial/synthetic fertilisers.

Whilst flood mitigation was identified as a major co-benefit, in turn, this co-benefit would result in a longer growing capacity for crops because of improved resilience and, what is more, this could improve crop yield and agricultural productivity. Moreover, soils are a major source of global food production; therefore, improving the health of our soils, both physically and chemically will bolster its productivity whilst resulting in enhanced ecosystem services, healthier plants, healthier diets and, ultimately, a healthier global population.

Furthermore, although ~21–37% of total global GHG emissions are attributable to the food system and 10–14% are attributable to agriculture (mean of 2007–2016 period) (Mbow et al., 2017), it should be recognised that a major and urgently required co-benefit of improved soil management is climate change mitigation—by lowering global net GHG emissions through carbon sequestration via increases in SOC—a process which can be accelerated by livestock grazing through sustainable production systems (see Reeder & Schuman, 2002). For such systems, examples of sustainable practices would include the use of N2-fixing legumes, growing multispecies swards and peatland restorations. These practices, as outlined in Table 1, can improve crop yield, farm productivity and help satisfy global food demands.

Especially among arable farms, the adverse impacts of tillage on SOC stocks along with potential benefits of reduced intensity tillage practices are well documented (see Schimel et al., 1985; Elliott, 1986 and DeLuca & Keeney, 1994; Sun et al., 2011 and Mehra et al., 2018). The benefits of reduced tillage go beyond reducing SOC loss and restoring stocks, and there are also financial gains of reduced dependence on intensive labour and resource units (i.e. machine usage), thereby improving key indicators of business economic performance including labour productivity and resource-use efficiency. At the centre of the financial co-benefits of improved soil management, SOC stocks and subsequent carbon sequestration potential are the position of agriculture within an agricultural emission-trading scheme. Such schemes would enable farmers to enter private markets to improve business competitiveness using a universal currency.

This currency would enable farmers to purchase and sell carbon credits to offset net GHG emissions and/or improve long-term business profitability, economic independence and net income (see McHenry, 2009). Most notably, aside from the benefits of a carbon market, improved soil management through smart data-informed techniques such as GPS soil sampling, precision nutrient applications and low-emission slurry spreading techniques (see Amon et al., 2006; Misselbrook et al., 2002; Webb et al., 2005 and Webb et al., 2010) offers significant potential for improvements in crop nutrition and yield, which in turn, will offer significant improvements in gross profits per hectare among both arable and livestock production systems.

