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The opportunities of agri-carbon markets: policy and practice

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The opportunities of agri-carbon markets: policy and practice

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This report is summarised in *The opportunities of agri-carbon markets: a summary*, available to download from www.green-alliance.org.uk

1. Introduction

The 2015 Paris Agreement aims to limit global warming to 1.5°C compared to pre-industrial levels by achieving net zero greenhouse gas emissions through a combination of emission reductions and carbon capture, use and storage (CCUS). To meet its net zero targets, the UK will need to make major changes in the way it uses land. UK emissions from agriculture, land use and peatlands were 58MtCO_2e in 2017, with agricultural emissions accounting for about nine per cent of UK emissions. The Climate Change Committee estimates these emissions could be reduced by 64 per cent by 2050 through a combination of low carbon farming practices, afforestation and agroforestry, peatland restoration, bioenergy crops and reducing the consumption of carbon intensive foods.[1]

These changes are likely to be stimulated by a combination of investment from government (eg via new agri-environment schemes) and the private sector (eg via carbon offsetting). A number of voluntary initiatives are driving net zero declarations across the private sector (eg the United Nations' Race to Zero campaign and the Science Based Targets initiative) which, in turn, are driving increased interest in carbon markets. The Taskforce for Scaling Voluntary Carbon Markets reported that the global volume of annual carbon offsets doubled between 2018 and 2020, to over 200 MtCO_2e .[2] However, there are concerns that this could lead to the market being flooded with low integrity credits with improper carbon accounting (ie double counting), re-release of stored carbon and negative unintended impacts on humans or ecosystems.[3]

In the UK, most voluntary carbon offset projects are provided by afforestation, via the Woodland Carbon Code, followed by peatland restoration, via the Peatland Code. These voluntary standards provide guidance to project developers to deliver high integrity carbon benefits and reassure voluntary carbon buyers that the climate benefits they purchase are real, quantifiable, additional and permanent. Standards are now being developed in the UK, funded by the Environment Agency's Natural Environment Investment Readiness Fund, including the creation of a proposed UK Farm Soil Carbon Code, to reward farmers for carbon sequestration through more regenerative practices, and a Hedgerow Carbon Code. The Farm Soil Carbon Code is being developed and will focus on farming practices where there is robust evidence of increased soil carbon storage.

This report reviews the state of scientific knowledge on a range of opportunities for sequestering carbon on working farms in the UK, and the existing and near to market carbon sequestration offset and inset mechanisms, both in the UK and globally, that could be relevant to developing a credible on-farm carbon sequestration market in the UK.

Throughout this report we make no assumptions and indicate no preference for a particular technology or methodology due to its perceived connection to nature. Instead, we assess each on its ability to sequester carbon, its potential co-benefits and any necessary trade-offs or other impacts. This is because defining 'nature-based' is unclear and the term is often used to lobby for one solution over another. For example, is a monoculture non-native spruce plantation, regularly harvested for wood, nature-based? If so, then coppiced willow used to supply a bioenergy and carbon capture and storage (BECCS) plant could also be described as such.

Our review first considers the evidence and challenges around arable to grassland conversion and grassland soil carbon interventions, before considering a range of regenerative practices (such as reduced tillage, cover crops and hedgerow planting) and innovative technological carbon sequestration solutions (such as enhanced rock weathering, biochar and BECCS). For each of these, we consider their scientific rigour, credibility, feasibility, timescales, costs and environmental (and other) trade-offs. In doing so, we identify real world, scientifically credible opportunities for on-farm carbon sequestration in the UK, and discuss the challenges and opportunities for on-farm agri-carbon markets to "increase the amount of agricultural land that is put into long-term carbon sequestration initiatives" (one of WWF and Tesco's 2021 Sustainable Basket Metrics) and accelerate the transition to net zero.[4]

Finally, we review carbon sequestration offset and inset mechanisms that are, or could be, relevant to on-farm sequestration in UK agriculture, to identify issues and options for developing on-farm carbon markets.

2. Potential for on-farm carbon sequestration in the UK

In our assessment of potential on-farm measures to sequester carbon, we have only considered options that allow the land to remain in agricultural production rather than being given over to forestry or rewilding. Whilst both options have their potential, the purpose of this report is to assess how farmers could be paid for sequestering carbon, alongside their existing business and without the risk of creating a greater reliance on imported food, and thus the potential for indirect land use change in other countries. While some of the measures considered, such as fallow field margins and agroforestry, may decrease the amount of food production possible, these are relatively small decreases and offer other benefits such as enhanced biodiversity and soil health. Whilst peatland restoration in the uplands could be considered as keeping land in agricultural production, we do not cover it in this report as there is already an existing national carbon crediting scheme through the Peatland Code.

For each measure, we review the evidence base, focusing on UK studies where possible, and try to quantify the rate of carbon sequestration possible alongside benefits, disbenefits, trade-offs and barriers to adoption. We have focused on peer reviewed literature, where possible, but have included grey literature where we deemed it to be relevant (eg reports from the Climate Change Committee and the Royal Society). We have employed a qualitative 'traffic light' system based on how well each measure performs for each of these metrics.

There is still some uncertainty around the potential of soil carbon sequestration as a climate mitigation technique in the UK. The Climate Change Committee has recommended the adoption of low carbon farming practices, such as controlled release fertilisers and improving livestock health and slurry acidification but, in its 2020 report *Land use: policies for a net zero UK,* the committee did not recommend shifting towards more regenerative practices that could sequester and build soil carbon. We explore the committee's reasons for taking a precautionary approach to soil carbon in appendix 1, page 64.

On-farm measures that can sequester carbon do so either by increasing the amount of biomass grown or by increasing the stock of soil carbon. The soil carbon stock is based on the balance between additions of carbon, through plant residue and root exudates, and removals, via harvesting and decomposition. To sequester carbon, several typical approaches can be taken, summarised here:

a) Increasing the amount of biomass in the system (eg adding hedgerows or trees)
b) Increasing below ground productivity and reducing removals of above ground biomass (eg incorporation of crop residues)
c) Adding carbon produced outside the system (eg organic amendments or biochar)
d) Minimising the decomposition of organic matter (eg reducing soil disturbance through ploughing or maintaining high water tables in paludiculture)
e) Minimising soil erosion (eg cover crops)

A common theme that runs through on-farm measures that use soil carbon, rather than trees or hedgerows to store carbon, is the rate at which the saturation of soils is reached, and how management changes in the future could re-release stored carbon. The former represents a physical limit to how much carbon can be sequestered whilst the latter must be dealt with in the legal structure of any incentive scheme.

Although the overall abatement potential of soil carbon may be limited, as soils reach equilibrium levels of carbon in up to 20 years (depending on the condition and type of soil), this matches the time it is expected to scale up engineering approaches that are currently being trialled in the UK, including biochar, enhanced rock weathering and BECCS. As such, it is anticipated that private investment in on-farm carbon might transition over this period from an early focus on regenerative farming practices and hedgerow planting, towards engineering solutions as soil carbon stores become saturated and engineering options become increasingly cost effective.

Stimulating a shift towards regenerative practices through carbon markets over the next 20 years could generate a range of co-benefits, for example increasing soil macro fauna and farmland biodiversity, and increasing the adaptive capacity of agricultural soils under future climate scenarios (eg increasing tolerance to drought by enhancing the water holding capacity of soils).

One issue that presents itself in assessing on-farm sequestration methods is that many interventions sequester carbon, but not by enough to offset emissions elsewhere on the farm. For example, grazing management can lead to soil carbon gains but it is not enough to offset the methane emissions of the cattle grazing the field. Similarly, in arable systems, N_2O emissions are likely to remain even if soil carbon can be increased.

On-farm and land use change carbon sequestration capacity may only just cover the residual emissions from the agricultural sector in 2050. This leaves an open question about different sectors reaching net zero. If farms sell their carbon credits when they still have significant on-farm emissions, it will be even harder for the agricultural sector to decarbonise and reach net zero in the future.

Overall, our analysis suggests the most promising measures for on-farm sequestration in the short term are hedgerow planting and residue incorporation, although it must be noted that the sequestration potential of these is relatively small compared to UK agriculture emissions.

There is significant potential for reducing emissions via paludiculture or raising water tables on lowland peat. No and low till agriculture, cover crops and leys in arable rotation have significant co-benefits, but there is scientific uncertainty about their effectiveness for soil carbon sequestration, meaning they are likely to only store carbon in some conditions.

Agroforestry and hedgerows both have relatively high sequestration rates per hectare, although the potential application area is smaller than for regenerative agricultural practice. A holistic approach, adopting multiple measures, tailored to local conditions, is likely to be important to maximise carbon sequestration.

In the medium term, enhanced rock weathering and biochar could play a large role with their high carbon sequestration rates and scalability. Grazing management and arable land use change suffer from carbon leakage because the emissions from the ruminants used to graze the land are likely to outweigh the carbon sequestered in the soil.

In the longer term, BECCS can offer a means of sequestering large amounts of carbon. However, the more this is relied on to meet climate goals, the greater the impact on the wider land use sector and nature as more land would be required to grow biomass crops. BECCS is unlikely to be available at scale until the 2030s and so relying on it is a risk to achieving climate targets if decarbonisation is delayed now, with the assumption that carbon removals will readily available in the future.

We summarise our assessment of the measures below. A full review of the evidence on each of the measures is in appendix 2, page 66.

Combined summary assessment of different carbon sequestration measures

A note on nature-based solutions

Many negative emissions technologies are described in both academic literature and in policy documents as being 'nature-based', suggesting that, by association with natural processes, they are inherently better than other 'unnatural' options, which are presented in contrast as being not 'natural' or 'nature-based'.. This framing has created a discrepancy in the way technology options are assessed, as nature-based solutions are assumed to be more mature and offer more co-benefits, often without rigorous assessmentt.

This enthusiasm for nature-based solutions has often led to inaccurate or misleading claims about their potential For example, one study suggested global afforestation could sequester 205Gt of carbon at a price of only £0.30 a tonne.[5] After much questioning of these results, an erratum was published to this report where the authors suggested this headline figure would best be understood by the range of 133– 276 Gt of carbon that their modelling suggested, ie the uncertainty in what could be achieved was very large. This uncertainty arises from the use of global models, which do not account for local conditions, to assess potential sequestration rates.

Similarly, headline grabbing studies about the UK's potential for climate mitigation through afforestation have also given overly optimistic assessments, with one study providing reduction potentials based on conversion of all pasture to forestry without consideration of the planting methods, planting on peatlands or the economics of such a schemes.

For soil organic carbon, optimistic assessments of its potential have been suggested by basing future gains on those achieved in the first few years, despite diminishing returns as the soil reaches a new equilibrium. An analysis of the literature on grazing management showed that the carbon benefits stated in non-peer reviewed articles were often an order of magnitude higher than those in academic journals, again leading to over optimistic assessments of the potential of for 'nature-based' solutions.s.

As with promises of plentiful BECCS in the future, there is also potential for mitigation deterrence if nature-based greenhouse gas removals are assumed to be plentiful and cheap. Many decarbonisation measures that incur costs to businesses or governments now, appear not to be cost competitive compared against hypothetical future offsetting, especially if this is available at £0.30 per tonne. It is, therefore, necessary to subject negative emissions technologies to the same level of rigour whether they are nature-based or not, as well as understanding the potential promise of cheap offsets to delay current climate action.

Defining what is and is not nature-based is also unclear and used mainly as a way of lobbying for one solution over another. For example, is a monoculture non-native spruce plantation, regularly harvested for wood, nature-based? If so, then surely coppiced willow used to supply a BECCS plant could also be described as such. Throughout this report make no assumptions nor indicate preferences for a particular technology or methodology due to its perceived connection to nature. We instead assess each on its ability to sequester carbon, its potential co-benefits and any necessary trade-offs or other impacts.

2.1 Assessment of on-farm measures that sequester carbon

Grazing management

Most UK pasture is in rotational grazing, where cattle or sheep are moved between pastures and grazed at relatively low stocking density for a long period of time. Some claims have been made that optimised grazing systems, such as 'mob grazing', where animals are grazed at high stocking densities for a short period of time, or 'holistic' management which aims to match grazing time to plant growth periods to allow recovery, could sequester large amounts of carbon. Sequestration happens by increasing below ground productivity and reducing removal of above ground biomass

Grazing management has potential to contribute to increasing soil carbon stocks, however the gains are not great enough to offset the continued emissions of the ruminants grazing the land, leaving a net positive greenhouse gas balance at the field level. For this reason, grazing management presents a problem for farmers wanting to sell carbon credits, as this will leave significant methane emissions from the farming sector which will also require offsetting to reach net zero. Using grazing management to advertise meat products as lower carbon is, therefore, more scientifically credible that selling carbon credits.

As with most soil carbon measures, large gains are commonly observed in the first few years of the intervention, meaning the results of longer term studies should be used to assess the total sequestration potential over 15-20 years. Whilst grazing management cannot generate large soil carbon gains in all scenarios, it could contribute to the preservation of existing grassland soil carbon, which is comparatively high in the UK compared to southern Europe, for example. This is a worthwhile goal in any case.

Summary assessment of grazing management

Criteria	Colour	Reasoning
Scientific evidence	Amber	Reviews of research have conflicting findings; very positive findings tend to come from non-peer reviewed sources and occur in first few years of management. Soil carbon gains are not enough to offset emissions from ruminants.
Timescale of carbon sequestration	Amber	Most gains within the first 15-20 years.
Potential threat of carbon loss or leakage	Amber	Manure and urine from livestock have the potential to enter aquatic systems, labile carbon, which breaks down quickly, may contribute to soil carbon losses and enhanced greenhouse gas emissions; there is potential for increased soil erosion with high stocking rates and long grazing rotations
Co-benefits and interdependency with other on-farm measures	Amber	Grazing may encourage plant growth and animal excretion may contribute to organic matter accumulation; preservation of existing high soil carbon stock
Socioeconomic barriers	Amber	Increased labour demands if stock is moved more frequently

Permanence	Potential loss if management changes. Will require legal protection and pooled buffer of credits; does not offset emissions from ruminants
Monitoring, reporting and verification	Monitoring of soil carbon stocks and ruminant numbers
Next steps required to improve adoption or the science case	Need to establish the optimal grazing conditions for enhancing soil carbon in UK context; education on management practices

No and low till

Although tilling has been used in many conventional agricultural systems for millenia, there is a global shift towards reduced and no tillage systems, also known as conservation tillage or direct drilling, with the aim of protecting soils and improving their quality in cropping systems.[6] These techniques can sequester carbon by minimising the decomposition of organic matter and soil erosion.

Conservation tillage practices, on their own, are unlikely to result in significantly enhanced soil carbon stocks in all settings. Instead, these approaches may have greater promise in achieving wider sustainability goals (eg improved soil aggregate stability and hydrology, soil fungal diversity and increased yields).

If soil carbon stocks are to be increased then conservation tillage will probably need to be enacted alongside residue incorporation, but it will need to be carefully implemented to reduce the risk of increased N_2O emissions. As such, it is likely that conservation tillage will need to be carried out alongside a range of other management practices to mitigate potential negative outcomes. In these instances, carbon accumulation rates of 0.3-0.6tC per hectare per year may be possible, depending on the type of soil and climatic conditions present.[7] It should be noted that these techniques are harder to adopt on heavy clay soils and in organic agriculture where ploughing is sometimes used to suppress weeds. In many situations, conservation tillage practices are incorporated alongside other measures (eg low inputs and two to three year ley systems) which may achieve better results across the rotation than tillage practices alone.

Summary assessment of no and low till systems

Criteria	Colour	Reasoning
Scientific evidence	Amber	Multiple global level meta-analysis suggests results are mixed, unless combined with other measures
Timescale of carbon sequestration	Amber	Gains are likely to be in the first 15 to 20 years in topsoil
Potential threat of carbon loss or leakage	Amber	Risk of increased N2O emissions when residues are incorporated, particularly in the early years. Preferential flow paths can increase leaching of nitrogen and phosphorus.
Co-benefits and interdependency with other on-farm measures	Green	May improve soil aggregate stability and soil hydrology, fungi and yield. Can be combined with other measures, such as residue management and biochar.
Socioeconomic barriers	Green	Possible early reduction in crop yields when tilling is completely excluded from the landscape (depending on soil type), otherwise barriers are low.

Permanence	Potential loss if management changes. Will require legal protection and a pooled buffer of credits
Monitoring, reporting and verification	Monitoring of soil carbon stocks to depths over 30 cm, potentially N2O and CH4 emissions
Next steps required to improve adoption or the science case	Need to establish if soil carbon gains can be made whilst limiting N2O and CH4 emissions, and with NO3 leaching

Cover crops

Cover cropping is the growth of alternative crops (often cereals, legumes or brassicas) between harvest and establishment of the subsequent crop, typically with the intention of reducing nitrate leaching and soil erosion as well as to suppress diseases and pests.[8] Cover crops can help carbon sequestration by increasing below ground productivity and reducing removals of above ground biomass, minimising soil erosion and increasing the amount of biomass in the system.

Although international evidence suggests soil carbon gains are possible in some cases, there is a need for further UK-specific research, as well as consideration of the net impact once N_2O emissions are included. The main advantages of cover crop systems may instead be seen as the potential for reduced soil erosion and NO_3 leaching and increased crop yields with mixed cover crop systems. Cover crops may result in a net reduction of global warming potential, in part by suppressing NO_3 leaching and N_2O emissions. However, it is possible that N_2O emissions will increase following crop harvesting and with residue accumulation and fertiliser application. Whilst there is some potential for soil carbon gains, increased crop yields and reduced soil erosion, uptake of cover cropping without incentives may be limited due to increased labour demands and production costs.

Summary assessment of cover crops

Criteria	Colour	Reasoning
Scientific evidence	Amber	Limited UK research with some review and meta-analyses showing positive and negative effects or no significant difference from control
Timescale of carbon sequestration	Amber	Majority of gains happen in around the first 20 years
Potential threat of carbon loss or leakage	Amber	N2O emissions and NO3 leaching may rise following harvest, though it is not common practice to harvest cover crops in the UK
Co-benefits and interdependency with other on-farm measures	Green	Reduced soil erosion, nutrient, soil organic matter and water loss; nitrogen fixation from legumes; yield increases
Socioeconomic barriers	Amber	Increased labour demands and costs of production

Permanence	Suppressed NO3 leaching and N2O emissions may only occur whilst cover crops are in place. Potential loss of permanence if management changes and it is likely cover crops will only be used in some years in a rotation. Will require legal protection and a pooled buffer of credits
Monitoring, reporting and verification	Monitor soil carbon stocks, need to account for N2O and NO3.
Next steps required to improve adoption or the science case	Greater UK research required, including evaluating UK mixed cover crop system effects on soil carbon and greenhouse gas fluxes

Hedgerow planting

Planting hedgerows offers a way of increasing the amount of woody biomass produced in a system and increases soil carbon retained beneath the hedgerow, minimising carbon decomposition by creating an undisturbed area. This measure has benefits for biodiversity and new research based on data collection in the north of England, shows that, on average, planting hedgerows sequesters soil carbon at a rate of 1.49tC ha^{-1} yr^{-1}.[9] Combining this with biomass gains from the hedge itself, produces an overall carbon sequestration rate of 2.1 and 5.2tC per hectare per year for 50 and 20 years respectively.[10] Management of the hedgerow to produce biomass for BECCS, or similar, could further increase this potential However, harvesting can decrease soil carbon in the shorter term as organic matter inputs through leaf fall are decreased while the hedge re-establishes.

Summary assessment of hedgerow planting

Criteria	Colour	Reasoning
Scientific evidence	Green	Soil and biomass carbon evidence, however the effect is unclear on other greenhouse gases
Timescale of carbon sequestration	Amber	Rapid accumulation for 20 years, slower thereafter
Potential threat of carbon loss or leakage	Green	Increased soil health suggests low issues with leakage, though some land sacrifice is required; lossis possible through fire or management change; can shade crops and has high water use.
Co-benefits and interdependency with other on-farm measures	Green	Decreased soil erosion, enhanced biodiversity, can be used in conjunction with BECCS using harvest biomass
Socioeconomic barriers	Amber	Need to sacrifice some productive land, increased labour demands

Permanence	Biomass harvest creates a cycle of accumulation and loss of above ground and below ground carbon which will need to be accounted for. Potential loss if management changes. Will require legal protection and a pooled buffer of credits
Monitoring, reporting and verification	Hedgerow length and density, soil carbon measurements
Next steps required to improve adoption or the science case	Hedgerow Carbon Code under development; further work on CH_4 and N_2O emissions; comparison between hedgerows and control fields in arable and grassland

Residue incorporation

Soil carbon can be increased by increasing organic matter inputs, for example by incorporating crop residues, which improves below ground productivity and reducing removals of above ground biomass. Similar results can also be achieved by incorporating manures or organic matter from outside the farm

Overall, there is good evidence that crop residue incorporation can have beneficial effects on soil carbon in some contexts, but this is strongly affected by factors like soil clay content with higher clay content leading to higher carbon levels due to stabilisation effects. Whilst greater soil carbon may be achieved with residue incorporation, increased N_2O emissions may be observed. As such, crop residue incorporation for the purpose of greenhouse gas mitigation needs to be implemented in sites with appropriate soils and it is important to note that not all residues or manures will become stable carbon.

Summary assessment of residue incorporation

Criteria	Colour	Reasoning
Scientific evidence	Green	Most studies are carried out in temperate settings and there is a strong evidence basis. Though evidence is also clear it will only work in some conditions where carbon stabilisation is possible.
Timescale of carbon sequestration	Amber	Most gains are in the first 20 years
Potential threat of carbon loss or leakage	Amber	N_2O emissions may increase with residue degradation; there is an opportunity cost of not using residues elsewhere which may increase with time once BECCS or sales to the bioplastics industry becomes an option
Co-benefits and interdependency with other on-farm measures	Green	Improved soil health indicators such as earthworm populations and aggregate stability; increases water holding capacity
Socioeconomic barriers	Green	Loss of income from potential bioenergy feedstock or use on-farm for livestock eg bedding

Permanence	Potential loss if management changes. Will require legal protection and a pooled buffer of credits
Monitoring, reporting and verification	Will require monitoring of the balance of soil carbon gains versus N_2O emissions
Next steps required to improve adoption or the science case	Assessment of performance versus compost and other amendment schemes. Assessing appropriate locations for residue incorporation.

Introducing leys in crop rotations

Traditional rotations in the UK used to consist of a combination of cash crops and crops to feed livestock and, while the exact rotations used varied, they typically included clover leys for fertility building and for livestock to graze. However, agricultural intensification over the last 60 years has resulted in a switch to continuous arable cropping where the ley fertility building phase of the rotation has been replaced with artificial fertilisers. The use of leys, in particular using grass and legume mixes, is common in organic farming and is now being adopted across many regenerative systems.

Whilst some important research has evaluated the effects of using leys in crop rotations on soil health and crop yields, there is limited quantified data on its effects on soil carbon content in meta-analyses and reviews for UK and Europe, though organic systems incorporating multiple techniques may differ. There is some evidence of benefits to be gained, such as reduced nutrient depletion and soil erosion, but further research assessing the effects on carbon and nitrogen cycling is required. Using leys in crop rotations in the UK may be useful in achieving wider sustainability goals, beyond enhanced carbon sequestration but socioeconomic barriers, such as lack of reliable pricing for legume crops outside contract growing, need to be addressed for wider uptake.

Summary assessment of introducing leys in crop rotations

Criteria	Colour	Reasoning
Scientific evidence	Red	Much of the research on the impacts on soil carbon has focused on tropical settings and there are limited meta-analyses in Europe
Timescale of carbon sequestration	Red	There is insufficient data in UK settings to directly discuss carbon sequestration
Potential threat of carbon loss or leakage	Amber	Increased nitrogen rich residues may contribute to increased N_2O emissions
Co-benefits and interdependency with other on-farm measures	Green	Reduced nutrient depletion and reduced pest populations, disease, weeds, soil erosion. Increased biodiversity
Socioeconomic barriers	Red	Crop geometry; poor prices for legumes outside contract growing

Permanence	Legume residues are likely to degrade quickly but may enhance soil carbon stocks over multiple rotations. Potential loss if management changes. Will require legal protection and a pooled buffer of credits
Monitoring, reporting and verification	Studies need to evaluate the effects of entire rotations and on carbon and nitrogen cycling
Next steps required to improve adoption or the science case	Quantified soil carbon studies need to be carried out in north west Europe

Agroforestry

Agroforestry systems can be defined as landscapes combining trees and shrubs with arable or pastoral uses. Having more trees integrated in farmland increases the amount of biomass in the system, increasing above and below ground productivity and leaving more biomass in the field through leaf fall and accumulating woody biomass.

It is estimated that agroforestry in the UK has the potential to sequester carbon on the order of millions of tonnes. However, research indicates that gains in soil carbon will be small relative to above ground biomass and is largely limited to the first decade following establishment. Although much of the soil carbon gains would be lost if the land is returned to arable production in a rotational system, the difficulty of reversing agroforestry systems may increase the permanence of soil carbon gains under agroforestry (eg it has been suggested that reverting from agroforestry to arable could be more expensive than clearing primary forest).[11] Carbon crediting is, therefore, only likely in agroforestry systems where trees become a permanent feature, though harvesting and replanting could be possible if soil carbon losses are quantified further. Management will also be needed where trees begin to shade out crops in silvoarable systems to ensure a balance between woody biomass growth and crop yields. Carbon gains may be maximised by combining agroforestry with other interventions such as biochar, as well as appropriate placement of agroforestry schemes in suitable soils and where irrigation requirements are low. Overall, there is a lack of research assessing the carbon impacts of agroforestry systems in the UK. However, trials are underway in the Southwest of England through Innovative Farmers as part of the development of the Environmental Land Management scheme (ELMs) to assess the carbon balances and farmers' willingness to adopt agroforestry schemes.

Summary assessment of agroforestry

Criteria	Colour	Reasoning
Scientific evidence	Amber	Most studies are from the tropics, but process understanding is strong
Timescale of carbon sequestration	Amber	Soil carbon gains are primarily in the first 14 years, harvesting and replanting can increase biomass gains
Potential threat of carbon loss or leakage	Green	There is no evidence of significantly increased soil greenhouse gas emissions; risk of management change; reduces area for crops, therefore, displaces food production, though fruit and nut trees can offset this; risk of trees not establishing if exposed to water stress which may worsen with climate change
Co-benefits and interdependency with other on-farm measures	Green	Increases in biodiversity, soil organic matter (and related nutrients), improved animal health. Decreased soil erosion, pollutant mobilisation, surface runoff
Socioeconomic barriers	Amber	Increased work complexity, management costs, labour requirements. Already exists in the UK in some forms.

Permanence	Biomass harvest creates a cycle of accumulation and loss of above ground and soil carbon which will need to be accounted for. Potential loss if management changes. Will require legal protection and a pooled buffer of credits
Monitoring, reporting and verification	Monitoring soil carbon accumulation, tree biomass measurements
Next steps required to improve adoption or the science case	Further field studies carried out in the UK with long term assessment of carbon cycling effects; design of incentive schemes

Arable land use change

Converting arable to grassland or other habitats can increase soil carbon over long periods by increasing below ground productivity and reducing removals of above ground biomass, minimising decomposition of organic matter and minimising soil erosion. Converting land to grassland from arable can sequester 0.51 tonnes of carbon per hectare per year according to long term studies by Rothamstead Research. If cattle were to be introduced to the system, carbon accumulation in soils would offset the emissions of around 0.05 cows per hectare, assuming 100kg of methane produced per cow per year and using the global warming potential of methane over 20 years, as this is the same period over which most soil carbon gains take place. Alternative uses for the converted land, such as grazing for sheep or baling for biomass are likely to be less carbon intensive.

As there is strong evidence that conversion of arable to grassland can sequester soil carbon, but also strong evidence that these gains are cancelled out by methane emissions from cattle, the balance of emissions comes down to market dynamics and dietary change rather than science. Lower demand for meat could mean a reduced need for grazing or a switch to more extensive grazing systems. Also, a reduction in arable land could mean carbon leakage due to greater reliance on imports of arable crops. If carbon offsetting incentives are high enough for land managers to switch out of arable land, afforestation would be a more likely choice as this would have much greater soil carbon and above ground biomass sequestration potential[12] Indeed, competition for converted arable land is likely between afforestation and bioenergy crops, both of which can also increase soil carbon above that of arable systems.[13] While there is strong evidence of soil carbon benefits from taking land out of arable production, the net result will depend on the balance of herd numbers, imports of displaced arable production, grazing management and the opportunity cost of not using that land for BECCS or afforestation.

Summary assessment of arable land use change

Criteria	Colour	Reasoning
Scientific evidence	Green	Very strong evidence, from long term UK studies
Timescale of carbon sequestration	Amber	Most soil carbon gains are in the first 20 years
Potential threat of carbon loss or leakage	Red	Taking arable out of production risks displacing emissions elsewhere; adding cattle to the system cancels out carbon benefit; future management change
Co-benefits and interdependency with other on-farm measures	Amber	Biodiversity gains are possible if change is to species rich grassland or short rotation forestry; potential for synergy with grazing management
Socioeconomic barriers	Amber	Declining demand for red meat; carbon credit incentives would favour land use change to forestry or biomass crops

Permanence	Potential loss if management changes. Will require legal protection and pooled buffer of credits
Monitoring, reporting and verification	Soil organic carbon and bulk density measurements
Next steps required to improve adoption or the science case	Design of incentive schemes that avoid cancelling out gains via increased herd numbers

Field margins

Field margins are features that exist on the edge of agricultural landscapes, and interact with adjacent arable land.[14] They could help by increasing the amount of biomass in the system, increasing below ground productivity and reducing removals of above ground biomass, minimising decomposition of organic matter and soil erosion.

Field margins can be important settings for increased biodiversity relative to arable land, but adjacent management practices can significantly affect them. While there is limited evidence directly concerning field margins, there is a great deal of overlap between this and other measures considered, in that the margins could be used to form part of an agroforestry system, be planted as larger hedgerows or be returned to grassland. In that sense, the science is much more well understood, even if there are few studies analysing the impact of field margins directly. Trade-offs exist with food production as field margins essentially take land out of food production, though this could be used for biomass harvest in an agroforestry or hedgerow system and field margins tend to be the least productive areas of a field.

Summary assessment of field margins

Criteria	Colour	Reasoning
Scientific evidence	Amber	Limited studies on soil carbon in field margins directly, though there is evidence on agroforestry, hedgerows and grassland reversion.
Timescale of carbon sequestration	Amber	Most carbon gains are in first 20 years; this is cyclical if biomass is harvested
Potential threat of carbon loss or leakage	Amber	The larger the field margin, the less food produced and, therefore, the greater need for imports, though this is partly mitigated by improved pollination and biodiversity
Co-benefits and interdependency with other on-farm measures	Green	Biodiversity, pollination, buffering of nutrient and pesticide transport to rivers. Can be used to harvest biomass for BECCS.
Socioeconomic barriers	Amber	Incentives will have to compensate for loss of crop area; there is significant familiarity through set-aside schemes already

Permanence	Biomass harvest creates cycle of accumulation and loss of above ground and soil carbon which will need to be accounted for. Potential carbon loss if management changes. Will require legal protection and a pooled buffer of credits
Next steps required to improve adoption or the science case	Area under management, soil carbon and biomass measurements
Next steps required to improve adoption or the science case	Evaluate the potential effects on crop yields as well as wider co-benefits and potential limitations in UK settings

Paludiculture

Paludiculture is the practise of wet agriculture, that is, farming techniques on land where the water table is at or near the surface for all, or a significant part of, the year. It is a significant departure from typical agricultural practice in the UK which has relied on drainage to increase yields for crops which are intolerant of wet conditions.

Paludiculture reduces significant emissions from drained peat by minimising the decomposition of organic matter and can be used to grow some food crops like spinach and berries, but is mostly used for biomass crops like miscanthus and trees which can tolerate a high water table.

While paludiculture has significant barriers to adoption, 'wetter' rather than truly 'wet' agriculture may offer significant carbon savings whilst keeping current land use. Assessing data from 41 locations in the UK and Ireland, Evans et al (2021) suggest that many drained peatlands used for agriculture are 'over-drained', meaning that water tables could be increased without negatively affecting crop production.[15] They suggest many peatlands are drained to over two metres depth and that every ten centimetre increase in mean water table depth would create an emissions reduction of around 3tCO_2e per hectare per year, up to 30 centimetres depth, at which point the effect is lowered due to methane production. They suggest that halving the water table depths of croplands on organic soils could avoid emissions of 15.3tCO_2e per hectare per year. Similarly, Thomson et al (2018) suggest a potential UK-wide emissions saving of 1.5MtCO_2e a year by seasonal raising peatland water tables in cropland systems.[16] Both these techniques would allow full agricultural production to continue on lowland peat by working with existing Internal Drainage Boards. However, they only offer emissions reductions so the peatlands would still be net emitters of CO_2e.

Summary assessment of paludiculture

Measure	Colour	Reasoning
Scientific evidence	Green	Most studies are outside the UK but the science base is strong
Timescale of carbon sequestration	Green	Peat is capable of continuous sequestration over thousands of years
Potential threat of carbon loss or leakage	Amber	Lower agricultural production than in drained systems, therefore, there are risks to food security and of a greater reliance on imports; future management change
Co-benefits and interdependency with other on-farm measures	Green	Increased biodiversity through habitat creation; can potentially be combined with biochar application and provide biomass for BECCS
Socioeconomic barriers	Red	Currently uneconomic compared to drained use of peatlands and low level of UK knowledge of paludicultural techniques and markets

Permanence	Potential carbon loss if management changes. Will require legal protection and a pooled buffer of credits
Next steps required to improve adoption or the science case	Monitoring of peat depth and water table depth; to be confirmed via UK field trials
Next steps required to improve adoption or the science case	Field trials, design of incentive schemes

Enhanced rock weathering

Enhanced rock weathering is an acceleration of the natural processes of silicate rocks weathering to store carbon over long timescales. The acceleration is achieved by grinding rocks to increase their surface area and then applying the resultant material over large areas, such as croplands. The rocks themselves can be quarried in the UK with significant sources in Scotland and Northern Ireland. This is important as transporting the rocks is a determinant of the carbon efficiency of the process and may be the controlling factor on where the technology can be adopted successfully.

Experiments in the UK have demonstrated a trial enhanced rock weathering system which used crushed basalt on a clay-loam agricultural soil and achieved a 21 per cent increase in yield as well as a 2 to $4tCO_2$ per hectare per year of sequestration.[17] While UK field scale data are currently lacking, UKRI has funded a trial through its greenhouse gas removal demonstrator project which will test the application of basalt on farms in mid-Wales, Devon and Hertfordshire. Results from these large scale trials will need to be analysed and any risks assessed before the adoption of enhanced rock weathering in a UK farming context. Modelling protocols will have to be developed to understand the variation in carbon sequestration with soil, climate and crop variations to ensure confidence in expected results. We, therefore, suggest that enhanced rock weathering is unlikely to be deployed before 2025.[18]

Summary assessment of enhanced rock weathering

Measure	Colour	Reasoning
Scientific evidence	Amber	The physical science is understood but evidence is needed of trials on UK soils, crops and conditions. Current evidence is mainly from the USA.
Timescale of carbon sequestration	Green	Repeated applications possible over a long time period
Potential threat of carbon loss or leakage	Green	Limited
Co-benefits and interdependency with other on-farm measures	Green	Strong co-benefits for crop yield and health, reduced N2O emissions, works in synergy with BECCS
Socioeconomic barriers	Amber	Analogous to application of lime which is well practiced by UK farmers; incentives are needed; public perception

Permanence	Good permanence and chemical weathering is well understood
Next steps required to improve adoption or the science case	To be confirmed via UK field trials
Next steps required to improve adoption or the science case	Field trials, design of incentive schemes

Biochar

Biochar is the residue produced during pyrolysis and incomplete combustion of organic matter; pyrolysis is the process where organic matter is heated in the absence of oxygen and has been used for centuries for charcoal production. Biochar can be added to soil, where it is stored. Overall, UK biochar amendment schemes have the potential to sequester carbon in the order of millions of tonnes per year, though this will vary significantly with issues like biochar feedstocks and production conditions as well as the characteristics of the amendment site, including soil clay content, fertiliser treatment and soil hydrology.

Although biochar has the potential to increase soil carbon stocks as well as mitigating greenhouse gas emissions, it is important that the site is assessed prior to amendment, as there is the potential for increased soil caron degradation and greater greenhouse gas emissions in some cases.

Additionally, it is important to consider sequestration trends over time, as early phases of amendment may exert different effects on greenhouse gas fluxes and soil carbon stocks to latter phases. As such, biochar application will have to be targeted to maximise carbon sequestration and will not be suitable for all soils and management practices.

Biochar application is currently being trialled at field scale at several UKRI greenhouse gas removal demonstrator projects and these will go some way to assessing the UK potential of this technology.

Summary assessment of biochar

Measure	Colour	Reasoning
Scientific evidence	Green	There is a growing body of research from the UK and Europe and the evidence basis is strong
Timescale of carbon sequestration	Green	Carbon storage for centuries, possibly millenia
Potential threat of carbon loss or leakage	Amber	Small (around three per cent) carbon losses and possible microbial degradation of soil carbon in first year; potential land use change for biomass crops to produce biochar
Co-benefits and interdependency with other on-farm measures	Amber	Amendments can mitigate N_2O and CH_4 emissions. Biochar may increase crop yields, soil water capacity and nutrient content though these effects are unclear in temperate settings; can be combined with agroforestry, paludiculture or other measures.
Socioeconomic barriers	Green	Costs of biochar production and amendment, biomass availability. Farmers are likely to have equipment available for spreading biochar to soils.

Permanence	Biochar incorporated into soils shows high stability so there are minimal permanence issues
Next steps required to improve adoption or the science case	Monitoring of amended sites to observe long term biochar degradation
Next steps required to improve adoption or the science case	Detailed assessment of biochar performance in a wider range of settings including wetlands; design of incentive schemes

Bioenergy with carbon capture and storage (BECCS)

BECCS is a proposed method of achieving negative emissions by taking carbon stored in biomass via photosynthesis, burning this biomass to generate electricity, and then capturing and storing the resulting CO_2. At present, this technology is not available but the UK industry intends to have a pilot plant working by 2027, with scale up through the 2030s.

The UK has good storage potential for CCS with the Energy Technology Institute (2016) estimating offshore verified total storage potential of 1GtCO_2 with more potential capacity. The likely constraints on BECCS in the UK, therefore, comes down to the strain it puts on other land uses and fertiliser consumption. Using fertiliser with bioenergy crops can increase yield and, therefore, increase the carbon benefit per hectare, after accounting for emissions in the production of the fertiliser.[19] However, the scale of BECCS which is likely to be required suggests that, by 2045, fertiliser demand for bioenergy crops could add a further 30 per cent to current global usage.[20] While BECCS could help the UK to meet its climate targets, it could also move the Earth closer to other defined planetary boundaries (eg from nutrient run-off and the exhaustion of phosphate supplies).[21]

Significant trade-offs occur in deciding how best to provide biomass for a UK BECCS industry: using grasslands may produce high yields but displaces food production and will cause soil carbon loss, importing biomass may be cheaper but causes leakage of emissions as land use change occurs elsewhere, and using waste biomass is attractive but it is also needed for other industries. We give a more extensive assessment of the biomass requirements of BECCS in a UK context in appendix 2, page 64, as the estimate of land potentially available from biomass plantation (likely to be short rotation coppice with some miscanthus in the South West) varies greatly.

As much of the current understanding of what a BECCS industry in the UK might look like is based on modelling and extrapolation from small trials, there is an urgent need to test and model assumptions at scale to improve the robustness of the science. UKRI are currently funding a greenhouse gas removal demonstrator project which will assess the potential for miscanthus and short rotation coppice willow in Lincolnshire and Lancashire; the results of these trials are likely to go some way to reducing the uncertainty around expected biomass yields and fertiliser usage and, therefore, the land requirements for BECCS.

Summary assessment of BECCS

Measure	Colour	Reasoning
Scientific evidence	Amber	The science is understood but, at present, there has been very limited testing at scale
Timescale of carbon sequestration	Green	Very long term sequestration is possible
Potential threat of carbon loss or leakage	Amber	Displacement of food crops could increase imports if agricultural land is required; increased fertiliser usage; soil carbon loss if grasslands are converted to biomass; potential reliance on imported biomass if imports are cheaper
Co-benefits and interdependency with other on-farm measures	Amber	Some biodiversity increase, particularly where wood biomass is used
Socioeconomic barriers	Red	Currently untested at scale; low level of knowledge of the cultivation of biomass crops in the UK

Permanence	Engineering solutions to CO_2 storage. Biomass harvest creates cycle of accumulation and loss of above ground and soil carbon which will need to be accounted for
Next steps required to improve adoption or the science case	Amount of CO_2 stored. Unclear how direct and indirect land use change will be accounted for
Next steps required to improve adoption or the science case	Field trials of biomass crops, a BECCS test plant I sexpected in the late 2020s

2.2 Expected levels of different technology options

The total carbon sequestration potential of the interventions outlined depends not just on the technical capacity but also on how widely they are applied by farmers. In this section, we explore the capacity and willingness of farmers to implement carbon sequestration interventions.

We assessed farmers' willingness to adopt different on-farm practices by looking at data on which measures were the most popular in agreements under the 2016-17 Countryside Stewardship scheme (see appendix 3, page 92).[22] While many of the most popular measures were to do with biodiversity, with no direct impact on soil carbon, this still gives some insight into which practices are the easiest for farmers to adopt, either because they are close to current management practices, require no new equipment or are perceived as beneficial to the farm business. From the data we can infer that farmers are willing to take part in management interventions around hedgerows, field margins, grazing management and rotation measures at the current level of incentives, though the rate of uptake will have to increase rapidly, perhaps facilitated by the carbon markets we discuss elsewhere in this report.

Whilst this information is useful in understanding which measures have low barriers to adoption, it cannot be used to suggest measures which may be popular in future carbon markets as the incentive structure is likely to be completely different. That is, very different measures may have been popular in previous schemes if the focus was on rewarding soil carbon rather than increasing biodiversity. It should also be noted that the Countryside Stewardship scheme followed a 'payment for intervention' model rather than payment by results, which any credible farm carbon code would have to follow.

It is difficult to assess how farmers are likely to interact with soil carbon markets given that so few are in operation, or close to operation, at present (early examples include Soil Heroes, Soil Capital and Gentle Farming).[23] There are currently low levels of market activity, with each individual transaction being negotiated on a case by case basis between buyers (investors) and sellers (farmers), via intermediaries.

Recent research with English farmers on their attitudes to soil carbon markets has shown both enthusiasm and wariness, with many farmers deferring entry to schemes due to a lack of transparency around carbon prices and liquidity in existing soil carbon markets, and concerns around contract lengths and flexibility.[24] In particular, the farmers were keen to learn more about potential new income streams from soil carbon markets, in the context of anticipated declines in payments from agri-environment schemes. Given policy imperatives to reach net zero, and the role farmers could play in this, it was perceived that farmers should be rewarded for any efforts that helped sequester and store carbon in agricultural soils. In addition to this, regenerative agriculture and practices designed to build soil organic carbon were perceived by most interviewees as "the right thing to do", and they would continue to pursue strategies that built soil carbon whether or not they were paid. Having said this, farmers who had transitioned to more regenerative practices already argued that the transition made good financial sense, if it is possible to maintain yields while reducing inputs and, therefore, costs.

When considering soil carbon markets, there are two components that farmers must engage with. First, they must consider whether or not to adopt the on-farm interventions designed to sequester and store carbon (eg herbal leys or hedgerow planting). There is already a well-developed literature on the adoption of on-farm interventions, which we summarise here. However, the second component they have to consider is whether they are willing to adopt an intervention as part of a carbon market scheme, including moral (eg around the identity and motives of investors) as well as technical considerations (eg project development and contract lengths).

For each of these two aspects of a decision around carbon market adoption, a range of factors are likely to influence whether a farmer will engage. Although important, the financial return is just one of many internal and external factors influencing their perception and the likelihood of engagement.[25] Internal factors are more likely to influence attitudes, whereas external factors are more likely to influence whether they are pre-disposed to adopt a carbon sequestration intervention within a market scheme. A full outline of the factors affecting a farmer's decision making around this can be found in appendix 3a, page 93.

The most important factor influencing farmer engagement with a soil carbon market scheme is risk perception. While payment by results schemes pass some performance risk onto the farmer, recent trials for biodiversity interventions in the UK suggest farmers are willing to take part in such schemes, as they are rewarded for good performance and can use their own local knowledge and expertise rather than following a prescribed plan.[26] These trials considered two interventions in upland grassland and lowland arable farming systems and showed that payment by results schemes could deliver significantly better results than control plots under conventional schemes. Though farmers were initially concerned about the risk of receiving no payment if they scored the lowest possible outcome, this was partly mitigated by safeguards, in case there was exceptional weather and the farmers did not achieve results for reasons beyond their control. The pooled buffer of credits approach adopted in the Peatland Code could be seen as analogous to such a safeguard as the risk of project failure is spread out amongst scheme participants.

Jones (2021) also uncovered concerns about the length of carbon contracts, in addition to other contractual issues such as how to share benefits and risks and what the tax implications were.[27] Moreover, there were concerns about transparency of pricing and farmers did not feel able to judge whether they were being offered a fair price for their carbon. Others felt it was unfair that farmers who had degraded their soils stood to gain most from soil carbon markets, while those who had already switched to regenerative approaches would not be rewarded for the carbon they had already stored (this is explored further in section 3.5, pages 47-8).

Given that many of the measures proposed in farm soil carbon schemes have been readily adopted in the Countryside Stewardship scheme and farmers have been positive about the use of payment for results methods, we can infer that many carbon sequestration measures, such as hedgerows, field margins, grazing management and rotation measures will have low barriers to adoption. Other options, such as enhanced rock weathering and biochar, require the farmer to spread powdered solids onto their land, a process already practiced and for which new farm machinery is not likely to be needed. This, therefore, also has low barriers to adoption. However, at present it is unclear what level of adoption is likely for more radical interventions, such as planting biomass crops or converting to paludiculture, as there is a low level of knowledge of these practices in the UK.

2.3 Challenges with negative emissions technologies

There are some challenges which are common to all or some greenhouse gas removal technologies, including the on-farm agri-carbon measures we assess above. These include mitigation deterrence and the large land use requirements if large amounts of emissions must be balanced to get to net zero.

Mitigation deterrence

One emerging problem with large scale greenhouse gas removal technologies is the concept of mitigation deterrence, whereby action on decarbonisation is delayed due to the promise of the future availability of often cheap negative emissions.[28] Indeed, the cheapness of later action, brought about by the discounting of future costs in economic models, creates an inherent preference for action in the future rather than now. Negative emissions technologies can, therefore, create rebound effects; for example, based on cost modelling, the availability of BECCS and direct air capture and storage (DACCS) allows the continued use of gas turbines for power generation which would otherwise be forced off the grid earlier to meet carbon goals.[29] While this is true of future negative emissions by afforestation, as much as by BECCS, it is particularly concerning for BECCS due to the scale at which it is being relied on to meet climate targets and the fact that it is not currently operational

It has been suggested that this reliance stems from the co-development of climate models, technology and policy, meaning that new technologies (in this case, BECCS) are used to deal with any temperature target overshoot in a climate model, despite being currently unproven at scale.[30] Suggested new nuclear deployment after the Rio 1992 UN climate conference and climate capture and storage in the 1990s and 2000s are suggested as examples of this technological optimism delaying decarbonisation and this could be happening now on a large scale in relation to BECCS.[31]

This is largely because climate policy models give different outcomes based on the question asked; solving climate change as cheaply as possible will favour future removals through BECCS and DACCS as these costs will be heavily discounted, whereas solving climate change with the lowest risk of failure would involve deep emissions cuts now at greater cost .[32] Reliance on future carbon removals, either by technological options or 'nature based' measures, such as afforestation, increases the risk of missing climate targets compared to rapid decarbonisation now.

This is relevant to the discussion of negative emissions technologies in the UK as, for many options, the greatest trade-offs occur due to the scale of deployment needed to balance future residual emissions. BECCS and afforestation both require significant amounts of land which may displace food production or room for nature, whereas soil carbon measures are not large enough to meet all net zero offsetting requirements.

The problem here is not with the technologies themselves, but with the large amount of emissions they are expected to balance. If we view this problem through the lens of mitigation deterrence, we might reframe the problem of BECCS land use requirements as "how do we decarbonise faster to limit our reliance on BECCS?" rather than the current framing of "how do we make BECCS more land efficient so we can rely on it more?".

Land use and trade-offs between different negative emissions technologies

A recurring issue with many negative emissions technologies is the requirement for significant areas of land which will either compete with food production, space for nature or, at the very least, compete with each other. Direct air carbon capture and storage (DACCS) of CO_2 is the exception to this rule as the land footprint required is expected to be tiny compared to the amount of CO_2 it could remove. The role of DACCS in meeting net zero by 2050 is, however, uncertain as it is an immature technology. Although deployment later in the century could release land being used for other negative emissions technologies. Enhanced rock weathering also has minimal land requirements, beyond that required for quarrying, as the evidence we have reviewed suggests spreading on arable land will increase yields and does not compete with food production. But it is, at present, unclear how much of the UK's arable land will be suitable for use and what application rates will be optimal with ongoing trials aiming to answer these questions.

A trade-off is therefore likely to occur between technologies with significant land requirements like BECCS, afforestation and biochar, as well as food production. At the scale BECCS is currently being relied on in UK modelling to meet net zero, our analysis suggests around one million hectares of biomass plantation will be required, using land not currently in agricultural production. For context, this is approximately 4.1 per cent of the UK's land area, the majority of which would become short rotation coppice (see appendix 2 on page 66 for detailed discussion of BECCS biomass requirements and how figures of land use differ between studies).

Whilst a million hectares of coppice and miscanthus would represent a dramatic change in the way the UK landscape is managed, BECCS still performs comparatively well when compared to other negative emissions technologies, in terms of land use efficiency when assessed in a UK context (see table over).

Carbon sequestration land use efficiency for different negative emissions technologies[33]

Technology	Land efficiency $tCO_2e\ ha^{-1}yr^{-1}$	Source	Total potential $MtCO_2e\ yr^{-1}$	Assumptions
Direct air capture and storage (DACCS)	1,818	P Smith et al, 2016[34]	1 – 25	Speculative estimate of potential deployment by 2050 (Climate Change Committee (CCC))
Bioenergy with carbon capture and storage (BECCS)	3 – 12	P Smith et al, 2016	20 - 70	Scale up during 2030s (Royal Academy of Engineering and Royal Society estimate)
Enhanced rock weathering	0.8 – 10.9	P Smith et al, 2016	12 -27	Application ranges from ten to 30 tonnes per hectare (Royal Academy of Engineering and Royal Society estimate)
Biochar	1.15 – 7.5	P Smith et al, 2016	6 - 41	Limited by availability of domestic biomass (Royal Academy of Engineering and Royal Society estimate)
Afforestation	3.4	P Smith et al, 2016	16 – 28	Planting at 30,000 to 50,000 hectare per year to 2050 (CCC)
On-farm measures				
Paludiculture	19.0 – 39.0 *	C Evans et al, 2017[35]	2.0 – 4.1 *	25 per cent of lowland peat drained for agriculture becomes paludiculture to meet CCC target
Halving drainage depths for arable on peat	12.7 – 18.9 *	C Evans et al, 2021[36]	5.3 - 7.9 *	Drainage depth halved on all drained lowland peat
Agroforestry	4.4 – 10.0 (mainly tropical data so likely in the lower range in the UK)	D Kim et al, 2016[37]	1.8 – 4.2	Adoption at 416,700 hectares, A Thomson et al, 2018[38]
Hedgerows	3.1 – 7.3	S Drexler et al, 2021[39]	0.5 – 1.2	Adoption at 168,200 hectares, A Thomson, et al 2018
Organic matter incorporation from residues or amendments	-0.9 – 2.3 depending on clay content of soil	C Poeplau et al, 2015[40]	-1.1 – 2.8	Mid-range rate, adoption at a third of arable area
No till system as part of conservation agriculture	0.3 – 0.6	S Jayaraman et al, 2021[41]	0.4 – 0.7	Mid-range rate, adoption at a third of arable area

* emission reductions rather than carbon sequestration

Note: total potential figures cannot be aggregated as many measures compete for land.

From this synthesis of information, we can see that, whilst BECCS and DACCS are the most land use efficient options, on-farm measures perform comparatively well.[42] Paludiculture and raising water tables on organic soils under arable perform exceptionally well at reducing emissions but will not sequester carbon unless combined with BECCS or biochar. This is important because, as the UK approaches net zero, all offsetting will have to be done via carbon sequestration rather than emissions reductions credits. Agroforestry and hedgerows are the best on-farm measures for carbon sequestration but will need management of woody biomass to sustain sequestration as the trees and hedges reach maturity. While soil carbon measures have low potential per hectare, and are limited in terms of the length of sequestration possible, they have perhaps the highest potential for adoption whilst also keeping land in food production.