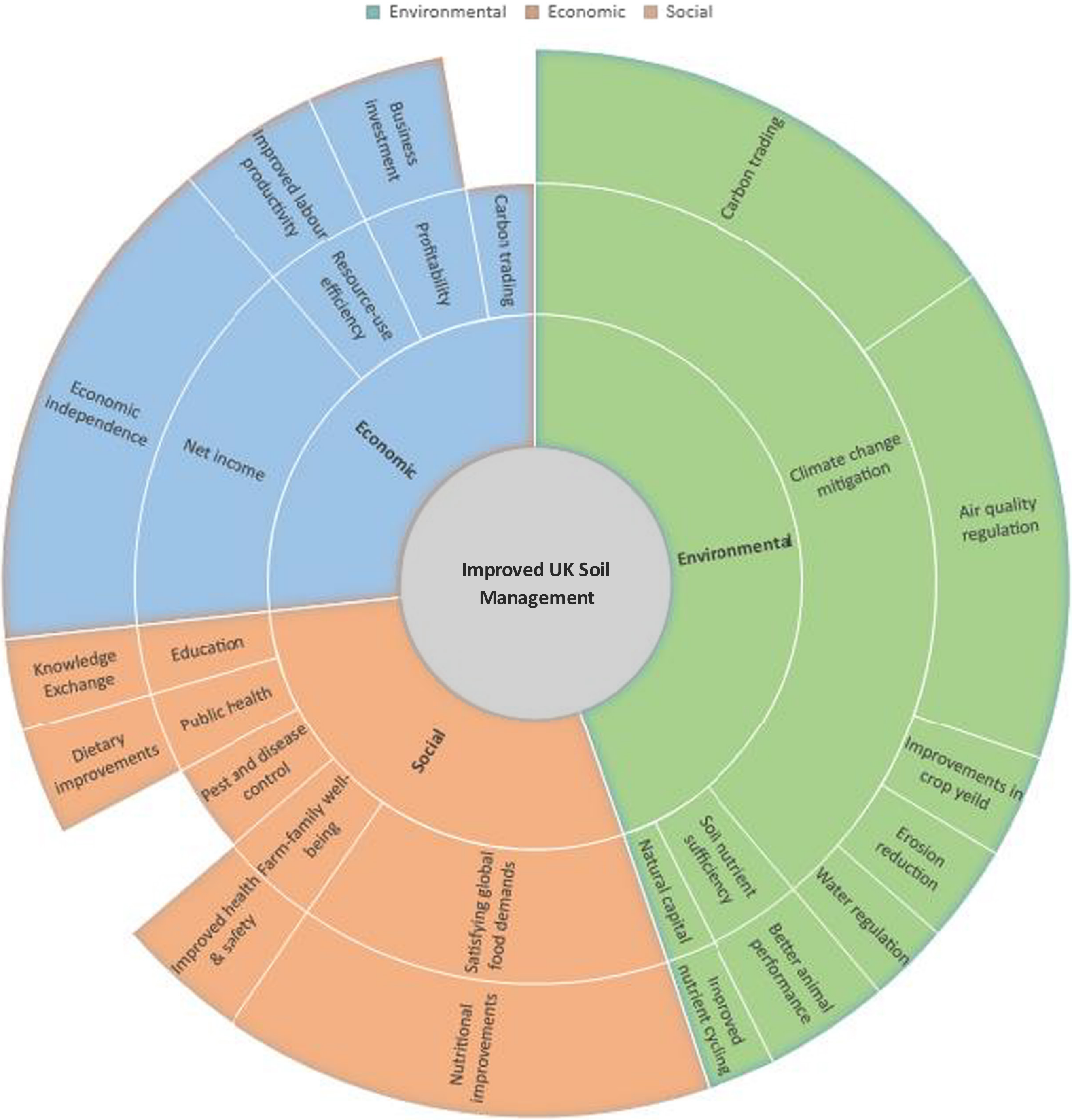

FIGURE 1 Potential Co-benefits of Improved Soil Management by 2050

Whilst the environmental and subsequent economic benefits of improved UK soil management are clear, there are also a number of fundamental and unique societal benefits at the individual (including farm), local, national and global levels. Probably, the most obvious benefit is the improved capacities of UK soils to strengthen food security through improvements in climate change resilience, crop yield, animal health and welfare, product quality and overall sustainability at regional, national and global levels. Moreover, public health and nutritional benefits may include dietary improvements, pest and disease control and the link between climate change mitigation and the environmental and societal determinants of health–including physical, social and mental health (Friel et al., 2009). More locally, the immediate recipients' benefits of soil management improvements are the farmers themselves. Overlapping economic gains result in a wide range of socio-economic benefits to farmers through improved farm income, resulting in improved farm business investment, reduced health and safety risk, better animal and

TABLE 1 A profile of key soil management practices and the significance of their potential impact on indicators of environmental, economic and social sustainability

Soil management practice	Environmental (climate)				Economic		Societal	
	Climate change mitigation	Improved crop yield	Better animal performance	Natural capital	Resource-use efficiency	Net income	Public health	Global food demands
1. MRV (measure, report verification)	++	++	++	+	++	++	+	++
2. Reduced tillage	++	+	+	+	+	+	+	+
3. N2-fixing legumes	++	+	+	+	+	++	+	+
4. Multispecies swards	++	++	++	++	++	++	+	+
5. Improved fertiliser applications	+	++	++	+	++	+	++	++
6. Peatland restoration	++	~	~	++	+	+	+	~
7. Grazing land management	+	++	++	+	++	++	+	+
8. Organic fertiliser applications	++	++	+	+	+	+	+	~

Note: ++, Significant improvement; +, Minor improvement; ~, Neutral.

crop performance, quality of life for farmers and overall farm-family well-being.

It is clear that if government take effective action to improve soil management, the co-benefits range greatly. Nonetheless, it is noteworthy that they may be summarised into six primary co-benefits: developing natural capital, climate change mitigation, carbon trading, improvements in crop yield, animal performance and human health (nutrition) (Figure 1). Additionally, given the extent and quality of science reinforcing the best practices to improve soil health, the main barriers are centred on knowledge exchange regarding agri-environmental techniques; the translation of scientific outputs into practical on-farm techniques and developing strategic and methodical plans better inform farmers of measures to improve soil health and reach NetZero. Importantly, this study finds that the most important remedies to help overcome such challenges rely on soil monitoring, reporting and verification; this includes high-quality data collection, investments in innovation and the creation and development of data-driven knowledge hubs (two-way) between farmers and policy makers—with evidence-based scientific communication at the centre.