As many of these technologies compete for land resources, Smith et al (2016) suggest the maximum achievable negative emissions in the UK to be 12-49 million tCO_2 per year, with a combination of BECCS, practices that increase soil carbon sequestration and enhanced rock weathering. For comparison, the CCC estimates UK agriculture and land use sectors will have residual emissions of equivalent to 21 million tCO_2 per year by 2050. As this is within the range of values estimated by Smith et al, it is currently unclear whether the land use sector can generate enough carbon sequestration to offset its own emissions before sales to other sectors are considered. It is important to note that this figure also assumes that sequestration from BECCS will be assigned to the land use sector. At present, the CCC assumes this sequestration is allocated to the energy sector, rather than agriculture, meaning total carbon sequestration attributable to the agricultural sector could be much lower.

Whilst BECCS, soil carbon sequestration and enhanced rock weathering together is the most efficient combined carbon sequestration option, in terms of land use and minimising competition with food production, it is important to note that these technologies also differ in how quickly they could be adopted. Whilst soil carbon measures could be deployed tomorrow, given the right incentives, whereas BECCS and enhanced rock weathering are unlikely to be deployed at significant scale in this decade.

On-farm measures offer an opportunity to deliver negative emissions in the shorter term whereas Smith et al suggest the combination of BECCS and enhanced rock weathering could deliver in the medium term, and DACCS in the longer term.

A significant problem with estimating the optimal configuration of land use for different negative emission technologies is the uncertainty over when technologies will be ready at scale and the sequestration levels which could be achieved. In the table above, we showed that many technologies span an order of magnitude in the best estimate of their land use efficiency, making definitive answers difficult and explaining the wide range of land requirements quoted in the literature.

Unfortunately, we are unlikely to be able to improve on these estimates until trials of biomass crops, biochar and enhanced rock weathering are completed in the UK. Until we have data from local field trials, estimates of UK biomass potential suggest a conservative estimate of one million hectares of land could be used for biomass crops without using land in food production, protected areas or national parks (see appendix 2 on page 66 for a more detailed breakdown of the biomass requirements of BECCS).

It should be noted that these are technical assessments of UK capacity, so they do not account for the economics of a biomass supply industry which may deviate from the most optimal solution from a carbon perspective, for example by relying on cheaper imports of biomass.

In the shorter term, some soil carbon measures and afforestation can be used to deliver negative emissions. For afforestation, this may lead to competition for land with biomass crops in the future, representing an opportunity cost of not using the available land for BECCS. For soil carbon measures, there is unlikely to be an opportunity cost as the land is required for food production.

Indeed, as most of the gains from soil carbon measures occur within the first 20 years, they only offer a short term opportunity which will need to be replaced by other technologies in the future.

The requirements for large scale carbon removals in the future links back to our earlier discussion of the concept of mitigation deterrence: the most assured way to reduce the land use requirement of any negative emissions technology would be to reduce the need for it by cutting emissions now rather than later.

2.4 Conclusions

Many on-farm measures can sequester carbon with significant co-benefits for biodiversity, climate resilience and, in some cases, crop yields. Soil carbon accumulation mainly occurs over around 20 years, depending on the site and intervention, after which the soil becomes saturated, whereas hedgerow planting and agroforestry can produce longer term sequestration. On-farm measures could, therefore, fill a gap in availability of carbon removals until technologies like BECCS are operational However, it must be noted that active management will have to continue to maintain higher soil carbon levels, to avoid risking the reversal of these gains which will need to be accounted for in any incentive scheme or carbon credit market.

Measures which increase biomass, such as hedgerow planting and agroforestry, offer another way to increase on-farm carbon sequestration. For these measures, management of the biomass, for example by harvesting and using it in a BECCS system, could create carbon sequestration potential over longer time horizons. Newer approaches, such as enhanced rock weathering, biochar and BECCS have a large potential for scalable carbon sequestration over long time periods. But they are currently still five to ten years away from deployment.

Management interventions for increasing soil carbon rarely work in all soil conditions, and poor planting methods for trees and hedgerows can lead to failure. Local farmer knowledge will be key to achieving positive outcomes. Multiple approaches could be adopted by a farmer, based on what they think is most suitable for their conditions. But, in the case of soil carbon, there is a finite limit to the amount that can be sequestered, based on factors like soil clay content and the local climate.

Soil carbon monitoring will have to take into account factors such as crop rotations, to smooth out inter-annual variability. This will be particularly true where woody biomass is harvested (eg hedgerows and agroforestry) creating cycles of carbon accumulation and loss in both biomass and soils.

Permanence is an important issue for any carbon offsetting scheme. The approach to assuring permanence depends on the intervention in question: for BECCS, this is an engineering problem in CO_2 storage; for enhanced rock weathering and biochar, this is based on the physical and chemical properties of the starting material; whereas, for soil carbon measures, which are easily reversible, this will require legal measures to ensure carbon levels are maintained.

An issue which has not been resolved is the fact that many farms will not be able to generate enough carbon credits to offset their own emissions, so selling credits outside the sector compounds the problem of agriculture reaching net zero. Similarly, measures which decrease overall food production will have to account for this potential carbon leakage.

Afforestation, BECCS and biochar will all require significant land for biomass production to sequester carbon. Of these options, BECCS is the most efficient in terms of carbon removed per hectare of land used.

Achieving the required negative emissions, while minimising land use, is most likely to be realised using a combination of BECCS, on-farm measures and enhanced rock weathering. The land use requirements to meet UK net zero targets via BECCS is likely to be met without using agricultural land, although this is still debated in the literature, with a large range of estimates of land available for biomass plantation. Economics may dictate the use of the limited supply of waste biomass between BECCS, bioplastics and biofuels, as well as the importation of biomass from overseas.

The promise of plentiful carbon offsets in the future, whether from BECCS or afforestation, risks deferring action on emissions reductions now, as future costs are heavily discounted in economic models. Similarly, many of the trade-offs around the land use requirements of negative emission technologies can be minimised by cutting carbon emissions faster, and relying on future removals less. Emissions reductions, rather than offsetting, should always be prioritised to ensure trade-offs are minimised.

3. The credibility and ethics of an on-farm carbon sequestration market

Carbon markets can be either voluntary or regulatory. In regulatory markets there is a requirement for the regulated industries to reduce or compensate for their emissions or face a penalty for polluting. The main example in use is a cap and trade system, such as the EU and UK Emissions Trading Schemes (ETS) and the California cap and trade programme. These schemes operate under a cap on the overall level of emissions from the regulated businesses, with participants able to trade emissions units they do not use to other participants who have exceeded their allowance. In the Californian system participants can currently meet up to four per cent of their obligations by buying offsets from outside the cap and trade scheme.

By contrast, voluntary carbon markets involve businesses which do not have formal emissions reduction obligations buying carbon credits to reduce their climate impact. This can give a reputational advantage to the company buying the credit. The global voluntary carbon market has grown in recent years.

It is not expected that the agriculture sector will be included in the UK's ETS compliance market any time soon. However, interest in the use of carbon credits in voluntary carbon markets continues to grow, with many companies setting targets to reach carbon neutrality which include plans to use carbon offsetting, or 'insetting' where carbon credits are created and kept within the supply chain. This has been reflected in recent years in the growth of global voluntary carbon markets, which nevertheless remain small (46MtCO_2e in 2017 to 104MtCO_2e in 2019, roughly equivalent to a third of yearly UK emissions).[43] It is predicted that demand for offsets will grow precipitously. For example, the Taskforce for Scaling Voluntary Carbon Markets (TSVCM) estimates that 2GtCO_2e carbon removal is needed per year to meet existing commitments made by companies.

However, increasing interest from the corporate sector and developments, such as the launch of former Bank of England Governor Mark Carney's TSVCM, have led to increasing concerns about whether offsetting is being used instead of, as opposed to as well as, internal emissions reductions. There are also long standing concerns about the credibility and robustness of offset credit schemes.

Furthermore, while voluntary offsetting has previously been dominated by financing renewables and forestry schemes, more recently standards have been developed to produce carbon credits by sequestering carbon on farms, mainly through increasing the carbon stored in soils. This has been done in compliance markets, such as in Australia, and in the voluntary market. Questions have been raised about the credibility of these on-farm agri-carbon schemes, for example Microsoft's purchase of credits from a Regen Network project in Australia.[44]

There is an important distinction between carbon credits created by verified reductions in emissions elsewhere, and those created by removing and storing carbon from the atmosphere. Both forms of offsetting are used by businesses to claim 'carbon neutrality', ie the activity that was offset has not led to a net increase in greenhouse gases in the atmosphere.

However, for offsetting using reduced or avoided emissions there has still been an extra tonne of greenhouse gases in the atmosphere after the offset, whereas for carbon removal offsets there is not (offsetting by reduced or avoided emissions leads to one additional tonne CO_2 in the atmosphere instead of two, carbon removal leads to zero additional tonnes of CO_2 in the atmosphere). Offset credits from reduced emissions elsewhere can help to limit the build up of greenhouse gases in the atmosphere while businesses decarbonise. But ultimately reaching net zero at a company, UK and global level will require carbon removal and storage to balance leftover emissions. As the UK gets closer to net zero, offsets by emissions reduction or avoidance will no longer be sufficient.

In this section we examine the credibility of markets for on-farm carbon, the impacts such markets may have on agriculture in the UK and make proposals for how risks can be mitigated.

3.1 What is meant by credibility?

A credible market for agricultural carbon sequestration on UK farms requires the following elements:

1. **A market,** ie there needs to be a supply of carbon sequestration, and there needs to be demand to pay for it. On the supply side this means a technical ability to sequester carbon, and a willingness from farmers and land managers to do it. On the demand side there should be organisations which finance carbon sequestration, and which choose on-farm carbon over other potential options.
2. **Confidence in the quality of the carbon credits or certificates being produced.** This involves proper measurement and verification, and measures to ensure carbon is stored permanently or that measures are in place to compensate for future releases. This is explored in more detail in section 1, and we look at how it is applied in codes and standards below.
3. **Confidence that the way the credit is used and traded benefits the climate.** This means making sure the creation of the credit does not lead to more emissions elsewhere (leakage), that the carbon credit is not used more than once (double counting and double claiming) and that the carbon sequestered is additional to what would have happened anyway.
4. **Confidence that the market is not leading to negative unintended consequences.** These include:
    a. Damage to policy goals including sustainable food production, nature restoration and net zero.
    b. Unjust incentives and rewards for farmers, based on previous actions.
    c. The ability of farmers to achieve their own sustainability goals.
    d. Unfair prices and share of the benefits of carbon sequestration between suppliers, intermediaries, and farmers.

3.2 Is there a market for on-farm carbon sequestration?

Entering into the business of creating and selling carbon credits is increasingly being presented as an option for UK farmers to make additional income.[45] In England, the government is replacing the Common Agricultural Policy area-based payments with a system of paying public money to farmers in exchange for delivery of environmental improvements through the new Environmental Land Management (ELM) scheme, which is intended to work in tandem with privately funded schemes such as carbon offsetting.[46]

However, the actual size of the carbon market opportunity for farmers is unclear and depends on a number of factors, including how much carbon can physically be sequestered on farmland, how much demand there will be for carbon offset credits and whether carbon offset prices will be sufficient to motivate the required action.

Impact of the existing voluntary carbon market in the UK

The UK voluntary carbon market consists principally of the Woodland Carbon Code and Peatland Code, which provide standards for landowners to create verified carbon sequestration or reduction units by planting new woodland or restoring upland peat respectively.

The Woodland Carbon Code is a government backed standard, run by the Scottish Forestry Commission, while the Peatland Code is an independent standard, created by the IUCN Peatland Programme. Recently, there have also been new opportunities for farmers to receive carbon finance for carrying out regenerative agriculture practices in the UK, through schemes like Soil Capital, Gentle Farming, and Soil Heroes.[47]

Including planned Woodland Carbon Code and Peatland Code projects, and assuming 147 soil carbon projects at 100 hectares each, we estimate about 600km^2 of land in the UK is being managed under voluntary carbon market schemes. This is a very rough estimate as area of land under soil carbon projects is not known but gives an idea of the overall influence that carbon schemes are currently having on UK land. It is roughly the size of Greater Manchester, or 0.25 percent of the total UK land area.

While this may seem a relatively small area, there has been rapid growth in recent years. Since its launch in 2012, 15,481 hectares of woodland have been planted under the Woodland Carbon Code, with a further 24,150 hectares registered and awaiting validation.[48] In total, the woodland projects currently registered are expected to sequester 13.7 million tonnes of CO_2 over their lifetime (up to 100 years). The area registered with the code more than doubled between March 2020 and March 2021, having been relatively flat since 2016, presumably because the introduction of the Woodland Carbon Guarantee scheme in England, by the government, created a more attractive market for suppliers of credits.[49] On average about 3,300 hectares have been planted each year since 2018, which represents about a quarter of total woodland planting in the UK. For a variety of reasons, not all registered projects are completed, so it remains to be seen whether the large increase in project registrations in 2021 will lead to an increase in planting rates (which have been steady since 2019).

The Peatland Code, launched in 2015, is much smaller than the Woodland Carbon Code, with a total of 5,237 hectares registered.[50] Seven projects have been validated which are expected to save 150,748 tonnes of CO_2e over an average 74 year project lifetime. A further 20 projects have been initiated and are estimated to avoid the loss of at least 570,000 tonnes of CO_2e of peat stocks to the atmosphere over their lifetimes, equivalent to taking 230,000 flights from London to Sydney. Interest from the corporate sector in peatland carbon has grown rapidly since the inception of the code, with demand from investors seeking to mitigate climate change now outstripping the supply of projects.

Regenerative agriculture schemes are relatively new, with Soil Capital launching in the UK in 2020. This scheme currently has 147 projects, growing from 20 in 2020. Soil Capital has sold €500,000 of certificates upfront. Soil Capital is currently only available for arable fields, although there are plans to extend to permanent grassland. Hedges, orchards, woodland and forests are not counted, but in-field trees in agroforestry systems are. The main focus is on no till practices, but other activities such as organic fertilisation, cover cropping and minimum tillage are also encouraged. Gentle Farming is also only available for cropland and is based on using minimum and no till agriculture, with a commitment not to disturb the soil below 10cms depth.

Capacity for on-farm carbon sequestration

Excluding the conversion of farmland to woodland, the on-farm carbon sink which has received most attention globally is sequestration in soils. A number of high profile global initiatives aim to increase carbon in agricultural soils to tackle climate change and increase the resilience and sustainability of farming. The '4 per 1000' initiative launched in December 2015 at the COP21 climate conference champions the benefits of increasing global soil carbon stocks by 0.4 per cent per year, focusing on increasing carbon in the top 30-40cms of soil where carbon has been lost due to agricultural practices. Achieving this would equate to about 22 billion tonnes CO_2 removed from the atmosphere each year, or about two thirds of global yearly CO_2 emissions.[51] Another initiative, the Terraton Challenge, was launched by Indigo Ag in 2019, offering prizes for innovation to increase soil carbon sequestration with the ambition of capturing and storing a trillion tonnes of CO_2 from the atmosphere.

These initiatives are using ambitious aims to encourage action but, as shown in the previous section, there are limits to the amount of carbon that can realistically be captured and stored in agricultural soils. Globally, capacity for soil carbon sequestration is estimated at between about two and seven billion tonnes of CO_2e per year, or about 6-20 per cent of current global emissions.[52] In the UK, estimates vary widely from about one to 30 million tonnes of CO_2e per year, or about 0.2 to seven per cent of current UK greenhouse gas emissions.[53] The NFU's pathway to reach net zero in agriculture in England by 2040 assumes five million tonnes of sequestration in agricultural soils per year, in addition to three million tonnes in restored peatlands and wetlands.[54] The Royal Society estimates that $10MtCO_2e$ sequestration in soils is achievable.[55] Our evidence review suggested lower levels of soil carbon sequestration are likely in practice, with a mid-range estimate of up to 3.5 million tonnes of sequestration per year based on regenerative practices such as no till and organic matter incorporation (see table on page 27).

Carbon can also be sequestered on agricultural land in the biomass of trees and hedges. In an agri-carbon context this means practices such as agroforestry, where trees are deliberately integrated with the agricultural activity on a piece of land, and planting hedges and managing them to grow larger and store more carbon. The UK Climate Change Committee estimates an additional one million tonnes CO_2e per year can be stored in hedges and on farm trees by 2035, and three million tonnes CO_2e by 2050.[56] We do not consider conversion of agricultural land to woodland and forestry, and it should be noted that this is potentially much larger carbon store.

Demand for carbon offset credits

There are different methodologies for estimating future demand for carbon offset credits. The simplest uses an assumed market growth rate and projects this into the future. More sophisticated estimates analyse commitments that companies have made to reduce and offset their emissions and consider the residual emissions that eed to be balanced by removal offsets to meet temperature rise targets. There is a lot of uncertainty in these estimates as they depend on assumptions about how far emissions will be reduced overall, and what proportion of offsets will come from emissions reduction or avoidance (such as avoided deforestation or renewable energy schemes) compared to carbon removals (such as reforestation and soil carbon sequestration). There is also a question of how much of the demand for removals will be met by voluntary offset markets, compared to compliance markets or other finance mechanisms.

Realistic estimates of the size of global demand for carbon offset credits range from 0.43 to 1.3 billion tonnes of CO_2e in 2030, to 1.1 to four billion tonnes of CO_2e a year by 2050.[57] Estimates for overall demand for carbon dioxide removal are larger, at seven to 13 billion tonnes of CO_2e per year, but it is unlikely all of this will be met by voluntary carbon offset markets.[58]

It is unclear what the demand for carbon offset credits in the UK will be. This is because of two factors: how much demand there will be from UK companies, and how much of the demand will be met by credits created in the UK.

To give an idea of the possible future demand for credits from UK businesses, we can consider what the UK's share of the overall global demand is likely to be. If we assume that demand for carbon offsets will be proportional to size of the economy, demand for offsets from UK companies would be 3.2 per cent of global offset demand, or 14-42 million tonnes CO_2e a year in 2030 and 35-128 million tonnes CO_2e a year in 2050.[59] Alternatively, if the current share of the voluntary carbon offset market remains the same then UK demand would be 24-74 million tonnes CO_2e a year in 2030 and 63-228 million tonnes CO_2e a year in 2050, based on the UK's current 5.7 per cent share of global voluntary offsetting demand.[60]

UK companies are the third largest buyers of voluntary carbon offset credits globally, purchasing 5.9 million tonnes of CO_2e offsets in 2019. However, the majority of these are bought from projects overseas, with the UK's Woodland Carbon Code creating only about 1.2 million tonnes of credits per year.[61] If this trend continues we would expect demand for carbon credits created in the UK to be smaller than overall demand for credits form UK businesses, as some of this demand will be met by credits from projects overseas.

Demand, supply and prices

How this translates into money depends on assumptions made about carbon prices. The costs of implementing measures to sequester carbon on farms will vary from one farm to the next. Therefore, the amount of carbon sequestration which takes place at a given carbon price is likely to be lower than the full technical potential For example, Trove Research estimates that over half the globally available forest and ecosystem restoration potential will only be realised at prices over \$50 per tonne.[62] It is not clear what the equivalent figure for agri-carbon interventions would be, although, at \$15 per tonne of CO_2e, the value of the global market in soil carbon sequestration has been estimated at between \$50 billion and \$102 billion a year.[63] As prices rise, this may also have an impact on the scale of demand for offsets. This will be the case in the voluntary carbon market where there is no obligation for businesses to offset their emissions.

In a global context, it appears that the technical capacity to sequester carbon in soils could meet all the voluntary carbon market demand. However, this is unlikely to be the case in practice since there are other offsetting and carbon removal options which will offer different benefits and costs.

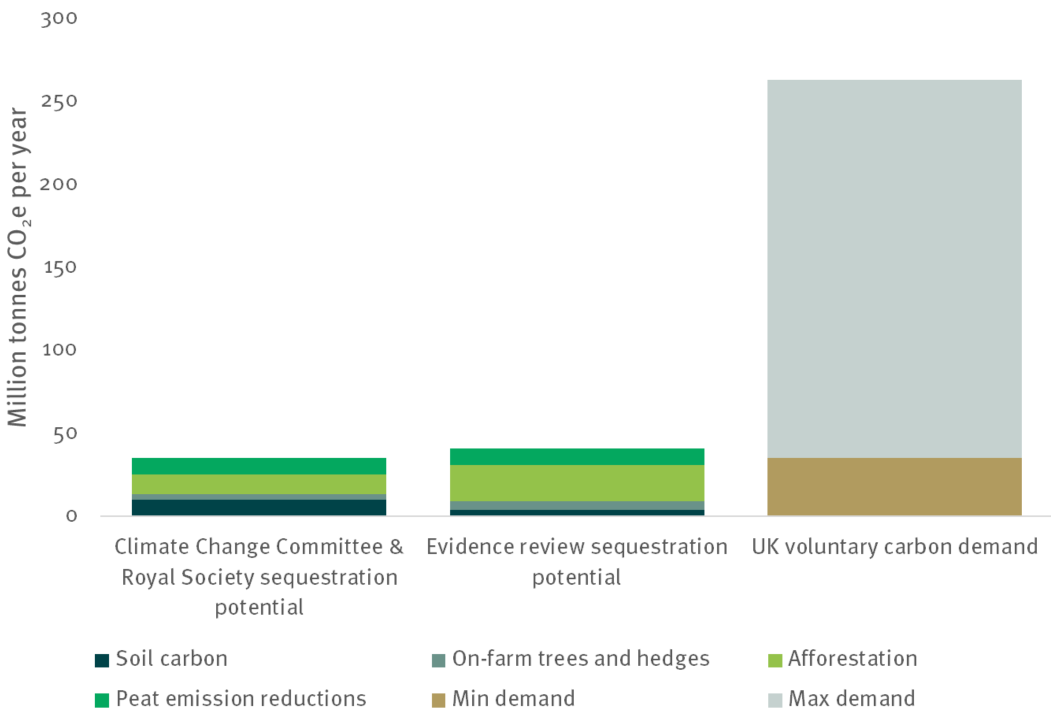
The voluntary offset market is dominated by credits from renewable energy projects and reduced deforestation and forest degradation (REDD+). While some companies are investing in offsets from soil carbon projects, others may be put off by some of the challenges presented by these projects, particularly around carbon leakage, permanence of carbon stored, and the difficulty of measuring and verifying carbon in soils (these challenges are explored further below). The amount of soil carbon sequestration that happens through carbon offset markets will depend on the level of confidence in this sort of offset and the price that these offsets can achieve compared to other available offsets.

Potential size of the market for UK farmers

In a UK context, offset demand is likely to be higher than the available soil and above ground carbon sequestration potential on farms, meaning that, theoretically, the voluntary carbon market could support all of this sequestration if businesses were to choose this sort of carbon credit.

Our lowest estimate of UK voluntary carbon market demand is 14 million tonnes of CO_2e a year by 2030 and 35 million tonnes a year by 2050 (see page 35). In terms of agri-carbon credits supply the Royal Society estimate that ten million tonnes CO_2 a year sequestration in UK soils is achievable, and the CCC estimates an additional $1MtCO_2e$ per year in the biomass of hedges and on-farm trees by 2035, and $3MtCO_2e$ by 2050, giving a maximum potential yearly supply of 13 million tonnes by 2050.[64] However, our evidence review in section 2 above finds a similar estimate on agroforestry and hedges of 2.3-$5.4MtCO_2e$ per year by 2050, but a smaller estimate on soil carbon sequestration of up to $3.5MtCO_2e$ per year by 2050, giving a maximum yearly total of 8.9 million tonnes CO_2e.

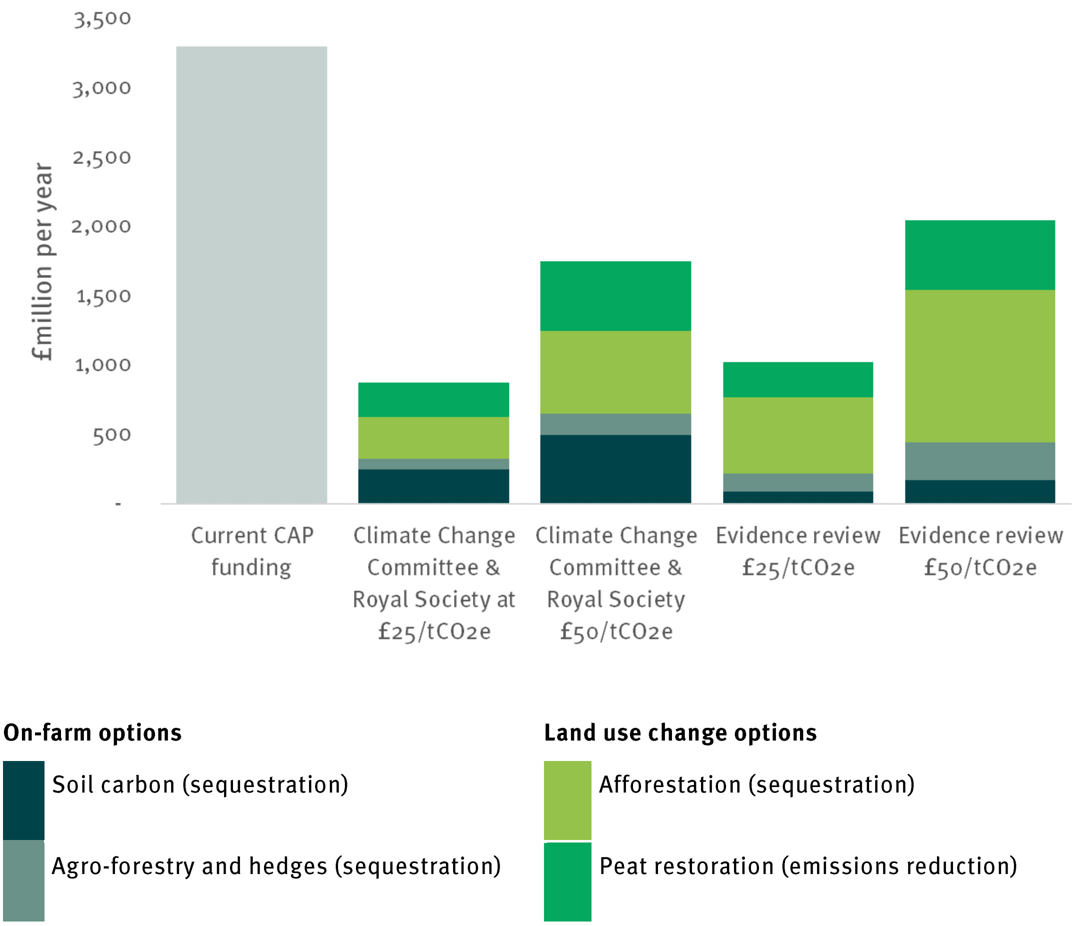
Yearly UK land-based carbon sequestration potential compared to voluntary carbon demand by 2050[65]



Again the size of the overall opportunity for UK farmers will depend on the appetite of offsetters to purchase this type of offset, and on how prices compare to other options. The UK government recently carried out an auction to buy woodland carbon code credits from UK landowners. In the first two auctions, the average price per tonne was reportedly £25 and £19 in the second auction.[66] Existing soil carbon sequestration schemes in the UK claim similar prices. This is about twice the price that Woodland Carbon Code credits were selling for in early 2020.[67] Peatland Code pending issuance units (the estimate of how many emissions will be avoided throughout the lifetime of a peatland project which can be sold upfront to finance the project) typically sell for between £10-£20 per tonne CO_2e.