5 | CONCLUSION

Government must look beyond the immediate benefits of satisfying global food demands, which focus less on environmental/ecological welfare and establish long-term sustainable solutions that meet production urgencies with zero environmental cost—or ideally facilitate environmental/ecological restorations with economic and social benefits. Importantly, although intensifying UK agricultural practices poses many environmental threats, including soil degradation, if practiced sustainably, there are many potential benefits of approaches that positively improve soil management and soil quality, such as 'sustainable intensification' or 'regenerative agriculture'.

The principal outcome of the 'Capturing the Potential of Soil' workshop has been the identification of such practices, subsequent benefits and the main barriers preventing the agri-food sector from implementing these practices. This paper has demonstrated that whilst potential barriers are centred on knowledge exchange regarding agri-environmental techniques, solutions are highly dependent on soil MRV, high-quality data collection and investments in innovation.

Specifically, at the farm level, these solutions include soil management practices such as precision farming, digital innovation, reduced tillage, incorporate cover crops, green manures and other sources of organic matter to improve soil structure and levels of SOC, more N2-fixing legumes, multispecies swards, species conservation to improve ecosystem performance and maximisation (and measurement) of aboveground biomass. Moreover, co-benefits were scattered across environmental, economic, social and political issues and included six primary co-benefits: developing natural capital, climate change mitigation, carbon trading, improvements in crop yield, animal performance and human health (nutrition).

It is noteworthy, the aforementioned soil management practices are at the centre of current and emerging agri-environmental policies at both the national and pan-European levels, for example, the European Green Deal, Farm to Fork Strategy, Horizon Europe (2030), the UK Agriculture Bill (2020) and the Environmental Land Management Scheme. Statutory requirements of such polices share one primary goal: targeting on-farm climate change mitigation and adaptation techniques and the integration of increased agri-food production with environmental remediation, animal welfare and public well-being—one principle model of global health. More specifically, given that agriculture is responsible for ~10% of UK and ~10–12% of global GHG emissions, climate change is at the core of these targets. Yet, it is noteworthy, that many, if not all, of the practices centred on improved soil management (i.e. precision farming, etc.) outlined in this paper are not only drivers of improved productivity but are also examples of highly effective climate change mitigation strategies (Table 1).

Most importantly, the narrative of these practices and subsequent benefits are subject to strategies of MRV, the need to improve the evidence base of the potential of improved soil management for ecosystem services and the overall environmental, economic and social benefits—linked through the SDGs. It is also important to reinforce that improvements in soil management will not resolve major environmental urgencies alone; they must work in harmony with other mitigation techniques. Such techniques must be integrated across the supply chain; yet, at the farm level, these include energy efficiency, maximising aboveground biomass, investment in renewables, low-emission nutrient applications and dietary shift among ruminants to reduce methane emission and nitrogen excretion.

Nonetheless, the current study finds that improved soil management does offer a vital contribution to climate change mitigation potential if combined with other strategic approaches to help achieve net zero. Examples of such approaches may include the use of alternative feeds (e.g. through gut microbial programming or dietary supplements and home-grown feeds), smart technology and precision livestock farming (e.g. animal genotyping and phenotyping, land use and manure management), enhanced calculation methods (controlling for differences in different GHGs) and improved education, knowledge exchange and adoption of whole-farm sustainability metrics. Nonetheless, there is a need by industry to implement the knowledge we have now, incentivised through appropriate policies, whilst science continues to increase our understanding of land-use patterns and environmental processes that contribute to changes in soil carbon to ensure that agriculture can play an important part in achieving climate change targets.

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REFERENCES

Amon, B., Kryvoruchko, V., Amon, T., & Zechmeister-Boltenstern, S. (2006). Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture, Ecosystems & Environment*, *112*(2–3), 153–162. https://doi.org/10.1016/j.agee.2005.08.030

Bruun, S., Clauson-Kaas, S., Bobuľská, L., & Thomsen, I. K. (2014). Carbon dioxide emissions from biochar in soil: role of clay, microorganisms and carbonates. *European Journal of Soil Science*, *65*(1), 52–59. https://doi.org/10.1111/ejss.12073

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., & Pulleman, M. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105–125. https://www.sciencedirect.com/science/article/pii/S0038071718300294