The chart below compares the theoretical maximum funding for land-based carbon sequestration with current funding for agriculture through the Common Agricultural Policy (CAP) legacy schemes. We assume that all the available sequestration could be marketed and sold at two carbon prices: £25 per tonne CO_2e and £50 per tonne CO_2e. In one example below we combine the Royal Society's estimate of 10MtCO_2e soil carbon sequestration with the Climate Change Committee's estimate of 3MtCO_2e sequestration in hedges and on-farm trees, 12 MtCO_2e sequestration in new forests and woodland, and 10 MtCO_2e avoided emissions from peatlands. This is compared alongside the figures emerging from our evidence review in section 2 above. In both cases, more than half of the potential sequestration comes from land use change options (afforestation and peat restoration) rather than on-farm agri-carbon interventions (hedges, agroforestry and agricultural soil carbon sequestration). The main difference between the two examples is that the figures from our evidence review suggest more sequestration from afforestation and less in agricultural soils.

Potential yearly value of land-based carbon sequestration and emissions reductions by 2050 compared to current CAP payments[68]



Overall, the sums are fairly significant in comparison to public funding, potentially the equivalent of more than half the current £3.3 billion CAP budget. [69] However, even at £50 per tonne CO_2e the on-farm agri-carbon component is less than 20 per cent of the CAP budget, using the Royal Society's estimate of soil carbon sequestration, and less than 15 per cent using the estimates from our evidence review in section 2 above. This assumes that all the potential sequestration capacity is achieved and sold through the voluntary carbon markets.

To increase the funding available and make market participation more attractive, additional payments for other benefits delivered by interventions, such as benefits to biodiversity and water quality, could be incorporated. Green Alliance has previously evaluated options for 'stacking' payments for multiple outcomes and we outline the options for stacking payments below.[70]

3.3 Quality of carbon credits

To create credible markets for on-farm carbon sequestration there needs to be confidence that the carbon certificates or credits created are good quality. Trial methods include a number of important features which will aid in developing this: first, a lifecycle assessment of all parts of the process so an accurate carbon balance can be obtained; second, the development of monitoring, reporting and verification (MRV) protocols to ensure projects deliver the emissions reductions claimed; and third, the development of a legal structure to ensure management interventions will continue into the future and pooled buffers exist to spread the risk of project failure.

To be considered high quality, carbon credits or certificates need:

- to be additional to what would have happened anyway
- permanent storage, so that the stored carbon is not released into the atmosphere in future, nullifying the credit
- all greenhouse gas impacts of the activity to be considered, including whether the activity causes more emissions elsewhere, for example by displacing food production (called leakage)
- accurate measurement, reporting and verification of the carbon

To evaluate options for developing on-farm carbon markets in the UK that could overcome some of the main concerns expressed by the CCC and others (appendix 1, page 64), we conducted a comparative analysis of international soil carbon codes, in collaboration with the UK Farm Soil Carbon Code consortium. Soil was chosen as there are a good number of well developed international standards and protocols to examine. A full assessment is available in appendix 4 on page 98, and we cover the main points here:

Additionality

At the most basic level, additionality requires that the activity carried out was not required by regulation, was not already happening or was not likely to happen, in the absence of carbon finance.

Approaches to additionality varied considerably across the codes. Most required that management practice(s) were new to the project area, but some also stipulated that new practices must not already be common in a region, eg there should be less than five per cent of farmers using the new management in the surrounding region. Five codes required the demonstration of financial and legal barriers to the adoption of the new management practices. In some cases, this was as simple as conducting an investment analysis to prove that the activity was not economically viable without generating carbon credits.

Other suggested tools included investment comparison analysis, benchmark analysis or a simple cost analysis. Most codes required projects to meet a legal additionality test to ensure that project activities were not already required by law and complied with legal, environmental, ecological and social regulations in the country of application. One code took a much simpler approach, stating that “if a landowner can prove that they are adding atmospheric carbon to the soil or trees, they have a right to sell that stored carbon”, whether or not they would have made these changes anyway or were compelled to do so by law. Both the Woodland Carbon Code and Peatland Code include barrier, legal compliance, contribution of carbon finance (called financial feasibility in the Peatland Code) and investment (called economic alternative in the Peatland Code) additionality tests.

Permanence and leakage

While biochar and enhanced weathering provide strong natural permanence, many regenerative farming practices can easily be reversed, leading to a potential future loss of carbon. This has been tackled in two ways in international soil carbon standards. First, minimum contract lengths can provide a degree of permanence and are legally enforceable, requiring landowners to either regain lost carbon or pay back carbon finance. It is anticipated that the Environment Bill in England will make Conservation Covenants available for use in carbon markets (equivalent post-Brexit legislation in each of the other UK countries has the potential to make similar provisions). These would provide buyers with additional confidence and recourse, as these can commit all future owners of a piece of land to maintain land use and management to maintain soil carbon storage in perpetuity (or until both parties to the covenant agree to dissolve it).

In our review of international soil carbon codes, we found significant differences in approaches to permanence, leakage and reversals. For example, there were requirements to quantify and monitor leakage for specific or multiple areas, eg loss in yields, displacement of grazing, conversion to agricultural land use, source of organic inputs, etc. In a few instances these losses could translate into credit deductions.

Most codes used buffers to manage uncertainty. The size of buffers was established in several ways; for example, based on the permanence period, frequency of sampling, model estimations of uncertainty, project-specific risk rating or quality of verification methods used. In one code, the size of a buffer could change over the course of a project based on changes in risk. Non-variable buffers ranged from five per cent to 20 per cent and up to 50 per cent for a temporary buffer in one code. Some of the codes did not require contributions to a buffer.

One of the most significant differences between codes was their treatment of permanence. Where indicated, permanence ranged from eight to 100 years, with 100 years being the most common period for permanence. Credits were generally issued based on MRV at intervals across the permanence period. Therefore, project costs would be significantly greater for a project with permanence of 100 years compared to a project with permanence of eight years. Some codes did not specifically describe the permanence period.

There can be a trade-off between the stringency of permanence requirements and participation in schemes. It has been argued that permanence requirements could be relaxed to stimulate activity in the short term and meet short term climate goals with land based sequestration.[71] The safety of this from a climate mitigation perspective will depend partly on how carbon credits are used and accounted for (see page 43).

Measurement, reporting and verification

Because of the variability and uncertainty of soil carbon sequestration between different soil types and combinations of management practices, accurate measurement of soil carbon is crucial for credible markets. The scope of the codes varied significantly, with most requiring the measurement of soil carbon stocks and greenhouse gas emissions in a net soil carbon sequestration approach. A few codes addressed only greenhouse gas emissions or soil carbon stocks.

The main approaches in quantifying soil carbon sequestration were direct measurement, modelling or a combination of measurement and modelling. One code only required measurement of soil carbon stocks, one code only required modelling, and the remaining codes left the options open to measure, model or use a hybrid approach. The minimum soil depth required for the quantification of soil carbon stocks ranged from 20 to 30cm, although most methods indicated that a soil depth of around 100cm was ideal Two methods indicated the use of 'equivalent soil mass' when quantifying a change in soil carbon stocks. Specifications around the laboratory methods to measure soil carbon (in per cent) and bulk density were covered in varying degrees of detail with respect to allowable methods, quality control and measurement errors. Specifications around modelling options also varied, with some prescribing the use of specific models while others left it open to any suitable model. All models required calibration to local circumstances using suitable data.

The case for new UK agri-carbon codes

While a range of soil carbon standards exist and are in operation internationally, to date these have been developed and applied outside the UK and are typically not well adapted to the variability of UK soils and size of land holdings. Furthermore, the costs of verifying to these standards (see appendix 4, page 98) are likely to impede the development of UK soil carbon markets. Finally, as identified above, there could be a significant opportunity for carbon sequestration in hedges and on-farm trees. New codes are needed to set the standard for verification of carbon units from these projects.

Using funding from the government's Natural Environment Investment Readiness Fund there are now projects in the UK developing carbon codes for hedgerows and soil carbon. The UK Farm Soil Carbon Code seeks to draw on international best practice via a comparative analysis of all the major existing international soil carbon standards (summarised in appendix 4, page 98), adapting them to the UK context, alongside the development of soil testing methods that can provide verification with the density of samples needed for UK farm settings. The code will be developed in line with the UK's Environmental Reporting Guidelines, which currently allow domestic carbon units from the Woodland Carbon Code and the Peatland Code to be used by companies in their carbon accounting under a number of legal frameworks.[72] It will also be developed in line with the Oxford Principles so that it can be used by companies pursuing net zero strategies via initiatives such as Science Based Targets, enabling investors to use validated carbon units to make net zero claims.[73]

In some cases, existing carbon codes and MRV processes could be adapted, for example the Woodland Carbon Code could inform the likely biomass and soil carbon gains in agroforestry; however, for others such as soil carbon and hedgerows new accounting and MRV protocols will have to be developed. MRV costs are a significant part of any carbon crediting project and there is significant scope for innovation as the requirement for low cost methods of assessing projects increases. New applications of drones and satellite technology offer one way of reducing costs alongside soil carbon analysis which, at present, requires expensive and time consuming sampling in fields to measure organic carbon content and bulk density in a laboratory.

It is important to distinguish between the proposed UK Farm Soil Carbon Code, which will become the third domestic carbon market in the UK alongside peatlands and woodlands, and the growing number of project developers and carbon brokers that are now operating in the UK. These currently operate to connect investors, who want to contribute towards the adoption of climate friendly farming methods (note that there are limitations on what they are allowed to claim and these are not offsets, see pages 44-5), and farmers who are willing to change their practices to sequester and store soil carbon.

Companies offering these brokerage or project development services may verify carbon claims themselves or work with third party verification bodies and they currently use a range of methods for verifying claims. It is expected that the majority of these groups will use the UK Farm Soil Carbon Code to certify their work to a common standard, but the existence of the code will not preclude ongoing collaborations between investors and farmers on a corporate social responsibility basis in future (ie funding emissions reductions or carbon sequestration for reputational benefits rather than to offset emissions).

Broadly, there are two types of investors interested in soil carbon storage. First, there are companies with dependencies on agricultural production (eg food manufacturers and retailers) seeking to reduce risks from climate change in their supply chains. These companies are typically interested in carbon insetting as part of a company net zero commitment and are targeting changes in land management in their supply chain to deliver it. Although a number of such initiatives are already underway, using third party verification via independent certification bodies, # a UK standard would provide increased credibility and value to this work.[74] Despite the issues identified by the CCC (see appendix 1, page 64), UK investors interviewed by Jones (2021) generally perceived UK soil carbon as more robust than many of the alternatives currently competing in the offset marketplace, and have more attractive co-benefits alongside maintaining food production.[75]

The UK Farm Soil Carbon Code plans to enable the sale of units via the UK Land Carbon Registry, which is currently used by the Woodland Carbon Code and the Peatland Code, offering transparency on price to buyers for soil carbon as a distinct asset class.

The UK Farm Soil Carbon Code is still under development and its focus will depend on the outcome of ongoing work to gather evidence. A draft code will be out for consultation in 2022, with the goal of it being operational in 2023.

3.4 How should credits be used and traded

Trove Research propose that the overall purpose of using voluntary carbon credits should be "to ensure the maximum benefit for the climate from corporate and government commitments to reduce emissions".[76] There are several features of carbon credit markets which can impact on the extent to which they provide the maximum benefit for the climate.

Double claiming

There is an ongoing debate about judging the additionality of carbon projects in the light of current and future policy goals. If a policy goal to reduce emissions by a certain amount has been set, should this be treated as a regulatory requirement so that any offsetting would need to be over and above that policy goal?

This is particularly relevant in the light of the Paris Agreement's Nationally Determined Contributions (NDCs), with some disagreement between offsetting standard bodies about whether voluntary carbon markets should be separate from this system, or whether the countries where offset credits are created will need to adjust their NDC so that the offsetting activity is not counted towards their national goal (called a Corresponding Adjustment).

The international voluntary offset standards body Verra, for example, accepts the need for corresponding adjustments in compliance markets, but not in voluntary markets on the basis that carbon offset claims made by corporations are not counted towards their country's NDC.

Thus, for the purposes of the Paris Agreement, the emissions reduction or removal is counted in the host country only and not in the country where the credits were purchased, so there is no double counting.[77] However, others argue that, while there is no double counting for the purposes of the Paris Agreement, there is double claiming and this can lead to the emission reduction being less than is claimed.[78] Because the host country counts the offsetting activity towards their own NDC, this may displace other actions they would have taken to reach the NDC in the absence of the offsetting project. Both the host country and the buyer of the carbon credit are claiming a one tonne reduction or removal, so two tonnes are being claimed, while only one has taken place. For this reason, Gold Standard takes the view that corresponding adjustments will be needed even in the voluntary carbon market to make sure offsetting activity is in addition to, not instead of, efforts to achieve NDCs.[79]

Why double claiming matters

One of the arguments that double claiming should be avoided is that it is dishonest, while offsetting claims should be based on the truth.[80] But more than this, in the worst case scenario it can lead to more emissions than would otherwise have occurred. This is the case if the host country counts the activity towards its own NDC, and the emissions of the buyer increase because of the offset and this rise in emissions is not compensated by the country the buyer is based in. The buyer's emissions could rise either because the offset leads to greater demand for its products, eg more people take flights believing them to be carbon neutral, or if they use the offset instead of an emission reduction they would otherwise have made.[81,82] The effect of this on global greenhouse gas emissions is summarised in the table below.

Emissions reduction/ sequestration project	Host country	Net impact in host country	Carbon credit buyer	Host country	Net impact in buyer country	Net global impact
-1 tonne CO_2e	Counts the project towards its own NDC	No change compared to if the project had not taken place	+1 tonne increase in emissions (due to increased demand, or substituting reductions)	Does not take additional measures to compensate increase in emissions	+1 tonne CO_2e	+1 tonne CO_2e

While the scenario in the table is a worst case scenario, it should be considered a significant risk since it presents benefits to all parties in the chain. The host country government benefits because part of their obligation to reduce emissions has been financed privately. The carbon credit buyer benefits because buying the credit has brought them additional income or has enabled them to save money compared to reducing their own emissions.

There is only a net benefit to global greenhouse gas levels from voluntary offsetting if the offset activity is in addition to anything the host country would have had to do anyway to meet their targets, and either the buyer's emissions do not increase as a result, or any increase in the buyer's emissions is compensated for by an increase in climate action by their government.

How offsetting is used in the UK

In the UK, meeting the legally binding net zero target will be challenging. This makes it very unlikely that the UK government would agree to 'release' carbon credits and not count any activity towards meeting domestic targets. Releasing carbon credits would make it more difficult to meet domestic targets, ie more emissions reductions and carbon removals would need to be found. International standards bodies like Gold Standard would not allow credits created in the UK to be sold internationally without a corresponding adjustment because of the double claiming risk. The UK based standards (Woodland Carbon Code and Peatland Code) only allow sales of carbon units to compensate emissions created in the UK.

This means the role of voluntary carbon markets in the UK is to take some of the burden off the public purse for achieving climate targets by bringing in private finance, but they do not lead to a net reduction in emissions overall, compared to what would have happened anyway. The legally binding net zero target mitigates the risk of increased emissions because it effectively requires the government to compensate for any increase in emissions due to the offsetting activity to still meet the net zero target.

The UK government has made clear its intention to encourage the use of domestic voluntary carbon offsetting to meet climate goals. For example, the 25 year environment plan states "We will strengthen domestic carbon offset mechanisms to encourage private sector investment and develop markets for domestic carbon reduction."[83]

While the focus so far has been on woodland and upland peat restoration, the *Net zero strategy*, released in October 2021, also states an intention to review "the potential role for voluntary or compliance markets to support cost effective decarbonisation" in the agriculture sector.[84] Having embedded domestic offsetting into its plans to reduce emissions, it can be argued that there would not be a double claiming issue between the UK NDC and the owner of the offset credit because the offset scheme is simply a delivery mechanism for the NDC.

This will not necessarily be the case if UK businesses buy offset credits from other countries, so businesses should check how the schemes they use mitigate double claiming risks. Businesses should also ensure that any offsetting they do is in addition to, not instead of, reducing their own emissions as far as possible.

One way to do this is to set a science based target to reduce emissions as much as possible in line with climate science. To ensure benefit to the climate, offsetting should only be used to compensate for emissions which cannot yet be reduced, or to balance left over emissions which cannot ever be reduced to reach net zero. Businesses can use the Science Based Targets Initiative, or similar schemes, to ensure they are reducing their emissions as much as possible before using offsetting.

Alternatives to 'offsetting' claims

The above risks pertain particularly to carbon offsetting, where the company buying the offset claims to have compensated for their emissions with the offset. However, businesses that want to go further in tackling climate change can also buy carbon reduction or removal certificates and claim to be contributing towards reducing emissions, as opposed to compensating for their own emissions.[85]

For example, Microsoft funded woodland creation in Ireland under the Woodland Carbon Code, but is not using the credits created towards its carbon neutral claims, instead claiming a contribution to supporting the environmental restoration in Ireland.[86] This helps avoid the double claiming risk, and is the approach taken by some schemes. For example, the Soil Capital regenerative farming scheme in the UK, France and Belgium creates verified emissions reduction certificates sold to companies (both food and non-food companies) that want to support more responsible agriculture and demonstrate that their supply chain emissions are reducing, but are explicit that the certificates are not carbon credits to use for offsetting.[87] This is undoubtedly 'safer', from a climate perspective, but still requires strong standards of measurement, reporting and verification to ensure claims of contributing to emissions reduction are credible.

Clarity about what claims can be made from a project, and measures to ensure only appropriate claims are made, are essential This may not always be the case. For example, the UK government guidance on greenhouse gas reporting for businesses states that Woodland Carbon Code credits "are not termed offsets or carbon credits because they do not meet all aspects of "additionality" requirements, in common with all domestic emissions reduction projects. (This is related to UK government policy towards reducing emissions under UNFCCC agreements)", and they should be reported separately from other offsets.[88] Similarly, guidance from the Peatland Code states: "Peatland Carbon Units can be reported in annual greenhouse gas, environmental or other reports as well as in signage, website or other promotional material but they cannot and should not be presented as carbon offsets or as tradable units on international carbon markets."[89]

However, the Woodland Carbon Code states: "A Woodland Carbon Unit (WCU) is a tonne of CO_2e which has been sequestered in a WCC-verified woodland. It has been independently verified, is guaranteed to be there, and can be used by companies to report against UK-based emissions or used in 'carbon neutral', 'climate neutral', 'net zero' or 'climate positive' claims for their current claim year."[90]

Emissions reductions vs carbon removals

Carbon offsets can be split into two categories: reducing or avoiding emissions elsewhere or removing and storing carbon from the atmosphere. On-farm carbon offsetting activities could include both emissions reductions and carbon removals. The main removal proposals are around soil carbon sequestration and sequestration in trees and other plants.

Emissions reduction credits are created from peat restoration. However, schemes are also emerging that seek to sell credits from reducing farm emissions. For example, a scheme in Switzerland is seeking to sell carbon credits created by dairy farmers feeding methane suppressants to their cows.[91] Creation of emissions reduction offset credits from agriculture may raise questions about additionality since the sector will need to decarbonise to reach net zero in any case.

Reduction offsets may have value in helping to move farming to low carbon practices, in the absence of other policies, and preventing the build up of carbon in the atmosphere as the country transitions to net zero, provided the buyer is using the offset in addition to, not instead of, reducing their own emissions. However, to reach net zero requires a shift from reduction offsets to removal offsets. Removal offsets both prevent the build up of greenhouse gases in the atmosphere ahead of 2050 and enable the UK to be net zero beyond 2050.

Implications of how credits are used and traded

Credibility of schemes depends on the interaction between the quality of the credit or certificate, and the claims that are made.

Because voluntary carbon markets are explicitly envisioned to play a role in meeting the UK net zero target, issues of double counting and double claiming are mitigated for domestic offsetting, provided claims are made in line with government guidance and climate science. This should be robust from a climate perspective. But, as outlined below, selling carbon offsets from agriculture may constrain farmer's choices in future which needs to be considered at both a national and farm level.

Because of the UK's net zero target, to be credibly sold abroad, credits from the UK would need a Corresponding Adjustment to its national carbon budget. Due to the challenge of reaching net zero and the fact the UK is not currently on track to meet forthcoming carbon budgets, it is highly unlikely that this would be granted by the UK government. So farmers should be aware that they will not be able to sell carbon offsets to offset emissions in other countries. They may still be able to receive carbon finance if the buyer is aware they cannot claim this as an offset. For example, Microsoft funded woodland creation in Ireland under the Woodland Carbon Code but is not claiming the credits created towards its own carbon neutral claims.[92]

Business considering using offsetting or financing carbon sequestration should take care that what they are buying adheres to a recognised and reputable standard, and that the claims they make about it are appropriate. Two standards, the Woodland Carbon Code and Peatland Code, are available in the UK and credits created under these standards are tracked through a UK Land Carbon Registry with government involvement.

3.5 Avoiding negative unintended consequences

The final element needed for credible on-farm carbon markets in the UK is to ensure they play a positive role in a just agricultural transition and avoid negative unintended consequences.

Control of carbon assets and ability to make claims against farm emissions

Not all schemes offer farmers the same control over the carbon certificates or credits they produce. For example, farmers taking part in the Soil Capital scheme are not able to sell the certificates created themselves, whereas farmers following the Gentle Farming scheme can choose to keep the certificates, sell them themselves, or Gentle Farming can sell them on their behalf.[93]

The type of certificate or credit created and sold may also affect the claims the farmer are able to make about their own impact. A carbon offset credit can only be used (or 'retired') once so, if it is sold, the emissions reduction or carbon sequestration cannot be used by the farmer to make claims about the emissions of their farm, or the sustainability of their products. This may have implications in the future, for example if buyers of the farm's products introduce requirements about the emissions embodied in them.

This is a particular risk if farmers enter contracts that involve transferring rights to use future carbon sequestration. For example, in both the Woodland Carbon Code and Peatland Code, landowners are able to sell all the carbon expected to be sequestered or emissions avoided for the entire lifetime of the project upfront as 'pending issuance units' (PIUs). This provides upfront finance for any works required, as well as removing the risk of future price volatility. PIUs are converted into Woodland Carbon Units or Peatland Carbon Units at intervals throughout the lifetime of the project as the actual sequestration or emissions reductions happen and are verified. These can then be 'retired' by buyers. Selling PIUs from agri-carbon projects could severely impact farmers' options in future for addressing their own emissions.

This situation would be avoided if the funder of carbon sequestration used the certificates to make claims about the emissions of the products they sell rather than using them as offsets. In this case, the claim applies equally to the farm and the carbon funder because the emission reduction is applied to the product, not the business.

Impacts on land use and food production

If a pure market approach was taken that focused on optimising for domestic carbon emissions reduction and removals, there could be undesirable consequences for other policy goals. For example, Green Alliance analysis shows that a carbon price as low as £35 per tonne of CO_2e would make it economically rational to stop farming all together on much lowland fen because of the high emissions from this type of agriculture that could be avoided by restoring the peat.[94] By comparison, the current UK ETS price is £64 per tonne on 11 October 2021, following a high of £74 per tonne at the end of September 2021.[95]

There is evidence of a growing number of green investment funds seeking to acquire land for carbon sequestration and other natural capital benefits, typically involving land use change from agriculture to forestry.[96] Concerns have been expressed about the impacts of this practice on local communities and economies.[97] Similarly, while restoring lowland peat may be a desirable outcome, from a carbon and nature perspective, these areas also produce about a third of UK food and the loss of this level of food production capacity is likely to be highly politically unpalatable. This suggests the need for some limits to be placed on the market to avoid these sorts of effects.

Ensuring that codes and standards for offsetting include assessment of leakage effects could go some way to addressing this. But there may also be an argument for exclusions of particular landscapes or soils from offsetting or placing limits on certain activities. This could be done within the standards themselves, for example the Woodland Carbon Code does not allow trees to be planted on deep peat, or by another government body.

Perverse incentives for farmers

A challenge with creating a market for carbon sequestration on farms is that it can reward those who have not followed environmentally friendly practice in the past and fail to reward those that are already doing the right thing. For example, farmers who have managed the health of their soil well are likely to have relatively high levels of soil organic carbon already. Since all soils have a saturation point, there will be limits to how much more carbon they would be able to sequester. In contrast, land that has been managed poorly may have lost a lot of carbon, and so will have more space to sequester carbon, attracting more funding. In a worst case scenario, this might be an incentive for the farmer to manage their land in a way that reduces soil carbon so that they can subsequently receive payments for re-sequestering the carbon. The same could also apply to on farm trees and hedgerows. A similar problem with forestry was identified with the early Kyoto Protocol agreement on climate action.[98]

To avoid creating perverse incentives, standards and codes for on-farm sequestration should include requirements on baseline measurement, with a sufficiently long look back period to ensure land management has not been changed for the purposes of gaming the carbon market. Soil Capital seeks to reward farms which are already sequestering carbon by measuring their carbon gains against a regional average baseline, instead of the farm's own baseline. But this approach raises questions about additionality that may make it unsuitable for offsetting claims.

A strong regulatory baseline and effective enforcement is also needed. For example, current hedgerow regulation should protect many (but not all) hedgerows from removal, if properly enforced, giving greater confidence that hedgerows will not be removed and re-planted for the purposes of claiming more carbon credits. Regulation around soil management is less strong, and is poorly enforced.

Finally, if rewards are available from the private market for those sequestering carbon then it may be appropriate to reward those who are already storing a lot of carbon with public payments. This raises some questions about the application of the polluter pays principle (ie it effectively involves paying someone not to release greenhouse gasses), but may be considered appropriate and efficacious given the potential for perverse incentives outlined above.

Public funding is already used in tandem with private carbon finance in tree planting and peat restoration in the UK. For example, public tree planting grants can be used to fund the capital costs of planting trees, while carbon credit payments provide ongoing revenue payments. Proposals for 'stacking' public and private payments are explored further below.

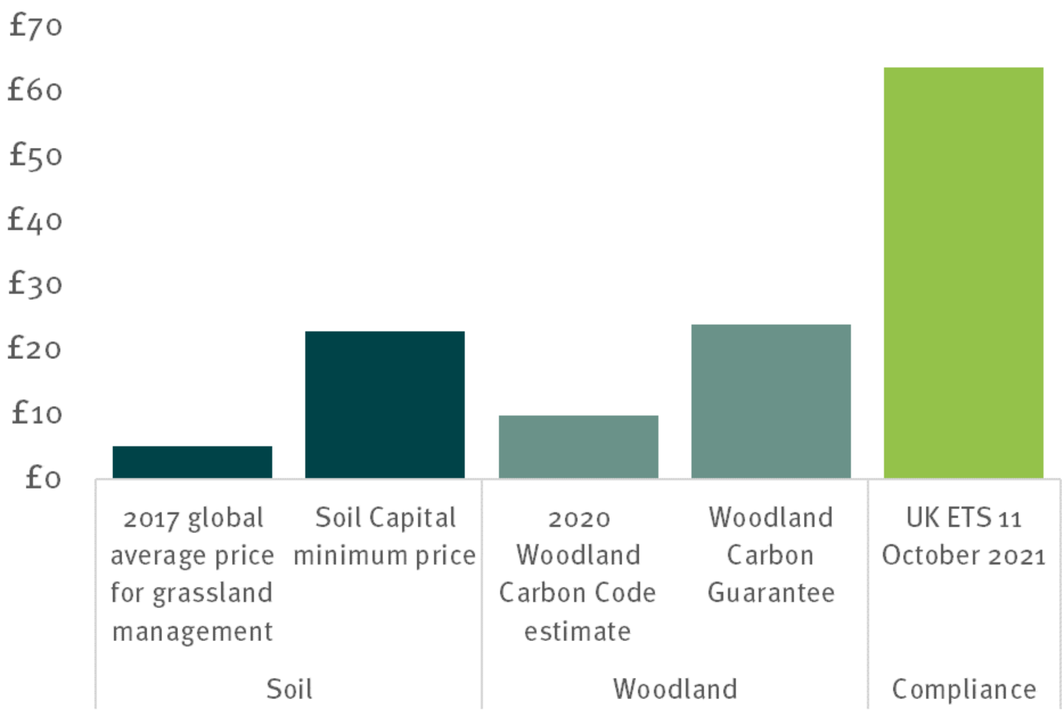
Fair prices for farmers

Carbon is priced in a variety of ways (eg taxes, cap and trade systems and voluntary carbon markets).[99] For an effective market, prices will need to balance attractiveness to farmers with demand. Farmers will also need to make decisions about whether the market is attractive to them now, or whether they think prices will go up in future.

Analysis by Green Alliance in 2019 found that the nascent agri-carbon market was achieving average global prices of just over £5 per tonne of CO_2, slightly below the global average for afforestation projects at the time.[100] Gentle Farming, which describes itself as the "UK's first soil carbon standard" estimates farmers could receive prices between £20-£30 per tonne of CO_2e based on current market data and insights from experts.[101] Another scheme available to UK farmers, Soil Capital, guarantees a floor price of £23 per tonne, at least 70 per cent of which goes to the farmer.[102]

Whether these prices are achievable in practice is unclear. It is difficult to accurately assess average prices in UK voluntary carbon markets as there is no publicly available data of actual sale prices. Based on anecdotal evidence, research by Green Alliance in 2020 estimated that Woodland Carbon Code PIUs would sell for around £10 per tonne.[103] Similarly, Peatland Code PIUs typically sell for £10-£20 per tonne CO_2e. However, a recent government auction for Woodland Carbon Code Credits under the Woodland Carbon Guarantee Scheme, of £17-£24 per tonne, suggested that prices will need to rise in the voluntary market.[104] All these prices are considerably lower than the current UK ETS price of £64 per tonne (on 11 October 2021), following a high of £74 per tonne at the end of September 2021.[105]

Comparison of carbon prices[106]



Many soil carbon interventions are estimated to be very low or even negative cost overall.[107] In other words, in the long term, interventions will save money for the farmer. For example, because they help to alleviate the costs currently associated with soil degradation. Therefore, even low prices could be considered fair for many interventions. But there will be some variability as this does not necessarily consider upfront costs, particularly for interventions like agroforestry and hedge planting.

Ultimately, it is for the farmer to decide if it is worth selling their carbon credits or holding onto them either to use themselves, or in the hope of a higher price in future. Higher prices may be achievable in future if demand in the voluntary carbon market rises, if the UK ETS is expanded or if outcomes based payments from government are introduced (for example, along the lines of the Woodland Carbon Guarantee).

There is also a risk that prices will go down in future. In the case of soil carbon most standards preclude selling the estimated carbon sequestered by the scheme upfront, as often happens with woodland and peatland projects, so there will be some uncertainty for farmers in the prices they will be able to achieve. Agroforestry and hedgerow projects may be able to follow the Woodland Carbon Code model of issuing PIUs, enabling farmers to receive payment upfront and face a lower risk of future price volatility. However, as outlined above, farmers must be aware that this could hurt their ability to meet their own climate goals or obligations in the future.

Blending soil carbon markets with payments from other schemes

Stacking payments for multiple benefits could play a role in making on-farm carbon interventions more viable and attractive. For example, where interventions have opportunity costs such as reduced yield or have higher upfront capital costs, for example new agroforestry. Green Alliance has explored how stacking payments for multiple benefits can increase the value gained by an intervention and achieved by the farmer, making more projects viable.[108]

While stacking payments for multiple outcomes may be seen as an opportunity, many farmers are also concerned that early entry to soil carbon markets may impact their eligibility for agri-environment schemes, which are still under development in each country of the UK.[109]

It will be important to clarify how carbon markets will interact with publicly funded schemes, to provide farmers with clarity, avoid double counting of carbon benefits (or payments) and ensure soil carbon markets provide climate mitigation benefits that are truly additional

Reed et al (2021) highlighted several potential areas of conflict between public funding for natural capital and carbon markets. These included the potential for public funds to out compete private funds (eg where public schemes offer more attractive terms including shorter contract lengths and simpler or more familiar application processes), that would otherwise have enabled the market to deliver the public good.[110] The research also identified considerable uncertainty over future public schemes as the UK develops and trials post-Brexit policy over a relatively long timeframe, which could freeze the market, with potential sellers withholding projects until they know whether they will get a better price or terms under existing private schemes versus future public schemes. A lack of integration between public and private schemes may also impact the supply of projects to the private sector where those supplying projects consider the terms of public funding preferable to those available from private schemes.

No decisions have yet been made on how agri-environment schemes might operate in relation to soil carbon markets, but it is possible to infer options from the operation of the UK's only existing soil carbon market, the Peatland Code. The additionality criteria in the Peatland Code allow projects to accept up to 85 per cent public funding, if at least 15 per cent of total project costs come from carbon finance.

Although not done in practice yet, the code would also, theoretically, allow stacking of payments for peatland carbon with private investment in co-benefits (eg biodiversity or water quality), as long as the relevant additionality tests are met. To pass these tests, the project would have to demonstrate that there is no legal requirement to restore the peat, at least 15 per cent of costs are covered by carbon finance and that, without finance from both the Peatland Code and the other scheme, the project would not be financially viable. Thus, if it were necessary to add payments for both carbon and water quality to the funding available via an agri-environment scheme for a project to be economically viable, the project would not go ahead without all three sources of funding. So it would meet the additionality criteria for the Peatland Code, whilst also being eligible under the agri-environment scheme and would be considered additional by a water company paying for the water quality outcomes.

There are alternative models that could be used to blend public and private funding for agricultural soil carbon interventions, a number of which are currently being explored by UK governments as part of their development of post-Brexit agricultural policies.[111] The options described in appendix 5, page 109, show how public funding might be designed in future to provide incentives for participation in privately funded 'payment for ecosystem services' schemes, enabling the market to deliver significantly more public goods than at present, while reserving public funding to address market failures and avoid distributional justice concerns about inequities arising from an entirely market driven system.

Several of these approaches may work best in combination. For example, funds delineation (see appendix 5, page 109) prioritises projects for the market that are able to deliver the most popular ecosystem services at the lowest price (often climate mitigation benefits), reserving public funds to pay for projects that are more expensive per tonne of carbon, but which offer other important ecosystem services that have a high value to society, such as biodiversity or recreational benefits. A cost-benefit matrix (appendix 5, page 109) or decision support tools such as that developed by Artz et al (2013) for Scottish peatlands, could be used to identify sites most likely to deliver cost effective carbon sequestration benefits on the soil type and level of degradation.[112]

At the same time, this tool could be used to delineate sites that would be more expensive to restore, but where there may also be important biodiversity and water quality benefits, reserving these sites for investors more interested in these outcomes, and prioritising public funding for sites or ecosystem services that the market fails to deliver.

An alternative to delineating funds in space is to offer private funding during a specific time window (eg via a reverse auction for a carbon guarantee mechanism, see appendix 5, page 109), and then opening publicly funded schemes for application, giving funding to more expensive projects that were not successful in the reverse auction or to landowners who do not wish to accept the terms of private investment.

4. Conclusions and recommendations

Following our review, we highlight four main conclusions which point towards next steps and action needed to ensure the agri-carbon market develops in a sustainable and robust way.

4.1 Selling agri-carbon offset credits upfront could limit farmers' future options

There are different ways that carbon reductions and sequestration can be financed and different claims that can be made. These can have significant implications for farmers, depending which sort of scheme they enter into.

If farmers take part in an offsetting scheme, then the credits will be entered onto a public registry and can only be used (or 'retired') once.

If the farmer sells the credits, they cannot be used to make claims about the farm's emissions or the agriculture sector's emissions. Effectively, the farm's emissions are increased by an equivalent amount. For some farmers this may be acceptable; for example, if they are able to be 'net negative' and, therefore, sell a surplus of sequestration credits and still be net zero themselves. For others, it may make marketing their produce harder in future if they are not able to make claims about its sustainability.

If farmers sell a large amount of PIUs upfront and then the farm's customers introduce requirements on the emissions intensity of the produce they buy then the farmer will need to reduce emissions further or sequester more carbon, on top of what they already have achieved, to meet the requirements. In a worst case scenario, the farmer may end up needing to buy carbon offset credits to meet decarbonisation requirements.

Taking part in schemes that do not allow offsetting claims but where buyers make claims about having contributed to climate mitigation activity could help to mitigate this risk for farmers.

The best case scenario would be an agreement within the supply chain to help finance emissions reductions, specifically for the purpose of making claims about the sustainability of the agricultural products.

Recommendation:

Food businesses should use on-farm carbon reduction and sequestration measures to reduce their scope 3 (ie supply chain) emissions, instead of using them to offset their scope 1 and 2 (ie their own) emissions.

Companies using agricultural products in their supply chain should support farmers to reduce their own emissions wherever possible. This benefits the company, which can make claims about the sustainability of the agricultural products they are selling, as well as the farmer.

Verified carbon sequestration credits could be used in addition to balance any emissions that cannot be reduced. These could be held and retired by the farmer to make a claim about the net emissions of the farm or transferred to the supply chain company and retired by them to make claims about their scope 3 emissions.

This approach ensures the emissions reduction benefit is shared between the farmer and the buyer.

Working with the supply chain to finance verified emissions reductions and carbon sequestration credits retired by the farmer is also more likely to be open to tenant farmers. Their ability to produce and sell carbon credits for offsetting will depend on a range of factors, including the length of their tenancy and the specific arrangements with their landlord around the ownership of carbon assets.

These shared benefits would not be evident if the supply chain business bought carbon credits from the farmer and retired them to offset their scope 1 and 2 emissions, or where credits were sold as offsets outside the food supply chain. In this case, further emissions reductions and sequestration would be necessary for a net zero claim to be made about the farm's own emissions or the emissions of the product.

How the benefits of different insetting and offsetting options are shared between buyers and farmers

Options	Benefit to the farmer (in addition to funding)	Benefit to food and agriculture supply chain business	Co-benefits
Food supply chain businesses work with farmers to finance verified emissions reductions and sequestration to reduce the carbon footprint of the farm and its produce	Low or net zero carbon produce and farm	Low or net zero carbon produce. Scope 3 emissions reduction	Supply chain relationships Buyer has an interest in the resilience of food production
Farmers sell offset credits to the domestic supply chain against scope 3 emissions (insetting)	Avoids risk of not being able to meet customers' emissions requirements	Low or net zero carbon produce. Scope 3 emissions offset	Supply chain relationships Buyer has an interest in the resilience of food production
Farmers sell offset credits to domestic supply chain against scope 1 and 2 emissions (insetting)	None	Lower scope 1 and 2 emissions, but this effectively increases scope 3 emissions	Supply chain relationships Buyer has an interest in the resilience of food production
Farmers sell offset credits domestically outside the supply chain	None	None	None

4.2 Agri-carbon sequestration is available now while engineered carbon removals are still in development

It will be useful to start implementing interventions on farms now when there are clear environmental benefits, even if the structures are not fully in place to robustly quantify and verify them. In our review of on-farm interventions, even where there was still some uncertainty on the quantity of carbon that could be sequestered, there were often other environmental co-benefits, for example for water quality or biodiversity. Sustainable and regenerative techniques should be encouraged wherever possible.

Agri-carbon sequestration, alongside afforestation and peat restoration offer carbon removal solutions now that can help to limit the UK's net emissions in the next ten to 20 years while engineered solutions are being developed and scaled up. But, to make verified claims about carbon sequestration and create and sell carbon credits as offsets, robust standards need to be applied to give market participants and the public the confidence that the benefits claimed are real

Recommendation:

Ensure the quality of agri-carbon sequestration credits with strong UK codes

On-farm carbon sequestration presents several challenges if used in offsetting schemes, particularly around additionality, leakage, permanence, and measuring and verifying actual carbon gains. In many cases there will be trade-offs between robustness and practicality; for example, while laboratory analysis of many soil samples is the most robust and accurate way to measure and verify carbon gains, it is also expensive.

While a range of soil carbon standards exist and are in operation internationally, to date these have been developed and applied outside the UK and are typically not well adapted to the variability of UK soils and size of land holdings. A UK Farm Soil Carbon Code is currently under development, alongside a Hedgerow Carbon Code.

The new codes should give investors, farmers and the public confidence in on-farm carbon sequestration schemes. There are a growing number of project developers and carbon brokers operating in the UK which are connecting investors who want to support climate-friendly farming methods and farmers who are willing to change their practices to sequester soil carbon. It is expected that most of these groups will use the UK Farm Soil Carbon Code to certify their work to a common standard.

Recommendation:

Strengthen the market with further research into the efficacy of on-farm carbon sequestration methods and accurate, low cost soil carbon measurement methods

It is clear from our review of on-farm carbon sequestration potential that there is still uncertainty in the science around the efficacy of some activities. The table below summarises the further research that would be beneficial to increase confidence and accelerate the growth of agri-carbon markets.

	Robustness of the science	Research needed
Grazing management		To establish the optimal grazing conditions for enhancing soil carbon in UK context; education on management practices
No and low till		To establish if soil carbon gains can be made whilst limiting N_2O and CH_4 emissions, and NO_3 leaching, in UK conditions
Cover crops		Greater research required in the UK context and evaluating UK mixed cover crop system effects on soil carbon and greenhouse gas fluxes

	Robustness of the science	Research needed
Hedgerow planting	Green	Further work on CH_4 and N_2O emissions; comparison between hedgerows and control fields in arable and grassland, impact on efficiency of field operations, landscape design for optimum co-benefits.
Residue incorporation	Green	Assessing performance versus compost and other amendment schemes. Assessing appropriate locations and methods for residue incorporation.
Leys in crop rotation	Red	Quantified soil carbon studies needed in North West Europe
Agroforestry	Amber	Further field studies carried out in the UK with long term assessment of carbon cycling effects; design of incentive schemes; understanding of market development, labour and skills needed
Arable land use change	Green	Design of incentive schemes that avoid cancelling out gains via increased ruminant numbers
Field margins	Amber	To evaluate potential effects on crop yields as well as wider co-benefits and potential limitations in UK settings
Paludiculture	Green	Field trials, design of incentive schemes, market and agronomy development
Enhanced weathering	Amber	Field trials, design of incentive schemes
Biochar	Green	Detailed assessment of biochar performance in a wider range of settings including wetlands; design of incentive schemes
BECCS	Amber	Field trials of biomass crops, BECCS test plant

Further research is also needed to develop robust soil carbon measurement techniques which are cheaper than laboratory analysis (the most robust method), and to understand how a range of sampling, measurement and modelling techniques can be used to accurately measure carbon gains.

4.3 Careful constraints on offsetting markets are needed to avoid damaging climate mitigation efforts

Because the UK government will count any emissions reductions and carbon sequestration that results from voluntary carbon offsetting towards the UK's climate targets, the additionality of the activity is limited. This is because in the absence of the offsetting activity, the government would have had to find another way to reduce emissions or sequester carbon. Because of this there is a risk that, if credits are sold to companies in other countries, there could be an increase in global emissions overall as a result of the offsetting.

If buyers of offset credits are using offsets instead of emissions reductions they would otherwise have made, it will be harder for the UK to achieve its net zero target as further carbon removals will be necessary to compensate for the emissions that should have been reduced.

The ability to buy and use offsets should be restricted to businesses which have a credible plan to reduce their emissions as far as possible, in line with climate science. Such targets can be created for a growing number of sectors through initiatives such as the Science Based Targets Initiative. Domestic carbon markets in the UK and international soil carbon markets do not currently require this evidence, although the international standard for carbon neutral claims, PAS 2060, does require a carbon management plan for reducing emissions to be in place before offsetting remaining emissions.

As explored above, farmers and land managers creating carbon credits should also consider how this affects their own need to move towards net zero.

Recommendation:

As with the existing Woodland Carbon Code and Peatland Code, agri-carbon offsetting must be used for UK-based emissions only, to avoid reducing capacity to meet net zero. New requirements on those making carbon neutral or net zero claims to reduce their own emissions, before they resort to offsetting, would reduce the risks further.

If credits are only sold to compensate for UK-based emissions, the risk of increased emissions because of double claiming is reduced, but not eliminated. All sectors of the UK economy fall under the legally binding net zero target. If offsetting leads to more emissions from the buyer of the credit, or in them avoiding making emissions reductions they would otherwise have made, those emissions will have to be further compensated for in future to achieve the net zero target.

Any new codes developed should be included in the government's emissions reporting guidelines so there is clarity about how credits can be used. It might also be possible to receive carbon finance from companies abroad, provided credits bought are not used to offset the buyer's own emissions but are used to make reputational claims about decarbonisation in farming.

To avoid the risk of offsetting increasing emissions in those sectors using credits, the government should consider new rules for businesses that use carbon offsetting to make carbon neutral or net zero claims which requiring them to cut their own emissions as well. Some existing voluntary schemes, such as the Science Based Targets Initiative and the Carbon Trust's Carbon Neutral certification, already demand that businesses have plans in place to cut emissions as much as possible before using offsets.

4.4 A market driven 'dash for carbon' in the land use sector could lead to undesirable consequences for food production, local communities, and nature

On-farm agri-carbon markets would enable food production to continue while rewarding farmers for the climate benefits of moving to regenerative agricultural practices. However, land use change options, principally afforestation and peat restoration have an even greater potential for sequestration and in many cases will offer low cost and low risk options to those seeking carbon outcomes. As well as carbon credits that are already available through the Woodland Carbon Code and Peatland Code, there are a growing number of green investment funds seeking to acquire land for carbon sequestration benefits, typically involving land use change from agriculture to forestry, although our analysis suggests that lowland peat could also be used in this way. A lack of policy co-ordination and local involvement in these developments could lead to negative unintended consequences for food production and rural communities.

Recommendation:

A new rural land use framework is needed to steer the market towards positive outcomes

A new rural land use framework would not oblige landowners and farmers to use land in ways they do not want to. Instead, it would set out, in a spatially explicit way, the data on natural capital – including the relative productivity of the land for producing food, priority areas for habitat and carbon conservation, areas of significant agricultural pollution, and opportunity areas for woodland and wetland creation. It would also outline how and where land might be used to achieve the government's carbon and nature goals. These would form the evidence base to help guide private market decisions, as well as support policy decisions on farm payments and regulation.

This echoes a recommendation from the National Food Strategy, which set out a 'three-compartment' model for land use as a means of achieving the food, livelihoods, nature and carbon outcomes society wants from land.[113] This approach identifies land that is most appropriate for semi-natural uses, low-yield farming with the goal of integrating nature into the farm and high-yield farming, which must be more nature-friendly than today but which principally focuses on food production.

More targeted frameworks linked to the planning system could also provide safeguards to limit the scale of land acquisition involving tree planting in certain locations or land uses, public interest tests for large scale land acquisitions, or development of place-based approaches to benefit sharing with tenants and local communities (including potential for Community Wealth Building), and development of schemes to protect or retrain land managers in the most affected areas (eg hill farming).

Recommendation:

Further development of farming policy is needed to avoid perverse incentives and facilitate market approaches

The availability of private payments to sequester carbon may provide a perverse incentive to release carbon from land in order to get payments for re-sequestering it. There is also less opportunity for farmers who have managed land well and are already storing a lot of carbon and cannot sequester much more. A strong regulatory baseline can help to ensure carbon is not deliberately released, and public payments through ELM could be used to reward those who are already storing a lot of carbon.

There will also need to be further clarity on how public ELM payments will interact with private markets to ensure markets pay for as much as possible with public investment prioritising payments to those who do not wish to engage with the market or for projects that are unlikely to attract private investment. Currently, farmers who are taking part in the ELM Sustainable Farming Incentive Pilot are not allowed to take part in the Soil Capital carbon scheme because of uncertainties around additionality. Such issues need to be resolved quickly, as the ability to 'stack' public and private funding would enable more ambitious interventions for the environment.

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Appendix 1
Why is soil carbon currently absent from UK net zero policy?

The Climate Change Committee (CCC) published *Land use: policies for a net zero UK* in 2020, setting out evidence and advice on agricultural and land use policies that could help deliver net zero emissions in the UK. It recommended the adoption of low carbon farming practices, such as 'controlled-release' fertilisers and improving livestock health and slurry acidification, but did not recommend shifting towards more regenerative practices that could sequester and build soil carbon, and did not consider evidence for biochar, enhanced rock weathering and BECCS in depth as these were considered to be "speculative options".

The CCC's report was informed by seven commissioned reviews, none of which considered non-peat soil carbon in any depth, focusing instead primarily on reducing greenhouse gas emissions from soils (mainly nitrous oxide). Exceptions to this included:

- Buckwell (2019) briefly mentioned the challenge of soil carbon permanence.
- Vivid Economics (2019) mentioned the potential for cover crops to reduce soil erosion and improve soil health but did not explicitly consider soil organic matter.

A Defra study commissioned from the Centre for Ecology and Hydrology (Moxley et al, 2014) was particularly influential It concluded that reduced tillage did not increase soil organic content consistently enough, and the soil organic carbon benefits of increased use of crop residues and manure or fertiliser would be outweighed by nitrous oxide emissions and nitrate runoff. On this basis, it concluded that the impact of cropland management interventions was likely to be "very small" compared to the impact of land use change (conversion from annual to perennial crops, fallow and set aside) on greenhouse gas budgets. However, as Moxley et al (2014) pointed out, the scope for land use change is limited, given the need to maintain food production, and the area over which soil carbon interventions could be applied is significant. As a result, the CCC have continued to catalogue the important publications on soil carbon storage, including 30 peer-reviewed papers published between 2005 and 2020. However, to date, there has been no systematic review or meta-analysis of reviews covering the full range of interventions that could potentially increase soil organic carbon, to inform the work of the committee.

Key concerns expressed by the CCC about the inclusion of agricultural soil carbon in UK net zero policy (and the greenhouse gas inventory) include:

- limited overall greenhouse gas abatement potential with mixed evidence for many interventions;
- soil carbon only represents a short term opportunity; although the amount of time will vary between soils depending on how degraded they are, most soils will only gain organic carbon up to an equilibrium point of around 20 years, with limited greenhouse gas abatement potential after this; and
- soil carbon gains can easily be reversed, and gains in one part of a farm may be offset by losses elsewhere ('leakage').

As such, the CCC is taking a precautionary approach to agricultural soil carbon storage. However, given experience managing soil carbon permanence and leakage issues in international carbon markets (see appendix 4, page 98) and the need for evidence synthesis on the reliability and scale of this short term opportunity, their position remains under review pending further evidence.

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Appendix 2 Assessment of carbon sequestration options

Grazing management

Managed temperate grasslands cover one quarter of the world, supplying 50 per cent of global livestock with livestock systems contributing around 12-19 per cent of global greenhouse gas emissions, mainly as CH_4 and N_2O (Ghahramani et al, 2019). Livestock grazing occurs at a range of stocking rates (ie the number of animals per hectare and how long they graze that area of land), with various types of vegetation and across multiple climate types, with these being significant factors in the impacts of such grazing systems on soil carbon (Conant et al, 2017).

Most UK pasture is in rotational grazing, where cattle or sheep are moved between pastures and are grazed at relative low stocking density for a long period of time. This is in contrast to 'mob grazing' where animals are grazed at high stocking density for a short period of time or 'holistic' management which aims to match grazing time to plant growth periods to allow recovery. Some claims have been made that optimised grazing systems could sequester large amounts of carbon. However, such claims have been criticised for the lack of scientific rigour (Nordborg, 2016), with the effects of grazing management likely to be highly complex and potentially leading to losses of soil carbon, as well as gains.

Garnett et al (2017) reviewed the effects of grazing systems on greenhouse emissions and soil carbon and state that 7.1 $GtCO_2e$ result from grazing systems, with 65 per cent of this originating from cattle. This report claims that the global sequestration potential from grazing management is between 295-800 $MtCO_2e$ yr-1 which would only offset 20-60 per cent of annual average emissions from grazing ruminants.

Furthermore, Garnett et al (2017) suggest that, if increased carbon sequestration is to be achieved via grazing management, it may be at the expense of biodiversity and that intensification and expansion of grazing would likely increase CH_4 and N_2O, as well as CO_2 from land use change. Garnett et al (2017) do state that grazing can promote plant and root growth leading to below ground organic matter accumulation and can also increase nitrogen inputs from urine and manure, both of which may enhance carbon sequestration.

However, grazing management may lead to changes in plant species composition and compact soils with high stocking rates and long rotations. Additionally, cattle urine and manure have the potential to increase NO_3 leaching from managed lands, increase soil carbon decomposition and potentially leaching into aquatic systems, as well as labile manure components degrading and releasing CO_2 and CH_4 (Garnett et al, 2017). These observations are supported by other reports assessing the effects of grazing on soil carbon and greenhouse gas emissions (eg Moxley et al, 2014).

Eze et al (2018) reviewed studies of grassland carbon stocks, with sites being managed from 0.5-146 years (average of 18.97 years). They found an overall reduction in soil carbon stocks of 8.5 per cent, with 15 per cent of this being attributable to grazing, though these losses were partially attenuated by fertiliser application and liming raising productivity.