DeLuca, T. H., & Keeney, D. R. (1994). Soluble carbon and nitrogen pools of prairie and cultivated soils: seasonal variation. *Soil Science Society of America Journal*, *58*(3), 835–840. https://doi.org/10.2136/sssaj1994.03615995005800030029x

Doran, J. W., & Parkin, T. B. (1994). Defining and Assessing Soil Quality. *Defining Soil Quality for a Sustainable Environment*. Soil Quality, *35*, 1st ed, USA: SSSA Special Publications. https://acsess.onlinelibrary.wiley.com/doi/abs/10.2136/sssaspecpub35.c1

Elliott, E. T. (1986). Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. *Soil Science Society of America Journal*, *50*(3), 627–633. https://doi.org/10.2136/sssaj1986.03615995005000030017x

FAO (2017). *Voluntary Guidelines for Sustainable Soil Management Food and Agriculture Organization of the United Nations*. Rome, Italy.

FAO (2019). *Measuring and modelling soil carbon stocks and stock changes in livestock production systems: Guidelines for assessment (Version 1). Livestock Environmental Assessment and Performance (LEAP) Partnership*. Rome, FAO (p. 170).

FAO (2021) Recarbonizing global soils (6 volumes). Available from: https://www.FAO.org/global-soil-partnership/resources/publications/en/ (last accessed: 10th November 2021).

Friel, S., Dangour, A. D., Garnett, T., Lock, K., Chalabi, Z., Roberts, I., Butler, A., Butler, C. D., Waage, J., McMichael, A. J., & Haines, A. (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *The Lancet*, *374*(9706), 2016–2025.

Guo, L. B., & Gifford, R. M. (2002). Global Change Biology Global Change Biology Full Access Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, *8*(4), 345–360. https://onlinelibrary.wiley.com/doi/abs/10.1046/j.1354-1013.2002.00486.x

Hardy, B., Sleutel, S., Dufey, J. E., & Cornelis, J. T. (2019). The long-term effect of biochar on soil microbial abundance, activity and community structure is overwritten by land management. *Frontiers in Environmental Science*, *7*, 110. https://doi.org/10.3389/fenvs.2019.00110

Hijbeek, R., van Ittersum, M. K., ten Berge, H. F., Gort, G., Spiegel, H., & Whitmore, A. P. (2017). Do organic inputs matter–a meta-analysis of additional yield effects for arable crops in Europe. *Plant and Soil*, *411*(1–2), 293–303.

Kibblewhite, M. G., Ritz, K., & Swift, M. J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 685–701.

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International*, *132*, 105078. https://doi.org/10.1016/j.envint.2019.105078

Lindsay, R. (2014). Commercial peat extraction. IUCN Briefing Notes on Peatlands No 6. http://www.iucn-uk-peatlandprogramme.org/resources/iucn-briefing-notes-peatlands (viewed on 07 May 2021)

Loveland, P., & Webb, J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil and Tillage Research*, *70*(1), 1–18.

Mbow, H. O. P., Reisinger, A., Canadell, J., & O'Brien, P. (2017). Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SR2). Ginevra, IPCC.

McHenry, M. P. (2009). *Synergies between conventional soil organic carbon, farm productivity, soil sequestration and soil carbon market risk in Australia*. Nova Science Publishers.

Mehra, P., Baker, J., Sojka, R. E., Bolan, N., Desbiolles, J., Kirkham, M. B., Ross, C., & Gupta, R. (2018). A review of tillage practices and their potential to impact the soil carbon dynamics. *Advances in Agronomy*, *150*, 185–230.

Misselbrook, T. H., Smith, K. A., Johnson, R. A., & Pain, B. F. (2002). SE—Structures and environment: slurry application techniques to reduce ammonia emissions: results of some UK field-scale experiments. *Biosystems Engineering*, *81*(3), 313–321. https://doi.org/10.1006/bioe.2001.0017

Noel, S. (2016). Economics of Land Degradation Initiative: Report for policy and decision makers_ Reaping economic and environmental benefits from sustainable land management.

Oldfield, E. E., Eagle, A. J., Rubin, R. L., Rudek, J., Sanderman, J., & Gordon, D. R. (2021). Agricultural soil carbon credits: Making sense of protocols for carbon sequestration and net greenhouse gas removals. Environmental Defense Fund, New York, New York. edf.org/sites/default/files/content/agricultural-soil-carbon-credits-protocolsynthesis.pdf.