Tropical regions have seen soil carbon losses of 22.4 per cent, largely due to heavy grazing management (classed as >10 sheep ha^{-1}), whilst temperate settings lost 4.5 per cent. Soil carbon declines were attributed to excessive grazing of vegetation limiting residue incorporation into soils. The negative effects of grazing on soil carbon stocks doubled with increased grazing intensity, but in temperate settings this negative effect was found to decline with increasing temperature and precipitation, indicating that grazed temperate grasslands could lose less soil carbon under climate change.

Abdalla et al's (2018) review of grazing intensity effects on soil organic carbon found that increasing stocks occurred with increased grazing intensities in moist cool climates (7.6 per cent), whilst soil carbon stocks decreased in moist warm climates across all grazing intensities (-19 per cent). Soil carbon stock increases in dry climates only occurred with low (5.8 per cent) and moderate (16.1 per cent) grazing intensities.

Abdella et al (2018) also found that grazing management was associated with significant increases in soil total nitrogen and bulk density but had no effect on soil pH. This review suggests that optimised grazing schemes must match grazing intensity to the climate zone and grass type of managed landscapes.

Conant et al (2017) found that soil carbon stocks increased under a range of management practices, with the greatest increases occurring from converting cultivated land to grassland (+39.2 per cent) and introduction of earthworms (+28.8 per cent), whilst altered grazing practices increased soil carbon stocks by 9.99 per cent (0.28 tC ha^{-1} yr^{-1}).

However, Conant et al (2017) state that altering grazing did not always result in increases in soil carbon stocks as this varied with climate, soil, and vegetation type.

Across the interventions assessed, the duration of study generally showed a good correlation to soil carbon increases, with short studies (≤10 years) seeing greater increases than long studies (~20-40 years). In the case of grazing management, this may indicate that peak soil carbon stocks had been reached in longer studies leading to reduced rates of sequestration. Whilst altering grazing may result in soil carbon gains, or mitigation of negative grazing effects, it is important to consider that such schemes may result in reduced farming profitability and increased logistical and labour demands (eg O'Reagain et al, 2014).

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No and low till

Tillage is used to create a suitable seedbed for crop planting and to suppress weeds, though inappropriate tilling can exert a range of negative environmental effects (Abdalla et al, 2013).

Whilst tilling has been used in many conventional agricultural systems, there is a global shift towards reduced and no tillage systems, also known as conservation tillage or direct drill, with the aim of protecting soils and improving their quality in cropping systems (Mehra et al, 2018).

There is some evidence that conservation tillage contributes to enhanced crop yields in some soils, as well as increasing soil carbon stocks, though the degree of tillage reduction and the duration of study periods can have important effects with the potential for reduced crop yields in the first five years of no tillage treatments (Fiorini et al, 2020).

It is important to note that even such modified tilling systems, designed to mitigate environmental degradation, can have deleterious effects on managed soils. Research has demonstrated that reduced tillage management with no crop residues left at the soil surface can result in enhanced surface runoff and soil erosion.

Jayaraman et al (2021) state that minimum tillage disturbance in conjunction with maximum soil cover (≥30 per cent crop residue cover) and diversified crops may mitigate soil degradation and improve soil aggregation and hydrology, with the potential to enhance soil carbon stocks. As such, it is likely that reduced or no tillage practices need to be enacted alongside additional conservation practices to see beneficial outcomes. Whilst altered tillage systems do have the potential for increasing soil carbon stocks, relative to conventional systems, recent meta-analyses have indicated that carbon is being redistributed in the soil profile rather than there being an overall increase in carbon stock, though these trends likely differ across climates and soils (Guenet et al, 2021). As such, Moxley et al (2014) concluded, from their review of relevant UK literature, that reduced tillage practices are not a viable option for increasing soil carbon stock at scale across the UK.

Whilst soil carbon stocks may show a varied response to conservation tillage systems in a range of geographic settings, with limited overall carbon stock gains, such management schemes also have the potential to interact with soil greenhouse gas emissions. A review of literature assessing the effects of tillage systems on soil N_2O emissions found that reduced and no tillage systems resulted in reduced N_2O emissions in experiments lasting >10 years (particularly in dry climates) and when nitrogen fertilisers were applied (particularly in humid climates) (Van Kessel et al, 2013).

Conversely, Mei et al (2018) found that conservation tillage practices lead to significant increases in soil N_2O emissions (increased by 17.8 per cent), compared to conventional tillage, though the greatest increases occurred during short term experiments and in tropical settings. These N_2O emissions were attributable to aeration of soils and substrate availability from crop residues. Furthermore, soil pH, soil clay content, and practices like water and residue management, significantly affected N_2O emissions following conservation tillage.

Whilst conservation tillage has the potential to increase N_2O emissions in short experiments and when crop residues degrade, there is some potential for mitigation of CH_4 emissions with reduced and no tillage. Maucieri et al (2021) evaluated the effects of conservation tillage on soil CH_4 fluxes and found that no tillage significantly decreased paddy field emissions by 23 per cent whilst having no effect on other dryland systems.

The key factors in observed CH_4 flues were crop type, climate, soil and duration of experiment.

Overall, Maucieri et al (2021) found that the effect of conservation tillage practices on CH_4 emissions was negligible, but that significant benefits could be achieved in rice paddies and similar systems.

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Cover crops

Cover cropping is the growth of alternative crops (often cereals, legumes or brassicas) between harvest and establishment of the subsequent crop, typically with the intention of reducing nitrate leaching and soil erosion, as well as to suppress diseases and pests (Chapman et al, 2018).

Whilst cover crop systems have been observed to reduce soil erosion and soil organic matter, nutrient and water losses in European settings, they are often not employed due to increased labour demand and production costs (Schütte et al, 2020). As such, Schütte et al (2020) suggest that incentive schemes for cover cropping are likely to require a consideration of the societal costs of soil erosion to be included, as the private gain is typically lower than the additional expenses. Therefore, it is important to note that, whilst cover crops systems may achieve a range of environmental benefits, they may not be implemented due to the expense and complexity of operation, though this is offset by reduced nitrogen fertiliser requirements. The success of the cover crop in delivering benefits is also highly dependent on when it is sown and the time until the first frost, which may kill off non-hardy cover crops.

In a review of global cover crop schemes, Abdalla et al (2019) found a significant effect on soil carbon stocks, with increases of 1.61 ± 1.82tCO_2-e ha^{-1} yr^{-1} for legumes, 5.12 ± 5.51tCO_2-e ha^{-1} yr^{-1} for non-legumes and 0.30 ± 0.37 tCO_2e ha^{-1} yr^{-1} in mixed cover crop systems. Cover crop systems were found to have no significant effect on N_2O emissions but could mitigate net greenhouse gas emissions by 2.06 ± 2.10 tCO_2e ha^{-1} yr^{-1} overall (Abdalla et al, 2019).

It is important to note for each cover crop type the range of uncertainty means the intervention could have both positive and negative impacts on net greenhouse gas emissions. Abdalla et al (2019) also evaluated the effects of cover cropping on primary crop yields and found that single cover crops (both legumes and non-legumes) resulted in around four per cent yield reduction, whilst mixtures of legumes and non-legumes increased primary crop yields by ~13 per cent.

Poeplau and Don (2015) reviewed carbon sequestration studies in cover crop agricultural systems. They found significantly higher soil carbon content than in reference croplands, which increased in a linear way over time since establishment of crop rotations (up to 54 years) at a rate of 0.32 ± 0.08tC per hectare per year at an average soil depth of 22cm. These increases in soil carbon stocks were predicted to increase until a steady state was reached by 155 years after establishment, with a total mean soil carbon gain of 16.7 ± 1.5t ha^{-1} at 22cm (Poeplau and Don, 2015). However, Poeplau and Don (2015) only considered soil carbon and did not take the effects of cover crops on N_2O emissions into account, which have the potential to increase in cover crop systems particularly when large quantities of organic residues with degradable carbon are present in soils and at the soil surface (Hansen et al, 2019). The applicability of this global review is also limited as although some German and French sites were considered, the majority came from North America and India.

Whilst cover crop systems have been observed to increase soil carbon stocks in some cases, a study from the UK found that over winter cover crops did not increase soil carbon stocks in four out of ten years, resulting in a loss of 5.5 ± 1.06t C ha^{-1} over the period of 2002-12 (Poulton et al, 2018). Similarly, Chapman et al (2018) found that 24 reviewed studies observed no change in soil carbon stocks and one found decreasing soil carbon stocks.

However, Chapman et al (2018) found that whilst there was a strong scientific understanding of cover crop systems, only one reviewed study was in the UK, with the non-UK studies using a single cover crop, whilst UK systems typically use a mix of crops. As such, some benefits of UK cover crop systems may not have been captured in these studies and will be influenced by many factors including differences in soil textures, crop rotation, cover crop species, weather during the study period, cover crop success rate, fertiliser rate, planting date and whether and how the cover crop was incorporated into the soil.

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Hedgerows

Planting and maintaining hedgerows on agricultural land has received research attention due to the multiple benefits they can provide, including improved crop yields (in dryland systems), reduced soil erosion, improved water efficiency, livestock protection and creation of wildlife corridors, with their ability to alter microclimatic conditions meaning they are a popular climate change adaptation measure (Hernández-Morcillo et al, 2018).

As well as capturing and storing carbon in their biomass, hedges have the potential to enhance soil carbon stocks, relative to adjacent agricultural soils, though there is limited insight into how fields with hedgerows compare to those without and the timescale over which carbon stocks may increase (Chapman et al, 2018).

A meta-analysis of hedgerow carbon sequestration in temperate settings found that the establishment of hedgerows on cropland increased average soil carbon stocks by 32 ± 23 per cent, with average above ground biomass constituting 47 ± 29tC ha^{-1} (Drexler et al, 2021). This study found no significant difference between soil carbon stocks for hedgerows and grasslands and suggested that the average carbon stocks are comparable to estimates for forests, with average estimated below ground carbon stock being 44 ± 28tC ha^{-1} but with a high degree of uncertainty. The total carbon stock of hedgerows was estimated to be 104 ± 42tC ha^{-1} more than croplands (84 per cent from biomass and 16 per cent from soils), with potential sequestration of 2.1 and 5.2tC per hectare per year for 50 and 20 years respectively, though soil carbon gains will be lower on grassland compared to arable.

New research based on data collection in the north of England, summarised by Biffi et al (2021), showed that on average, planting hedgerows stored an additional 30 per cent (42tC ha^{-1}) in the top 50cm of soil compared to improved grassland fields, with greater carbon storage under older hedgerows than young ones. They calculated a soil organic carbon sequestration rate of 1.49tC per hectare per year , which exceeded above ground sequestration estimates (1tC per hectare per year; Falloon et al, 2004). They concluded that 1.5m wide hedgerows could sequester soil carbon at a rate of 0.82tCO_2 km^{-1} yr^{-1}.

Drexler et al (2021) concluded that the establishment of hedgerows in croplands could be an effective method for enhancing carbon sequestration rates in agricultural landscapes, with co-benefits for increased soil protection and greater biodiversity, though they also point out that only one of the reviewed studies reported below ground biomass stocks and root to shoot ratios. As such, further measurement and monitoring of hedgerow carbon impacts are required to more fully understand their potential to contribute to soil carbon cycling.

Projections of the potential carbon sequestration gains in the UK considered enhancing hedgerows by 2050 under medium and high ambition efforts have been assessed by Thomson et al (2018). They suggested there are currently 62.2kha of managed and 58.2kha of unmanaged hedgerows in the UK, which is 30 per cent lower than in 1984. It was estimated that 0.2 and 0.3 $MtCO_2$ could be sequestered by hedges by 2050 under medium and high ambition schemes respectively, with hedges returning to 1984 levels by 2050 under medium ambition schemes and ten per cent greater than 1984 levels under high ambition schemes. However, Thomson et al (2018) assumed there was no change to soil carbon stocks and considered increased hedgerow biomass as a potential fuel source, suggesting that these carbon gains are in the form of above ground biomass that will in part only be temporary unless harvested biomass is linked to BECCS. Biffi et al (2021) also note hedgerow planting will have to be rapidly scaled up if the planting targets suggested by Thomson et al (2018) are to be met. They also found that soil carbon increases were possible by considering stocks underneath old hedges.

Field studies of changes in soil carbon under hedgerows are currently limited, with Chapman et al (2018) only finding 12 relevant studies, and they often lacked any control measures, had limited insight into the timescale at which carbon was sequestered and lacked comparisons of fields with and without hedges. Holland et al (2017) state that the key message for policy makers and funders should be to encourage longer term (ie >1 year) research that studies the effects of hedgerows on soil carbon, with a recent systematic review by Tresise et al (2021) emphasising the need for more research on the effect of hedgerow age on biodiversity.

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Crop residue incorporation

As Turmel et al (2015) discuss, soil carbon content is a key component of soil quality and can be maintained by slowing soil decomposition rates via reducing disturbance and increasing water content or through increasing organic matter inputs. Crop residues are some of the most readily available forms of biomass for such soil amendments. Crop residues include a readily degradable (‘labile’) component and a degradation resistant component. The former of these crop residue components contributes to initial residue degradation rates, whilst the latter contributes to long-term carbon storage and experiences physical and chemical protection once incorporated into soils. Crop residue degradation rates are controlled by soil type, climate and management factors (Turmel et al , 2015).

Lehtinen et al (2014) reviewed studies looking at greenhouse gas emissions and soil carbon stocks in European soils, comparing residue incorporation and residue removal treatments. Soil carbon stocks were found to increase by 7 per cent following crop residue incorporation, whilst a subset of studies found a 6x and 12x increase in CO_2 and N_2O emissions respectively. Lehtinen et al (2014) found that environmental zone (eg, continental, Atlantic, Mediterranean), duration of study and clay content were significant factors affecting the outcomes of crop residue incorporation. Soil carbon response was found to be 8 per cent higher when clay content was greater than 35 per cent relative to studies with 18 – 35 per cent clay content, whilst N_2O emissions were significantly higher in studies that lasted less than 5 years when compared to longer studies. CO_2 emissions were found to be higher in low clay (less than 18 per cent) soils. The correlation between soil carbon and clay content was attributed to physical protection of soil organic matter from microbial degradation. N_2O emission patterns were suggested to reflect peak microbial degradation of labile organic matter (Lehtinen et al , 2014).

Hansen et al (2019) similarly suggest that enhanced N_2O emissions may occur when easily degradable carbon and nitrogen are available, though they also suggest that previous residue incorporation may contribute to greater N_2O emissions. No significant correlation was found between soil carbon and crop yields, but Lehtinen et al (2014) concluded that long-term residue incorporation has potential for soil carbon increases in continental climates. However, it is important to note that there is limited data in this review for longer term studies meaning that continued reporting from the reviewed sites is required to more fully understand the effects of crop residue incorporation on soil quality and functioning.

Poeplau et al (2015) reviewed soil carbon stocks in six Swedish long-term residue incorporation experiments (27 – 56 years), where straw was either removed or incorporated into soils. Studied sites generally saw soil carbon increases from residue incorporation, with an average soil carbon stock change of 1.67 t C ha^{-1} for an average of 36 years, however they were not able to detect a significant change above the natural variability in soil carbon levels. Straw derived carbon stabilisation was significantly related to clay content, which ranged between 8-43 per cent. Poeplau et al (2015) concluded that the efficiency of soil carbon increases from crop residue incorporation depends on soil texture and that use of such residues for bioenergy production may represent a more effective option at at lowering net greenhouse gas emissions if they displaced fossil fuel use in energy production. As such crop residue incorporation may not be an appropriate intervention in certain settings but may be particularly useful in others, for example increasing water holding capacity in sandy soils.

In a review of organic amendments (which included animal derived matter) Chapman et al (2018) found that 69 per cent of reviewed studies observed significant increases in soil carbon stocks. In addition to these soil carbon observations, 83 per cent of studies observed positive effects on soil aggregate stability and 70 per cent saw benefits to earthworm populations, indicating that residue incorporation can improve soil health and mitigate erosion. Chapman et al (2018) state that there is a strong evidence base for their observations though it should be noted that whilst the reviewed studies did not include tropical or subtropical settings, they were not all based in Europe or the UK, meaning that important factors like climate and soil clay content may deviate from UK conditions.

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Introducing leys in crop rotations

Traditional rotations in the UK consisted of a combination of cash crops and crops to feed livestock and while the exact rotations used varied, they typically included clover leys for fertility building and for livestock to graze. However, agricultural intensification over the last 60 years has resulted in a switch to continuous arable cropping where the ley fertility-building phase of the rotation has been replaced with artificial fertilisers. The reintroduction of leys, in particular using grass and legume mixes, may redress some of the negative issues associated with continuous arable cropping through increasing organic matter inputs, fixation of carbon and nitrogen, and improvements to soil structure. Leys in crop rotations are implemented to reduce nutrient depletion, improve soil health and reduce pest populations, diseases and weeds, though they may also carry other benefits such as enhanced biodiversity and reduced soil erosion (Reddy, 2017).

Whilst leys in crop rotation can have a range of benefits in agricultural systems, there are a number of barriers to adoption including: crop geometry pushing farmers to not plant legumes in permanent planting basins, a lack of reliable markets for legumes outside contract growing and a shortage of improved seeds (Swaminathan et al , 2021). As such the main limitations of ley crop rotation systems relate to socio-economic constraints rather than lack of efficacy in general agricultural applications. However, there is limited data on the effects of ley crop rotations on soil carbon content in NW Europe (Rees et al , 2018), with much of the research on ley crop rotation soil carbon effects being carried out in tropical settings (Baum et al , 2009).

A review of the effects of crop rotations on soil quality in Europe and China, with systems covering at least five years, found that ley crop rotations had a positive effect on soil carbon and crop yields (Bai et al , 2018). The average response ratio of soil organic matter for crop rotations to monocultures was 1.25, indicating greater accumulation of organic matter in ley crop rotations, though this may not be relevant for UK systems where monocultures aren't adopted.

Costa et al (2020) reviewed legume life cycle assessment studies in Europe, Australia and Canada, where mixed ley crop rotations greater than two years had been analysed. The research indicated that the potential for soil carbon accumulation is dependant on the quantity and quality of residues available. Legumes produce residues that are high in nitrogen but occur in low quantities relative to cereal crops, which may contribute to declining soil carbon if legumes are introduced into cereal crop rotations. Costa et al (2020) state that various studies indicate long-term soil carbon declines in European arable soils, particularly due to short and cereal-dominated rotations as well as management practices like full, frequent ploughing and crop residue removal

Some of the research suggests that the effects of legumes varies across species and cultivars, with legumes typically producing nutrient-rich residues that decompose more rapidly than cereal residues. However, Costa et al (2020) found that many studies did not look at entire crop rotations and often ignored interactions between crops, instead focussing on a single cropping year. Additionally, studies were found to often overlook nitrogen fertilisation, meaning that eutrophication and global warming potential may be misattributed to legumes.

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Agroforestry

Agroforestry systems can be defined as landscapes combining trees and shrubs with arable or pastoral uses. In Europe agroforestry has multiple forms (Mosquera-Losada et al , 2009), including:

- Silvoarable systems: annual and perennial crops intercropped between widely spaced trees;
- Silvopastoral systems: combined animal and forage production with trees;
- Forest farming: production of naturally standing speciality crops (i.e. medicinal, culinary, ornamental crops) in forested areas;
- Improved fallow: planting fast growing woody species during fallow phases;
- Riparian buffer strips: strips of perennial vegetation between arable/pastoral land intended to protect water quality; and
- Multipurpose trees: fruit and other kinds of trees planted in arable and pastoral landscapes.

These systems have a long history of use in European settings, often with the intention of promoting some of the diversity of natural landscapes, which is typically absent from more conventional farming systems, whilst maintaining productivity (Mosquera-Losada et al , 2009). These systems have also been noted for their potential to contribute to enhanced carbon sequestration. Projections of the potential carbon sequestration in the UK considered agroforestry efforts by 2050 under medium and high ambition efforts (with low ambition strategies not including agroforestry efforts), where silvoarable systems would cover 165.2 and 330.3 kha respectively and silvopastoral systems would cover 251.5 and 503.0 kha respectively (Thomson et al , 2018). Under these schemes silvoarable systems would sequester 2.2 – 4.8 Mt CO_2 and silvopastoral systems would sequester 0.3 – 0.8 Mt CO_2 by 2050 (Thomson et al , 2018).

A meta-analysis of soil carbon sequestration in agroforestry systems found overall increases in SOC stocks when agricultural systems move towards greater complexity (i.e. away from conventional monoculture systems), whilst conversion of forest to agroforestry systems lead to significant decreases in SOC stocks i.e. -24 per cent SOC at 0-30 cm (Destafano and Jacobson, 2018). Conversion of arable landscapes to agroforestry systems resulted in significant increases in SOC stocks (40 per cent at 0 – 30 cm), whilst also increasing SOC stocks at 0-30 cm when pasture (9 per cent) and grassland (10 per cent) were converted to agroforestry systems (Destafano and Jacobson, 2018). For silvoarable systems this comes at the cost of a loss of approximately 18% of cropable area (Thomson et al , 2018) whereas co-benefits include: fodder and shelter provision for livestock, enhanced biodiversity, nitrogen retention in soils and the possibility of a second crop via planting of fruit or nut trees (Burgess and Rosati 2018).

Kim et al (2016) also found increased SOC stocks, averaging around 2tC per hectare per year in the first year after agroforestry establishment. However, this data synthesis found a diminishing rate of C accumulation up to 25 years after establishment, with a stable phase of change to carbon stocks between 10 and 100 years. This suggests that agroforestry has limited potential to contribute to SOC gains beyond the first decade of establishment. Furthermore, Kim et al (2016) state that sites at 14 years old had 70 per cent of carbon stocks being contributed by biomass whilst only 30 per cent of sequestered carbon was in the form of SOC, meaning how trees are harvested and managed will be key to overall carbon storage potential Finally, Kim et al (2016) found negligible differences in net N_2O and CH_4 emissions between agroforestry and agricultural land and no clear overall direction of change. Overall, agroforestry was estimated to sequester 7.2tCO_2e per hectare per year (70% in biomass and 30% in soil) for the first 14 years after establishment (Kim et al , 2016), after which all gains come from tree biomass.

Considering the duration and magnitude of SOC gains achieved in agroforestry systems, relative to biomass C, there may be a case to be made for combined interventions such as amending agroforestry soils with biochar. This kind of approach may maximise SOC gains, with biochar carbon persisting in soils between hundreds (Wang et al , 2016) and thousands of years (Ascough et al , 2020) as well as having the potential to mitigate soil greenhouse gas fluxes (Jeffery et al , 2016). Such combined schemes have shown some promise in recent research (eg Dahal et al , 2018), though European studies need to be undertaken to assess the potential validity of this approach in the UK. Indeed, most studies on SOC stocks in agroforestry systems have been performed in tropical settings (Chapman et al 2016).

A final point to consider in the UK context would be the potential for establishment of trees in certain settings to drawdown the local water table and encourage aerobic degradation of typically waterlogged soils (eg peat), with the potential for significant losses of carbon (Sloan et al , 2018). A study of peatland carbon balances found that afforestation led to soils becoming a net carbon source, resulting in an average emission factor of 1.68 - 0.33tCO_2 per hectare per year (Jovani-Sancho et al , 2021). Therefore, it is important that agroforestry systems are established in appropriate settings, with careful consideration of sites that have been historically drained or are in a degraded state (Holden et al , 2007). In such settings other agricultural interventions, such as paludiculture (see below), may have a greater potential for maintaining and enhancing soil carbon sinks.

A study of the perceptions of agroforestry systems in Europe, with 344 stakeholder responses, found that the main perceived benefits were: improved landscape aesthetics, improved animal health and welfare, and enhanced biodiversity and wildlife habitats. The perceived negative outcomes were: increased management costs and administrative burden, increased labour requirements, and increased work complexity. In this study, enhanced biodiversity and wildlife habitat were the highest ranked issues in France, Germany and the UK, whilst complexity of work was ranked as the highest negative issue in grazed UK orchards (de Jalón 2018). Future trials will therefore need to assess whether carbon financing and other co-benefits offer adequate compensation for the increased complexity of agroforestry systems.

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Arable land use change

The UK has excellent soil carbon data on the effect of land use change from arable systems thanks to the long-term studies at Rothamstead, dating back more than a hundred years. This indicates soil carbon gains as a result of converting arable to grassland can be made at the rate of approximately 0.51 tC per hectare per year with the majority of increases in the first 25 years, reaching a new equilibrium after around 100 years (Powlson 2011). These long-term trials offer the best evidence as rapid gains are often observed in the first years of land use change, meaning studies with only a short monitoring period may overestimate the overall rate of sequestration and therefore their climate change mitigation potential (Conant et al 2017).

A global meta-analysis of 42 studies containing 161 sites suggests an average global sequestration rate of for grassland reversion of 0.84 tC per hectare per year, higher than that observed in the UK (Conant et al 2017). Variation is to be expected, however, with the rate and total amount of carbon likely to be sequestered depended on the initial soil carbon stock, subsequent management practices, climate and the proportion of clay in the soil (Don et al 2009). Generally, better sequestration rates and net carbon gains are seen in soils with a low starting point, high clay content and which are managed with high inputs of organic material

Perhaps more important than the rate of carbon accumulation under grass, however, is how the grassland is subsequently managed as adding ruminant livestock to the system can switch a grassland from a net sink of carbon to a net source due to methane production (Chang et al 2021). Only an estimated 20-60% of cattle emissions can be offset due to soil carbon gains (Garnett 2017), making grassland creation or switching to a mixed arable system less attractive at the farm level if it is used to increase herd numbers.

The issue of methane production by ruminants is critical to understanding carbon balances in grazing systems. Due to a better understanding of atmospheric processes, the IPCC will increase the global warming potential value of methane used in future carbon accounting from 25 to 28 or 34 times the effect of CO_2, once all feedbacks on the carbon cycle are included. This accounting increase makes generating soil carbon credits from grazing systems less likely unless they are tied to decreases in herd numbers.

Declining herd numbers is, in fact, the current direction of change in the UK with an approximate 11% reduction in total cattle and calves between 2005 and 2020, and an 8% reduction in total sheep and lambs during the same period (Defra 2020). The CCC propose around a further 20% reduction in the consumption of lamb, beef and dairy by 2050 (CCC 2020), which would free up around 2,700 ha of grassland (Thomson et al 2018). The CCC also model land use scenarios which free up more land for afforestation, peatland restoration and the planting of energy crops which include 50% decrease in red meat consumption, an increase in stocking density and moving some horticulture to indoor systems.

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Field margins

Field margins are features existing on the edge of agricultural landscapes, which interact with adjacent arable land (Marshall and Moonen, 2002). Management of field margins have been noted for their range of potential benefits, including enhanced biodiversity, pollination, pest regulation and limiting pollutant transport, as well as enhanced carbon sequestration (Cole et al , 2020). However, there is very limited data regarding the carbon cycling effects of field margins in the UK and Europe (Falloon et al , 2004), with much of the relevant research instead evaluating the effects of field margins on wider issues like biodiversity (eg Marshall and Moonen, 2002) and soil macrofauna (eg Smith et al , 2008).

Falloon et al (2004) carried out a preliminary analysis of the carbon sequestration potential of different field margin management strategies in the UK. They calculated changing carbon stocks based on long-term experiments and estimates from the literature, with the assessed scenarios including grass strips, hedgerows and tree strips. These field margin strategies were investigated at widths of 2, 6 and 20 m, which would require 2.3, 6.7 and 21.3 per cent of the total UK arable area. Falloon et al's. (2004) assessment of trace gas fluxes found that changes from arable land to managed field margin conditions significantly reduced N_2O emissions, whilst new soil carbon equilibriums would likely be reached around 50 years from establishment with the carbon sequestration potential of investigated strategies estimated at 0.16 to 3.76 MtC per year, depending on field margin width. Scenarios involving tree strips saw the greatest potential for carbon sequestration due to the large quantities of carbon sequestered in above-ground biomass as well as in soils. Falloon et al (2004) state that there is considerable potential for field margin management to be enacted alongside other strategies for management of UK arable land, but that more detailed analyses need to be performed, including assessment of wider environmental benefits, socioeconomic factors and the full system carbon balance.

Since this work by Falloon in 2004, Ferrarini et al (2017) carried out a meta-analysis of the effects of bioenergy field margins on ecosystem services. The studied field margin systems were found to have beneficial effects on ecosystem services related to climate, water quality, biodiversity and soil health, with herbaceous margins being observed to have a greater beneficial effect than woody margins. Ferrarini et al (2017) noted that knowledge gaps exist regarding the effect of field margins on climate and water ecosystem services during the establishment phase (0-3 years). Payments for the ecosystem service gains from bioenergy field margins were proposed as a means to improve the economic viability of such systems (Ferrarini et al 2017), offsetting the loss in cropable area.

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Paludiculture

Paludiculture is the practise of wet agriculture, that is, farming techniques on land where the water table is at or near the surface for all, or a significant part of, the year. It represents a significant departure from typical agricultural practise in the UK which has relied on drainage to increase yields for crops which are intolerant of wet conditions. Lowland peat, for example in the Cambridgeshire Fens, is some of the most productive arable land in the UK, yet this is predicated on it being in a drained state and thus emitting a large amount of carbon as the peat is rapidly mineralised. The CCC has a set a target for the restoration of 25% of lowland peat; paludiculture offers a method of keeping this land in agricultural production whilst stopping or reducing carbon emissions. Whilst restoring to near-natural status would be the most beneficial for greenhouse gas abatement, paludiculture could ameliorate the increased reliance on food and biomass imports if this land was taken completely out of production.

Food crops that can be grown in paludiculture systems include watercress, celery and various berries, though perhaps the greatest opportunity is in biomass crops as grasses and rushes, forestry with water-logging tolerant species, and sphagnum moss for use in growing media and peatland restoration (Mulholland et al , 2020; Salo, 1996). These techniques have been more widely adopted in continental Europe (eg Gaudig et al , 2018; Wichtmann et al , 2016) but are being trailed in the UK and a recent review of the suitability of paludiculture in the UK, commissioned by Defra, offers the best available evidence we have, given the low level of current commercial-scale adoption (Mulholland et al , 2020).

Lowland peat currently under arable or grassland will require the raising of water tables to move to a paludiculture system. Whilst this lowers the production of CO_2 from the mineralisation of peat, waterlogged conditions can lead the production of methane which can cancel out any net carbon benefit. As such, the best evidence available suggests the emission factor of land under paludiculture will be approximately 0 tCO_2e per hectare per year, with net carbon removal most likely to occur when the water table is maintained at approximately 8cm below the surface (Mulholland et al , 2020). This agrees with recent work from Denmark in which a rewetted agricultural fen used for paludiculture showed a net global warming potential of -3.0 (sequestration) and 8.1 (emission) $tCO_2e\ ha^{-1}$ for the two years of monitoring (Kandel et al 2020).

The indirect carbon benefits, for example through the use of biomass grown in a paludiculture system for energy and heat production, could lead to net carbon benefits of between 3.71 and 6.48 tCO_2e per hectare per year depending on the productivity of the system (Mulholland et al , 2020). These estimates are based on biomass displacing the current fuel mix in the energy system and would therefore be greater if coupled to CCS (i.e. a paludiculture-BECCS system). New techniques to improve the carbon balance of paludiculture are currently being trialled in the UKRI funded greenhouse gas removals demonstrator projects. This project will trial methods of suppression methane, new uses of biomass other than BECCS, and the use of lowland peat as a repository for biochar, all of which could increase carbon sequestration potential further.

The area where paludiculture is likely to be possible in England and Wales has been estimated at approximately 81,000 ha if lowland peat currently used for grassland was converted to paludiculture (Mulholland et al , 2020), whereas a separate assessment for Scotland suggested the suitable area was limited as lowland peat under grazing management is rare in Scotland (Aitkenhead et al 2021). While this area is comparably small, the benefits from moving from drained peat which emits carbon to a net sequestration system are potentially very large. Using the emission factor of 29.89 tCO_2e per hectare per year for intensive grassland on drained peat from Evans et al (2017) and a mid-range value for paludiculture biomass used for electricity generation of -5.10 tCO_2e per hectare per year from (Mulholland et al , 2020) would suggest a total benefit of 34.99 tCO_2e per hectare per year, though the majority of this is in avoided emissions and would require BECCS, methane suppression or biochar addition to achieve significant net carbon sequestration. Further research is also needed in characterising the N_2O flux from paludiculture systems as this is typically not measured and could alter the overall carbon balance (Jurasinski et al 2020).

As well as carbon benefits, paludiculture may offer co-benefits through cultural and recreation services, water quality benefits (Peh at al 2014), as well as biodiversity gains (Schäfer 2012). Despite this, adoption is likely to remain low without significant incentives due to lack of farmer knowledge of paludiculture and/or preference for traditional methods, investment required in new equipment, current lack of market for paludiculture products in the UK and the high profitability of lowland peat used in grazing and arable systems (Aitkenhead 2021). Current trials to demonstrate the profitability of a paludiculture system and create synergies with BECCS and/or biochar may lower some of these barriers, though farmer knowledge and willingness to adopt new techniques will still need to be addressed.

While paludiculture has significant barriers to adoption, 'wetter' rather than truly 'wet' agriculture may offer significant carbon savings whilst keeping current land use. Assessing data from 41 locations in the UK and Ireland, Evans et al (2021) suggested that many drained peatlands used for agriculture are 'over-drained' meaning that water tables could be increased without negatively affecting crop production. They suggest many peatlands are drained to over 2 m depth and that every 10 cm increase in mean water table depth would create an emissions reduction of around 3tCO_2e per hectare per year, up to 30 cm depth at which point the effect is lowered due to methane production. They suggest halving the water table depths of croplands on organic soils could avoid emissions of 15.3tCO_2e per hectare per year. Similarly, Thomson et al (2018) suggest a potential UK-wide emissions saving of 1.5MtCO2e yr^{-1} by seasonal raising peatland water tables in cropland systems. Both of these techniques would allow full agricultural production to continue on lowland peat by working with existing Internal Drainage Boards, however they only offer emissions reductions and would leave the peatlands as still net emitters of CO_2e.

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Enhanced rock weathering

Enhanced weathering is an acceleration of the natural processes of silicate rocks weathering to store carbon over long timescales. The acceleration is achieved by grinding rocks to increase their surface area and then applying the resultant material over large areas, such as croplands. The Royal Society suggested the UK potential for enhanced weathering could be around 15 $MtCO_2$ yr^{-1} by 2050, achieved by spreading 20 tonnes per hectare of rock over 5.4 million hectares of arable land, a mid-range estimate as application rates in the literature generally vary between 10 and 30 tonnes per hectare. This would come at a cost of about £44–361 tCO_2^{-1} where basic rocks are used, and £15–77 tCO_2^{-1} where ultrabasic rocks are employed, though these are in shorter supply (Renforth 2012). Costs are likely to dependent on the energy requirement during mining and processing, as well as the transport distance from mine to application site.

Overall, the UK has good capacity of suitable minerals, concentrated in Scotland and Northern Ireland. Given transport distance is a key metric for both cost and carbon efficiency, this would suggest arable land in these nations could offer a suitable repository for enhanced weathering. The main downside to using virgin minerals is the large energy requirement in mining and subsequent grinding of the rocks. It is also possible to use waste products, such as mining waste, ashes and slags, for enhanced weathering, however these materials would require further assessment before they could be applied to crops (Royal Society 2017).

Application of silicates to crops has a number of co-benefits for plant and soil health which we have summarised in table 1 below, along with key uncertainties in the process as field trials in the UK are only just beginning.

Table 1: Co-benefits and current uncertainties in enhanced weathering application in the UK. Summarised from Beerling et al 2018, Tubana et al 2017 and Royal Society 2017.

Co-benefits	Dis-benefits / uncertainties
Increase in yield, drought tolerance, soil carbon, pest and disease resistance of crops	Issues around contamination if using waste material rather than virgin minerals
Reduced N2O emissions	Fate of applied minerals not completely understood though ocean storage likely stable
Lower/no requirement for liming, lower fertiliser requirement due to P mobilisation	Uncertainty of variation in sequestration with soil, crop and climate.
	Monitoring, reporting and verification protocols as yet unestablished
	Risks due to silicosis in applying fine dust to fields

Long-term field trials in New Jersey, USA which included UK relevant crops (cabbage, corn, oats, winter wheat and grass) have demonstrated the potential for Si fertilisation to increase yields through better pest tolerance and diseases resistance, with improved water use efficiency (and therefore drought tolerance) reported in other trials (Tubana et al 2016). A further benefit of enhanced weathering is the potential synergy with BECCS or other biomass crop where it can help phosphorous availability and therefor yield (De Oliveira Garcia et al 2020) and reduce N_2O emissions (Blanc-Betes et al 2021), thus improving the carbon efficiency and lowering land requirements. While impressive yield improvements have been demonstrated with Si fertilisation, is should be noted that the best results have been observed in Si deficient soils with low pH and so may not be applicable to all soils.

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D J Beerling et al, 2018, 'Farming with crops and rocks to address global climate, food and soil security', *Nat Plants.*, 4(6), pp392–392

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E Blanc-Betes et al, 2021, 'In silico assessment of the potential of basalt amendments to reduce N2O emissions from bioenergy crops', *GCB Bioenergy*, 13(1), pp224–41

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Biochar

Biochar is the residue produced during pyrolysis and incomplete combustion of organic matter, whilst pyrolysis is the process where organic matter is heated in the absence of oxygen and has been used for centuries for charcoal production. Biochar has received much research interest due to characteristics like its high carbon content, stability and sorption capacity (Chang et al , 2018; Wiedemeier et al , 2015). As a result of these characteristics, biochar soil amendments have the potential to exert a range of effects on issues like arable crop yields, soil quality and carbon sequestration (Bass et al , 2016; He et al , 2020). Based on projections of future biomass energy use, it has been suggested that optimised biochar production through pyrolysis could sequester 5.5 – 9.5 Pg C yr^{-1} globally (Lehmann et al , 2006). According to the UKBRC (2011) the sequestration potential of biochar in the UK is ~3.5 – 21.8 Mt CO_2 yr^{-1} (~0.9 – 5.9 Mt C yr^{-1}), whilst The Royal Society (2018) state that it is in the higher range of 6 – 41 Mt CO_2 yr^{-1}. Research has also suggested that biochar soil amendment has the potential to significantly lower the emissions of key greenhouse gasses such as CH_4 and N_2O, though the effects vary with biochar and site characteristics (Jeffery et al , 2016).

Biochar stability, the longevity of biochar carbon in amended soils, is a key issue when considering the C sequestration potential of amendment schemes with the potential for only short-term soil carbon gains (i.e. decades). A meta-analysis of biochar stability in amended soils assessed the longevity of labile (3 per cent) and recalcitrant (97 per cent) biochar carbon pools and found mean soil residence times of 108 days and 556 years respectively (Wang et al , 2016). These findings are supported by a study of biochar degradation in UK soils, where 3 per cent biochar carbon degradation occurred over 164 days (Ventura et al , 2015). However, biochar soil stability is highly dependent on some key factors, namely biochar feedstock and production conditions, and soil clay content with higher clay content resulting in significantly lower biochar decomposition rates (Wang et al , 2016). As such it is important to consider that biochar amendment schemes may see initial phases of rapid degradation of some biochar components, followed by a slower phase of degradation where C may be stored for millennia depending on biochar and site characteristics (Ascough et al , 2020). Therefore, amendment schemes should aim to optimally apply specific kinds of biochar in specific settings.

Another important consideration for biochar amendment schemes is the availability of feedstocks for biochar production. Estimates of land requirements to achieve global biochar C sequestration goals of 1.1 Gt C yr^{-1} from dedicated biochar crops would require 40 – 260 Mha of land, with abandoned and degraded croplands having the potential to meet half of these needs (The Royal Society, 2018). UK biochar C sequestration of 0.9 Mt C yr^{-1} and 5.9 Mt C yr^{-1}, representing low and high resource availability scenarios, would require total biomass (virgin and non-virgin biomass) of ~1.0 Mt and ~4.7 Mt respectively (UKBRC, 2011).

Depending on the costs of issues like biomass acquisition and soil application costs, UK biochar amendments may cost in the range of £-148 – 389 t^{-1}, with negative costs indicating a high degree of profitability from production, though it is important to consider that costs may be considerably higher if virgin biomass is used (Shackley et al , 2011). Whilst dedicated biomass crops have the potential to play a key role in UK biochar production, it is important to consider that alternative biomass sources exist in the UK uplands which have previously been managed by fire (Worrall and Clay, 2014). Worrall and Clay (2014) estimated that 2,800 – 7,000 km^2 of heather dominated landscapes have been managed by fire in the UK, with productivity estimated at 54 – 410 kg dry matter per hectare per year. As such biomass that would otherwise be managed with burns in these settings may be available as a feedstock for BECCS schemes or the production of high carbon residues (Worrall et al , 2014). Indeed, a trial of such a heather-biochar system is currently being trialled in a UKRI funded greenhouse gas removals demonstrator project.

Liu et al (2016) analysed studies looking at the effects of biochar amendment on soil organic carbon (SOC) stocks, microbial biomass carbon (MBC) and CO2 fluxes. Overall, biochar amendments were found to have a significant effect on SOC and MBC, leading to increases of 40 and 18 per cent respectively, but did not significantly affect CO_2 emissions (Liu et al , 2016). This finding is in line with short term (<1 year) European biochar amendment studies, where gains in SOC are observed alongside negligible effects on CO2 emissions (eg Cui et al , 2021; Ventura et al , 2015), whilst slight increases in CO_2 emissions have been observed in longer studies (eg Reed et al , 2017). Indeed, Liu et al (2016) state that their results relate to studies <4 years and that longer duration field studies are required to understand the effects of biochar amendment more fully.

In addition to these increases in soil and microbial C stocks, biochar amendments have been found to limit losses of soil carbon (overall -3.8 per cent compared to non-amended soils) (Wang et al , 2016). These observations were largely in relation to biochar with a greater content of easily degradable C thus providing preferential substrates for soil microbes (Wang et al , 2016). This would suggest there is a trade-off between producing stable biochar that sequesters carbon in the char, and biochar which helps preserve existing soil carbon by offering a more readily degradable food source to soil microbes.

A meta-analysis of the effects of biochar amendment on CH_4 emissions found key effects from biochar characteristics, with reduced CH_4 emissions with biochar produced from biosolids from sewage treatment and where the biochar surface areas was high (Jeffery et al , 2016). Additionally, it was found that CH_4 emissions were reduced when biochar was applied to flooded soils, acidic soils and soils with

N fertilisers applied at ≤120 kg ha^{-1} (Jeffery et al , 2016). In a study of biochar amendments to a UK Miscanthus bioenergy site Case et al (2014) found a reduction of soil CO_{2e} emissions (CO_2, CH_4, N_2O) by 37 per cent under field conditions. Meanwhile a meta-analysis of Spanish, US and Brazilian soils amended with biochar found a 10-90 per cent reduction in N_2O emissions, with biochar's acid buffer capacity playing a key role in these effects (Cayuela et al , 2013). Variable effects on greenhouse gas emissions have been observed with the potential for increased emissions in some cases (Wang and Wang, 2019). Generally, this seems to occur where biochar is applied to non-flooded soils and where N fertilisation is high (Jeffery et al , 2016). As such biochar amendments to soils in some cases can have negligible effects on soil C cycling relative to more conventional agricultural practises, and may even increase fluxes of greenhouse gasses and increase degradation of soil carbon.

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BECCS

Bioenergy with carbon capture and storage (BECCS) is a proposed method of achieving negative emissions by taking carbon stored in biomass via photosynthesis, burning this biomass to generate electricity, and then capturing and storing the resulting CO_2. Whilst theoretically possible, this chain of different technologies (biomass growth and harvest, electricity generation and CCS) only currently operates at a small scale at a single site and therefore a lot of assessments of the potential impact of BECCS, both positive and negative, are based on estimates and modelling. The UK power generator, Drax, aim to have the first commercial UK BECCS facility operating by 2027 with scale up into the 2030s. The CCC estimate by 2050 BECCS could provide 20-51 $MtCO_2$ of removals in the UK each year with the NFU suggesting a value of 22 $MtCO_2$ in its pathway to net-zero by 2040. This would suggest BECCS may be a major part of the UK meeting its net-zero goal

Whilst capable of delivering large carbon removals, BECCS is not a magic bullet, however, as modelling of possible BECCS configurations suggest both carbon positive and negative carbon balances over the project lifetime. This is due to the potential for direct and indirect land use change and the need for transportation and processing of biomass as well as infrastructure construction (Fajardy and MacDowell 2017). One example system using switchgrass in the USA, when factoring in losses from transport and fertiliser use, suggested a 61.7% carbon efficiency if land use change is not considered, and 45.6% when it was. Configuring the supply chain to maximise carbon reduction potential is therefore key to a BECCS system which minimises trade-offs between BECCS land use, water use, CO_2 efficiency, fertiliser use and land use change (Hanssen et al 2020).

The Royal Society estimate that the land and water requirements for BECCS can be large with around 0.03 to 0.06 ha of land and 60 m^3 of water required per tCO_2 removed, though the actual figure will depend on the type of feedstocks used, their yields and requirements for irrigation. Using the NFU estimate of 22 $MtCO_2$ UK removals per year, this gives a range of 660,000 to 1,320,000 ha of land required for BECCS, or 2.7 to 5.4% of the total area of the UK. This would come at a cost of around $140 to 270 per tonne CO_2 sequestered, depending on variables such as biomass feedstock, the cost and lifetime of CCS plants, and whether efficiency improvements can be made (Royal Society 2018). For comparison, the CCC suggest a cost of £158 tCO_2^{-1}, assuming a mix of domestically and imported biomass.

The UK has good storage potential for CCS with the Energy Technology Institute (2016) estimating offshore verified total storage potential of 1 GtCO2 with more potential capacity. The likely constraints on BECCS in the UK therefore come down to land, and the strain this puts on other land uses, and fertiliser consumption. Using fertiliser with bioenergy crops can increase yield and therefore increase the carbon benefit per hectare (Creutzig 2014). However, the scale of BECCS likely to be required suggests that by 2045 fertiliser demand for bioenergy crops could add a further 30% to current global usage (Fuhrman et al 2020). While this would help us meet climate targets, this could move the Earth closer to other defined planetary boundaries (eg, nutrient runoff, exhaustion of phosphate supplies) (Heck et al 2018). Li et al (2021) estimate an even greater fertiliser demand from global BECCS operations at an approximate 57% increase and suggest whilst N requirements can be limited by intercropping with N fixing plants, P and K fertilisation will still be required. Further data is needed on fertiliser requirements for crop species suitable for UK soils and climate. This represents a key trade-off for BECCS adoption as higher fertiliser use will lower the amount of land required but put other pressures on the biosphere. The land required for BECCS is highly dependent on biomass yields and the availability of waste biomass and has been seen as a key drawback in application of the technology.

Many models of BECCS adoption assume the use of marginal or semi-natural land will be used for biomass which has led to the assumption of biodiversity loss as a result of BECCS. While this may be true in some cases, when adding bioenergy crops to existing farmland there are likely to be increases in biodiversity. This is particularly true where woody crops, for example coppiced willow, are added into existing farming systems, creating a mosaic of habitats across as farm rather than a monoculture of either food or biomass crops. In first meta-analysis of the biodiversity effects of biomass crops, Donnison et al 2021 found that significant biodiversity gains, particularly for bird species, could be realised with biomass cropping systems, particularly wood crops and perennial rather than annual biomass crops. In their analysis they note a trade-off between biodiversity gains, which were greatest moving from arable to wood systems, and food production. Similarly, annual grasses may offer the greatest yield in certain soils and climates yet offer the least in terms of increases in biodiversity. This represents a trade-off in biomass generation for BECCS as large monoculture plantations are likely to be the most cot efficient, whereas creating a mosaic of coppice across farms would be the best for biodiversity.

BECCS biomass requirements

Waste biomass, from sources such as forestry and crop residues and municipal solid waste, offer the best feedstock for BECCS in terms of land use and carbon efficiency (Zhang et al 2019). However, these biomass sources are also proposed as the best options as feedstock for other nascent 'bioeconomy' industries developing sustainable aviation fuels (O'Connell et al 2019) and bioplastics (Bos et al 2012), meaning there is a trade-off between the carbon efficiency of these industries as supplies of waste biomass are unlikely to meet demand. Virgin biomass sources, either grown in the UK or imported, will therefore be needed to supply a largescale BECCS industry in the UK.

Modelling studies on the potential for the UK to meet BECCS biomass requirements generally exclude land currently in agricultural production, inside a national park or with a SSSI designation (eg Zhang et al 2019; Hastings et al 2014) to avoid competition with food production, lower the risk of soil carbon losses from converting grasslands (Richards et al 2019) and increase public acceptability. With these conditions in place, modelling suggests it would be possible for the UK to meet the biomass demands for a domestic BECCS industry using mainly short rotation forestry except in the Southwest of England where Miscanthus offers the best yields (Hastings et al 2014, Zhang et al 2019, Richards et al 2019). Contributions from waste biomass can improve the carbon efficiency and also lower the cost of biomass by 16-36% (Zhang et al 2019), whilst future improvements in plant breeding (eg frost tolerant miscanthus) may improve yields further (Richards et al 2019).

These modelling studies, however, assume a large amount of land is available for biomass plantation (eg 2.3 million ha in Zhang et al 2019). Even though this comes from non-agricultural land uses this level of plantation may face issues due to public acceptability. Lower land availability values have been suggested by UK

Energy Technologies Institute (ETI) who estimated a maximum of 1.22 million ha of biomass land availability by 2050, whereas modelling based on providing economically and environmentally sustainable biomass suggested a lower figure of only around 0.4-0.5 million ha (Jones and Albanito 2020). Jones and Albanito also call into question the yield estimates used in many modelling studies as they are often scaled up from small intensively managed trials, rather than real world commercial systems and may be even further from realisable yields if marginal land is being used.

Significant trade-offs occur in deciding how best to provide biomass for a UK BECCS industry: using grasslands may have high yields but displaces food production and will cause soil carbon loss, importing biomass may be cheaper but causes leakage of emissions as land use change occurs elsewhere, and waste biomass is attractive but is also needed for other industries. Whilst estimates of land available for biomass vary widely in the literature, it is worth nothing even the more conservative estimate of ~1.2 million ha could meet the level of BECCS deployment suggested by the NFU, using the Royal Society estimate of 0.03 - 0.06 ha required per tCO_2 removed. Synergies exist between biomass crops and enhanced weathering, as basalt application may increase yields (Tubana et al 2016) and lower N_2O emissions (Blanc-Betes et al 2021) meaning that the carbon efficiency of combined BECCS and EW would be improved and the land use requirements for biomass decreased.

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Appendix 3
Countryside Stewardship management interventions

The top 15 most popular management interventions from 2016-17 Countryside Stewardship Scheme by number of agreements the option was included in (FERA 2018)

Management	Notes
GS2: Permanent grassland with very low inputs	Incentivise low inputs to increase biodiversity
BE3: Management of hedgerows	Maintenance of hedgerows for biodiversity
AB9: Winter bird food	Planting seed/flower mix for biodiversity
SW1: 4m to 6m buffer strip on cultivated land	Fallow buffer strip
AB1: Nectar flower mix	Biodiversity
AB8: Flower-rich margins and plots	Biodiversity
GS1: Take small areas out of management	Biodiversity
AB2: Basic overwinter stubble	Biodiversity; food for birds
HS1: Maintenance of weatherproof traditional farm buildings	Heritage
GS17: Lenient grazing supplement	Maintenance of multiple sward heights for biodiversity
WD2: Woodland improvement	Biodiversity; resilience to climate change
OT1: Organic land management - improved permanent grassland	Money to keep land in organic management
AB15: Two year sown legume fallow	Biodiversity; reduce blackgrass
SW4: 12m to 24m watercourse buffer strip on cultivated land	Water quality
AB12: Supplementary winter feeding for farmland birds	Biodiversity

Appendix 3a
Barriers and considerations for farmers entering carbon sequestration schemes

There are several barriers to reaching the scale and liquidity needed for soil carbon markets to make a significant contribution towards net zero targets. These include:

- a lack of consensus on the most appropriate methods for monitoring, reporting and verification (eg sampling of soil carbon and greenhouse gas emissions, permanence and leakage), approaches to risk mitigation (eg buffering versus insurance based approaches) and issuance of credits (eg crediting periods and payment schedules);
- uncertainties around current and future carbon prices, and how carbon markets will interact with future agri-environment schemes; and
- whether it will be possible to stack carbon finance with public payments (eg from agri-environment schemes) or to stack market payments for multiple ecosystem services (eg biodiversity and water quality payments on top of soil carbon payments (Keenor et al, 2021; Reed et al, in press).

While there is significant (though qualified) interest from the investment community in soil carbon, there remain several barriers that could prevent farmers engaging with soil carbon markets. When considering whether to engage with soil carbon markets, there are two components that farmers must engage with.

First, they must consider whether or not to adopt the on-farm interventions designed to sequester and store soil carbon (eg herbal leys or hedgerow planting). There is already a well developed literature on the adoption of on-farm interventions, which we summarise here.