Parliament House of Commons (2016). Soil Carbon and Climate Change: Soil Health Environmental Audit. .

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57.

Poulton, P., Johnston, J., Macdonald, A., White, R., & Powlson, D. (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. https://doi.org/10.1111/gcb.14066

Prout, J. M., Shepherd, K. D., McGrath, S. P., Kirk, G. J., & Haefele, S. M. (2020). What is a good level of soil organic matter? An index based on organic carbon to clay ratio. *European Journal of Soil Science*, *13*, 12. https://doi.org/10.1111/ejss.13012

Reeder, J. D., & Schuman, G. E. (2002). Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. *Environmental Pollution*, *116*(3), 457–463. https://doi.org/10.1016/S0269-7491(01)00223-8

Reynolds, B., Chamberlain, P. M., Poskitt, J., Woods, C., Scott, W. A., Rowe, E. C., Robinson, D. A., Frogbrook, Z. L., Keith, A. M., Henrys, P. A., & Black, H. I. J. (2013). Countryside Survey: National "Soil Change" 1978–2007 for Topsoils in Great Britain—acidity, carbon, and total nitrogen status. *Vadose Zone Journal*, *12*(2), 1–15. https://doi.org/10.2136/vzj2012.0114

Schimel, D. S., Coleman, D. C., & Horton, K. A. (1985). Soil organic matter dynamics in paired rangeland and cropland toposequences in North Dakota. *Geoderma*, *36*(3–4), 201–214. https://doi.org/10.1016/0016-7061(85)90002-3

Smith, P., Chapman, S. J., Scott, W. A., Black, H. I., Wattenbach, M., Milne, R., Campbell, C. D., Lilly, A., Ostle, N., Levy, P. E., & Lumsdon, D. G. (2007). Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978–2003. *Global Change Biology*, *13*(12), 2605–2609. https://doi.org/10.1111/j.1365-2486.2007.01458.x

Smith, P., Keesstra, S., Silver, W. L., Adhya, T. K., De Deyn, G. B., Carvalheiro, L. G., Giltrap, D., Renforth, P., Cheng, K., Sarkar, B., & Saco, P. M. (2021). Soil-derived Nature's Contributions to People and their contribution to the UN Sustainable Development Goals. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*, 20200185. https://doi.org/10.1098/rstb-2020-0185

Smith, P., Soussana, J.-F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., Batjes, N. H., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J. E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., & Klumpp, K. (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*, 219–241. https://doi.org/10.1111/gcb.14815

Stafford, R., Chamberlain, B., Clavey, L., Gillingham, P. K., McKain, S., Morecroft, M. D., Morrison-Bell, C., & Watts, O. (Eds.) (2021). *Nature-based Solutions for Climate Change in the UK: A Report by the British Ecological Society*. . Available at: www.britishecologicalsociety.org/nature-basedsolutions

Stockdale, E., Griffiths, B., Hargreaves, P., Elphinstone, J., & Bhogal, A. (2018). *Developing a practical and relevant soil health toolkit for UK agriculture. In Proceedings-International Fertiliser Society* (No. *824*, pp. 1-28). International Fertiliser Society.

Sun, B., Hallett, P. D., Caul, S., Daniell, T. J., & Hopkins, D. W. (2011). Distribution of soil carbon and microbial biomass in arable soils under different tillage regimes. *Plant and Soil*, *338*(1), 17–25. https://doi.org/10.1007/s11104-010-0459-2

Tveit, A. T., Hestnes, A. G., Robinson, S. L., Schintlmeister, A., Dedysh, S. N., Jehmlich, N., von Bergen, M., Herbold, C., Wagner, M., Richter, A., & Svenning, M. M. (2019). Widespread soil bacterium that oxidizes atmospheric methane. *Proceedings of the National Academy of Sciences*, *116*(17), 8515–8524. https://doi.org/10.1073/pnas.1817812116

UK Government. (2020) Agriculture Bill: https://www.gov.uk/government/news/landmark-agriculture-bill-becomes-law

Webb, J., Menzi, H., Pain, B. F., Misselbrook, T. H., Dämmgen, U., Hendriks, H., & Döhler, H. (2005). Managing ammonia emissions from livestock production in Europe. *Environmental Pollution*, *135*(3), 399–406. https://doi.org/10.1016/j.envpol.2004.11.013

Webb, J., Pain, B., Bittman, S., & Morgan, J. (2010). The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response—A review. *Agriculture, Ecosystems & Environment*, *137*(1–2), 39–46.

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