However, the second component they have to consider is whether or not they are willing to adopt an intervention as part of a carbon market scheme, including moral (eg around the identity and motives of investors) as well as technical considerations (eg project development and contract lengths).

For each of these two components of a soil carbon market adoption decision, a range of factors are likely to influence whether a farmer will engage. Although important, the financial return is just one of many internal and external factors influencing the perception of the farmer and the likelihood they will engage (Mills et al, 2017; Rust et al, 2020). Internal factors are more likely to influence attitudes towards engaging with carbon markets, whereas external factors are more likely to influence whether a farmer is pre-disposed to adopt a soil carbon intervention within a market scheme. External factors likely to influence engagement with soil carbon markets include:

- land tenure (tenants will not normally be able to enter into carbon contracts, though landlords may make benefit sharing agreements);
- farm characteristics (eg farm size, soil condition and hence potential for improvement, farm infrastructure and availability of relevant equipment, and

the type and suitability of the land for the specific soil carbon interventions included in a market scheme);

- characteristics of the soil carbon intervention that make it more or less adoptable (in particular its perceived relative advantage over current practice, trialability, adaptability, observability and perceived complexity);
- the perceived flexibility or inflexibility of a market schemes, including flexibility in how carbon outcomes may be delivered and flexibility within contracts (eg whether or not there is a pooled buffer that can be used to meet contractual obligations if the project fails through no fault of the farmer); and
- levels of support available within schemes or within existing advisory networks, eg infrastructure, training and other forms of support that enable successful implementation of a market scheme on the ground (Reed, 2007; Siebert et al, 2006; Ruto and Garrod, 2009; Wilson and Hart, 2000; Emery and Franks, 2012; Proctor et al, 2012; Kusmanoff et al, 2016; Mills et al, 2017).

The most important factors influencing whether farmers engage with a soil carbon market scheme is risk perception. The extent to which a farmer is likely to believe that engaging with soil carbon markets as risky depends on:

- the type of risks perceived (eg the extent to which carbon markets are perceived as new versus familiar, and whether taking risk of entering a market scheme is voluntary or involuntary);
- personal capabilities, characteristics and related demographic factors (eg knowledge and skills, formal educational status, disabilities, age, gender and succession status);
- access to capital, including financial capital (eg availability of working capital and level of dependency on farm income), social capital (eg access to expertise, credit and other support, and levels of connectedness and trust in social networks), and time;
- farm profitability and capitalisation influences the ability of farmers to transition to more regenerative practices eg if they are unable to raise capital for new machinery needed for lower input farming practices due to lender perceptions that new practices may impact yields;
- cognitive biases such as the availability heuristic, where risks that can be easily called to mind tend to be over weighted compared to risks that are less familiar (even if they are in fact more likely); and
- confirmation bias, where risks are interpreted in a way that confirms existing preconceptions; or the general tendency to overweight very low probability risks and underweight very high probability risks (Tversky and Kahneman, 1992; Sutherland et al, 2012; Wynne-Jones, 2013; Wheeler & Lobley, 2021; New Economics Foundation, 2021).

Other important internal factors influencing the likelihood of farmers adopting soil carbon interventions in the context of a market scheme include:

- levels of perceived self efficacy (ie a farmer's belief that they will, through their actions, be able to implement the proposed intervention successfully and be able to meet their contractual obligations as part of a market scheme) and agency (ie freedom of choice to opt in or out of the scheme, versus feeling coerced to join a scheme, for example by a company they supply);

- pre-existing farmer attitudes towards and preferences for the interventions in a scheme and the idea of carbon markets more generally; these attitudes, in turn, are likely to be shaped by their values, beliefs and norms about the natural environment (the extent to which their value orientation is biospheric) and other people ('social-altruistic' orientation) compared to more self-interested 'egoistic' values, beliefs and norms;
- emerging farmer attitudes and preferences as they are shaped by members of social groups that share similar values (eg family and friends) and land use objectives (eg neighbours); understanding the monetary and deeper 'transcendental' values, beliefs and norms that underpin land manager attitudes and preferences for soil carbon interventions can enable smart targeting of options and tailoring of communication to meet the needs and preferences of contrasting groups of farmers; and
- the extent to which messages about carbon markets are framed in relation to the values, beliefs and norms of the individual or group receiving the message; evidence suggests that people and groups with biospheric or social-altruistic value orientations are more likely to enter into schemes that they believe will protect or enhance the environment; however, such messages are unlikely to resonate with farmers whose values are more egocentric; for these groups, messages about carbon markets are more likely to drive engagement and adoption when the financial benefits to the farmer, increased productivity, a sense of achievement, the respect of peers or greater opportunity for social interaction are emphasised;
- who delivers the message; there is evidence that UK farmers are naturally distrustful of information about regenerative agriculture in the farming press, and are more likely to adopt these practices on the recommendation of other farmers than any other source (De Groot and Steg 2007, 2008; Burton et al, 2008; Mills et al, 2017; Kenter et al, 2015; Burdett, 2020; Rust et al, 2021; in press).

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Appendix 4
Systematic comparative analysis of existing soil carbon standards and protocols: initial insights for a UK Farm Soil Carbon Code

What is a soil carbon code?

There is wide variety in the terminology used by organisations involved in soil carbon certification. For the purpose of this analysis, a 'code' is a document, or set of documents, that sets out the requirements and rules to establish and run a project that aims to generate verifiable soil carbon credits.

The use of the term code sets out an ambition to align a UK Farm Soil Carbon Code with the existing Woodland Code and Peatland Code initiatives and with the UK Land Carbon Registry. In this context, a code is the first component in a soil carbon certification programme which can deliver certified soil carbon credits that are acceptable to the voluntary carbon market. The entire ecosystem of a soil carbon code will also include standards, tools and forms, fee schedules and registry. In this analysis, we use the term 'code' for simplicity, but this may in some cases refer to the MRV methods within a code or wider elements of the programme within which a code sits.

It is important to appreciate that not all soil carbon certification programmes are the same. Some have developed and now maintain their own codes, standards and registry while others focus on specific components and affiliate with organisation in the marketplace and elsewhere. For example, several do not run their own registry or they may use codes and standards produced by other organisations.

Robust methods and standards in monitoring, reporting and verification are essential to the soil carbon marketplace. All carbon reduction projects, whether offsetting or insetting, are reliant upon reliable monitoring, reporting and verification (MRV) to generate verified carbon credits. Since MRV methods are common to all soil carbon certification programmes, these method documents provided a common starting point for this comparative analysis.

Approach

The primary aim of this analysis was to learn lessons from existing soil carbon codes by exploring the commonalities and differences between the existing MRV methods and associated programme documents.

The initial selection of the code documents started in 2019 with selection in March 2020. Several additional documents were added early in 2021 to reflect new geographies and significant revisions to existing code documentation. The selection was made to represent the range of existing codes in use around the world, and not as a comprehensive review of all available codes or a performance comparison between codes. In total 12 documents were selected from eight organisations where: i) there was detailed guidance on MRV methods; ii) it was publicly available; iii) it was for codes that were currently in operation. Codes under development, or with limited detail publicly available on their MRV methods, were excluded from the analysis.

A list of evaluation criteria was identified from expert knowledge across consortium and broadly reflect the components of carbon codes in which MRV methods were being applied. In the first stage, these criteria were used to extract relevant information from each code document and any associated MRV and programme documents. This extensive synthesis was time consuming and challenging to complete in a consistent manner for a number of reasons which include; the volume of inter-related documents, variation in terminology, use of discipline-specific technical language, navigation of individual programme structures.

In the second stage, data from the stage 1 comparative analysis was extracted to produce a revised comparison using a refined and expanded list of criteria that reflected the full range of commonalities and differences between the codes. The stage 2 comparative analysis is summarised in Tables 2 and 3, and forms the basis for the insights below.

Table 1: List of soil carbon MRV methods reviewed

Title for soil carbon MRV method	Version year	Owner Organisation	URL	Review abbreviation
GSOC-MRV Protocol A protocol for measurement, monitoring, reporting and verification of Soil organic carbon in agricultural landscapes (2020). UN FAO	2020	UN-FAO	https://doi.org/10.4060/cb0509en	GSOC_MRV (GSP FAO)
Carbon Credits (Australian Carbon Farming Initiative) - Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018.	2018	Australian Clean Energy Regulator	http://www.cleanenergyregulator.gov.au/ERF/Pages/Choosing%20a%20project%20type/Opportunities%20for%20the%20land%20sector/Agricultural%20methods/The-measurement-of-soil-carbon-sequestration-in-agricultural-systems-method.aspx	AU SOIL CARBON_1
Carbon Credits (Australian Carbon Farming Initiative) - Soil carbon method: proposed new method under the Emissions (2021) Reduction Fund	2021	Australian Clean Energy Regulator	https://consult.industry.gov.au/soil-carbon-method-proposed-new-method	AU SOIL CARBON_2
NORI Pilot Croplands Methodology Version 1.2 Last Updated: March 05, 2021	2020	NORI Inc. USA.	https://storage.googleapis.com/nori-prod-cms-uploads/Nori_Croplands_Methodology_1_2_5435488110/Nori_Croplands_Methodology_1_2_5435488110.pdf	NORI
Climate Action Reserve - Soil Enrichment Protocol V1.0 September 2020	2020	Climate Action Reserve	https://www.climateactionreserve.org/wp-content/uploads/2020/10/Soil-Enrichment-Protocol-V1.0.pdf	CAR SEP

Title for soil carbon MRV method	Version year	Owner Organisation	URL	Review abbreviation
Gold Standard. Soil Organic Carbon Framework Methodology. Version 1.0 Published January 2020	2020	Gold Standard	https://globalgoals.goldstandard.org/standards/402_V1.0_LUF_AGR_FM_Soil-Organic-Carbon-Framework-Methodolgy.pdf	GOLD STANDARD
VERRA Soil Carbon Quantification Methodology. Approved VCS Methodology VM0021 Version 1.0, 16 November 2012 Sectoral Scope 14	2012	VERRA	https://verra.org/wp-content/uploads/2018/03/VM0021-Soil-Carbon-Quantification-Methodology-v1.0.pdf	VERRA VM0021
VERRA Adoption of Sustainable Agricultural Land Management. Approved VCS Methodology VM0017 Version 1.0, Sectoral Scope 14 (2011)	2011	VERRA	https://verra.org/wp-content/uploads/2018/03/VM0017-SALM-Methodolgy-v1.0.pdf	VERRA VM0017
VERRA VCS Methodology VM0042 METHODOLOGY FOR IMPROVED AGRICULTURAL LAND MANAGEMENT Version 1.0 19 October 2020 Sectoral Scope 14. (2020)	2020	VERRA	https://verra.org/wp-content/uploads/2020/10/VM0042_Methodology-for-Improved-Agricultural-Land-Management_v1.0.pdf	VERRA VM0042
Bcarbon - Protocol for Measurement, Monitoring, And Quantification of The Accrual of Below-Ground Carbon Over Time (2021	2021	Bcarbon inc (Baker Institute)	https://static1.squarespace.com/static/611691387b74c566a67f385d/t/6127d43cbc940c49c7b6cfdc/1630000191203/082621_Metrics_Protocol.pdf	Bcarbon
Label Bas Carbone - Carbon Agri Method, September 9, 2019	2019	Ministry of Ecological Transition, French Government	https://www.ecologie.gouv.fr/label-bas-carbone	LBC_Carbon Agri
Label Bas Carbone - Field Crop Method, July 23, 2021, V1.1	2021	Ministry of Ecological Transition, French Government	https://www.ecologie.gouv.fr/sites/default/files/M%C3%A9thode%20%C3%A9levages%20bovins%20et%20grandes%20cultures%20%28Carbon%20Agri%29.pdf	LBC_Field Crop

Initial insights

The comparative analysis used 110 criteria in stage 1, which were refined to 165 criteria in stage 2, which were used to interrogate each of the 12 codes, resulting in 1,508 and 1,980 points of comparison in the stage 1 and 2 analyses respectively (see Tables 2 and 3 for a summary of the stage 2 analysis). The results presented here provide an overview of the rapidly growing landscape of soil carbon codes with an illustration of the range of approaches currently in operation.

(A) Code scope

Documentation, review and approval

- Most codes were approved and operational, with one under consultation and one being piloted.
- Approved codes had been approved for use under the auspices of an 'owner' organisation, having undergone a process of development from independent engagement and consultation to pilots.
- In a few cases, new methods to address new areas of interest or to refine approaches are in the process of approval (consultation or draft). The production of new methods illustrates the ongoing requirement to update methods based on new evidence, improved techniques and experience gained from active projects.
- Finding the relevant documents for this analysis proved time consuming. Signposting throughout the substantial documentation required for a UK Farm Soil Carbon Code would benefit people new to codes and assist projects in navigating effectively through a code ecosystem.

Ownership, affiliation and alignment

- There were eight owner organisations for the 12 codes reviewed. Five were not-for-profit organisations based in the USA and the remaining three were national governments (Australia and France) and intergovernmental (UN FAO) organisations.
- Most of organisations were affiliated with recognised international and/or national Standard setting bodies (eg ISO, ASEA) and aligned to national legislative frameworks. The National Government programmes and FAO method were also aligned to obligations under the Paris Agreement and as such MRV methods explicitly reflecting IPCC guidelines and methods.
- Who owns a code has significant implications for its operation, and a UK code will need to adhere to UK legal, financial and other obligations.

Geographic coverage, active projects and contracting

- The National Government codes were developed for country specific use while all other methods were considered to be globally applicable, and as such were designed to be applicable to a range of natural, social, economic and farming contexts.
- The approaches taken in different codes partly reflected the availability of information available from projects, leading to differences in quantification approaches, levels of crediting that could be achieved and levels of risks mitigation.
- At the time of review, six codes had been used by projects to generate soil carbon credits in Australia, France, USA, South Africa, Kenya and India. There were many more projects in development worldwide at this time.

- The areas covered by active and planned projects varied considerably. Where stated, project areas ranged from tens of 1,000s to millions of hectares.
- From the project start date, the minimum contract length allowed in the protocols ranged from one year to 25 years while the maximum contract length ranged from five years (with options to renew) to 100 years.

Carbon scope

- The terminology used to define the required impact on soil carbon included 'soil carbon stocks', 'soil carbon sequestration and reduced greenhouse gas emission', 'greenhouse gas emission reductions and removals' and 'net abatement'. The different terminology reflects, amongst other things, affiliations, aspirations and historical context, while also reflecting the different goals and MRV methods of each code.
- Approaches to quantify soil carbon included use of emission factors, direct measurement, modelling and a hybrid combining both modelling and measurement. The approachthat was applied had significant implications for all aspects of a code, eg carbon impact, baseline data needs, uncertainty, risk mitigation, additionality, effort, reliance on tools, etc.

(B) Project eligibility, rules and administration

Project ownership and project land relationships

- Project owners ranged from project developers to farmers (and, in some cases, owners were undefined). All codes required legal right to the land either through property ownership or contractual obligations. Projects could be implemented by either the landowner or a farmer leasing the land as long as they had agreement from the landowner for the duration of the contract. It was assumed that individual contracts addressed project-owner-leasing relationships across permanence periods.

Eligible and ineligible land uses

- Croplands and pasture or rangeland were the most common eligible land uses, whether in a combination or covered by separate methods. Vineyards and orchards were included in one code. There was no explicit reference to horticulture or mixed farming as eligible systems.
- Ineligible land uses generally included forested lands, wetlands, and lands with histosol soil types. In some cases, there was also consideration of the duration of preceding land use, eg how long since conversion from pasture or years of current management.
- The definition of eligible practices differed across the codes. One code required the adoption of a single tillage option while three provided defined lists of management practices from which at least one option must be adopted, eg type of cover crop or type of reduced till. Seven codes took a less prescriptive approach and provided eligible categories where one or more change was required in fertiliser use, water use, tillage, organic amendments, crop types, rotations, etc. One code had an open approach with no eligibility rules for management practices.

Additionality and stacking

- Approaches to additionality varied considerably across the codes. Most required that management practice(s) were new to the project, some stipulated that new practices must not be not common to a region, eg less than five per cent of farmers using the new management the surrounding region.

- Five codes required demonstration of financial and legal barriers to the adoption of the new management practices. In some cases, this was as simple as conducting an investment analysis to prove that the activity was not economically viable without generating carbon credits. Various tools were provided or suggested for this analysis. These ranged from providing investment analysis tools to project developers to suggesting approaches such as investment comparison analysis, benchmark analysis or a simple cost analysis

- One code took a much simpler approach, stating that “if a landowner can prove that they are adding atmospheric carbon to the soil or trees, they have a right to sell that stored carbon”, whether they would have made these changes anyway or were compelled to do so by law.

- Most codes required projects to meet a legal additionality test to ensure that project activities were not already required by law and complied with legal, environmental, ecological and social regulations in the country of application.

- Several standards did not explicitly state whether or not they allowed stacking with payments from other (public or private) sources for the delivery of other outcomes from the project area. A few codes did not preclude stacking if the additionality criteria for their standard were met.

Leakage, reversals and permanence

- Most codes addressed leakage and reversals, with requirements varying significantly across the codes. For example, there were requirements to quantify or monitor leakage for specific or multiple areas eg loss in yields, displacement of grazing, conversion to agricultural land use, source of organic inputs, etc. In a few instances, these losses could translate into credit deductions. Many codes accounted for unintentional reversals via a buffer account with requirements from five per cent to 20 per cent of credits.

- Two codes considered leakage or reversals to be unlikely and did not have rules.

- One of the most significant differences between codes was their treatment of permanence. Where indicated, permanence ranged from eight, ten, 25 to 100 years, with 100 years being the most common period for permanence.

- Credits were generally issued based on MRV at intervals across the permanence period. Therefore, project costs would be significantly greater for a project with permanence of 100 years compared to a project with permanence of eight years.

- Some codes did not specifically describe the permanence period.

Baselines

- There were several approaches in setting baselines for projects which reflected, in part, the different quantification approaches employed by each code, characteristics of cropping cycles, past land use and management histories and the availability of suitable data to model or measure.

- Soil carbon baseline approaches included, fixed average, dynamic and model equilibrium. A few codes left this open and did not specify a particular approach.

- Baselines that used modelling approaches ranged from the use of IPCC emission factors to the application of accepted soil process models which had to be calibrated to a project's local conditions.
- In all cases, setting robust baselines was reliant upon the amount, quality and period of data available for a field, farm, region and country. Most codes specified that historic data was required, varying from three, four, five to ten years across the codes.
- Uncertainty around baselines was widely reflected in risk mitigation requirements, credits issued and ultimately payments.

Monitoring, reporting and verification

- Monitoring and reporting periods, with verification (MRV), varied across the codes. Most codes required MRV at a minimum of five yearly intervals across farm records, soil carbon stocks and greenhouse gas emissions, with the range from annually to every ten years depending on code or project circumstances. One code required MRV to reflect cropping cycles while another code allowed MRV linked performance certification.
- In all cases, MRV had to be maintained at defined intervals until the end of the permanence period, where indicated.
- Codes had different ways of deciding who could carry out verification. This included a 'qualified independent person' based on curriculum vitae and professional registration, or a body already accredited to a national or international standard such as ISO14065 or ISO17020 (many had white lists of approved verification bodies that projects could choose from). One code trained and approved their own third party verifiers and another did their own verification for registered projects. Most made it clear that the person or organisation doing the verification must have no financial or other conflicts of interest with the project. To mitigate risk of collusion or incompetence, one code required that verifiers were audited by a second verifier.
- Codes required different frequencies of auditing, typically at the start of a project (based on the project design document and initial application of interventions), midway and the end. The project proponent had to keep records of, for example, evidence of interventions applied on the land, land management strategies, soil sampling data and other farm management data such as the number and type of grazing animals, amount of biomass left on site, amount of fertiliser or manure inputs etc. Auditing information was publicly available in most standards. Quality assurance process typically conformed to ISO standards such as ISO19011, ISO14064, ISO14065 or IPCC guidance on quality assurance

Complaints and disqualifications

- Half of the codes provided accessible information on procedures for dispute resolution and complaints, while most codes provided information on conditions for disqualification during the project contract period.

Determination of soil carbon sequestration

- The scope of the codes varied significantly, with most requiring the measurement of soil carbon stocks and greenhouse gas emissions in a net soil carbon sequestration approach. A few codes addressed only greenhouse gas emissions or soil carbon stocks.
- The main approaches in quantifying soil carbon sequestration were direct measurement, modelling or a combination of measurement and modelling. One

code only required measurement of soil carbon stocks, one code only required modelling, and the remaining codes left the options open to measure, model or use a hybrid approach.

- The minimum soil depth required for the quantification of soil carbon stocks ranged from 20cm to 30cm, although most methods indicated that a soil depth of c.100cm was ideal. Two methods indicated the use of 'equivalent soil mass' when quantifying change in soil carbon stocks.
- Specifications around the laboratory methods to measure soil carbon (%) and bulk density were covered in varying degrees of detail with respect to allowable methods, quality control and measurement errors.
- Specifications around modelling options also varied from codes were the use of specific models was prescribed to codes that were open to using any suitable model. All models required calibration to local circumstances using suitable data.
- Quantification of uncertainty from measurement and modelling was also addressed to varying degrees. In most codes, uncertainties in soil carbon sequestration from measurement or modelling were reflected in requirements for crediting, eg buffers, insurance and claw-backs.

Marketplace

- Programmes issued their own credit units eg CRT, NORI token, ACCU, VCU, VER, with all credit units equal to one tonne CO2e. The period for crediting varied across the codes from 10 to 100 years.
- Three programmes were directly involved in payments from their registries. Two were government run registries (Australia and France) and the other was run by NORI, a not for profit organisation. Other codes issued credits to be sold in the wider marketplace through various registries.
- Most did not allow forward selling or provided pending issuance units without verification of actual greenhouse gas emissions abatement benefits. In a few codes, verified credits could be requested after the initial project validation in the understanding that these could be withdrawn later if verification reports showed that the project had failed deliver sufficient carbon. Payments were typically made at verification points once reports had been approved.
- Costs and fees to set up and run projects and ultimately sell credits varied by amount, types and timescales. The Australian government offered grants to support baseline measurement costs. Costs could add up to several thousand pounds over the lifetime of a project, with costs influenced by MRV requirements, permanence period and risk mitigation requirements.
- Risk mitigation is a key aspect of the market with uncertainty in soil carbon sequestration affecting renumeration in different ways. Various tools and approaches were being used to quantify risk.
- Most codes used buffers to manage uncertainty. The size of buffers was established in several ways, for example, based on the permanence period, frequency of sampling, model estimations of uncertainty, project-specific risk rating or quality of verification methods used. In one code, the size of a buffer could change over the course of a project based on changes in risk. Non-variable buffers ranged from five per cent to 20 per cent and up to 50 per cent for a temporary buffer in one code. Some of codes, did not require contributions to a buffer.

Carbon sales and values

- Soil carbon units were sold directly to buyers or via carbon brokers or other intermediaries. Sales happened in a variety of ways including carbon auctions with secondary markets and Dutch auctions (lowering the price until units are sold down to a floor price set by the supplier) for pre-qualified buyers and sellers.
- Soil carbon credits could also be sold units, via registries which managed transactions independently, direct to specific companies or via multiple intermediaries.
- Some standards operated 'know your customer' background checks before buyers were allowed to open accounts, eg to ensure they are in 'good legal standing', but none attempted to assess whether investors had first done everything possible to reduce their emissions at source.
- At the time of review, the average price per tonne CO2e in the two codes that provided this information was £8.50 and £11.

Table 2: Summary of code scope and project eligibility, rules and administration associated with reviewed soil carbon MRV methods

	Documentation	Review Method Abbreviation	GSOC_MRV (GSP FAO)	AU SOIL CARBON_1	AU SOIL CARBON_2	NORI	CAR SEP	GOLD STANDARD	VERRA VM0021	VERRA VM0017	VERRA VM0042	Bcarbon	LBC_Carbon Agri	LBC_Field Crop Method
CODE SCOPE		Year - current version	2020	2018	2021	2020	2020	2020	2012	2011	2020	2021	2019	2021
		Status (Nov 2021)	approved	approved	consultation	pilot	approved	approved	approved	approved	approved	approved	approved	approved
	Ownership	Owner of method	UN-FAO	Australian Clean Energy Regulator	Australian Clean Energy Regulator	NORI Inc. USA.	Climate Action Reserve	Gold Standard	VERRA	VERRA	VERRA	Bcarbon inc (Baker Institute)	Ministry of Ecological Transition, French Government	Ministry of Ecological Transition, French Government
		Sponsors / funders of method	UN	GOV	GOV	not for profit	not for profit	not for profit	not for profit	not for profit	not for profit	not for profit	government	government
		Code Scope	component	component	component	component	component	component	component	component	component	component	component	component
		Overarching Programme	RECSOIL (FAO)	Carbon Farming Initiative	Carbon Farming Initiative	NORI Carbon Removal Marketplace	CAR voluntary offset prgrame	Gold Standard for Global Goals (GS4GG)	Verified Carbon Standard (VCS) Program	Verified Carbon Standard (VCS) Program	Verified Carbon Standard (VCS) Program	The BCarbon Standard	Label Bas Carbone (LBC)	Label Bas Carbone (LBC)
	Approval, affiliation and alignment	Programme approved by	NS	Australian Government Carbon Credits (Carbon Farming Initiative) Act 2011	Australian Government Carbon Credits (Carbon Farming Initiative) Act 2011	NS	CORSIA, Approved Offset Project Data Registries (OPDR) in California	CORSIA	CORSIA, Approved Offset Project Data Registries (OPDR) in California	CORSIA, Approved Offset Project Data Registries (OPDR) in California	CORSIA, Approved Offset Project Data Registries (OPDR) in California	NS	French Government	French Government
		Aligned to recognised Standard setting body	NS	ASAE (3000, ASAE 3100, ASAE 3410, ASQC 1); ISO 14064-3:2006	ASAE (3000, ASAE 3100, ASAE 3410, ASQC 1); ISO 14064-3:2006	ISO 14064	ISO 14064- 2 ; WRI/WBCSD Greenhouse Gas Protocol for Project Accounting	NS	NS	NS	ISO 14064-2:2006, ISO 14064-3:2006; ISO 14065:2013	NS	ISO 14044 for Livestock Assessments	NS
		Affiliated to national legislation	N	Y	Y	N	Y	N	Y	Y	Y	NS	Y	Y
	Carbon scope	Carbon impact (terminology used)	soil carbon sequestration+reduced GHG emissions	net abatement	net abatement	soil carbon stock gain	GHG (eCO2) reductions	soil carbon sequestration+reduced GHG emissions	greenhouse gas emission reductions	greenhouse gas emission reductions	greenhouse gas (GHG) emission reductions and removals	soil carbon sequestration only	soil carbon sequestration+reduced GHG emissions	soil carbon sequestration+reduced GHG emissions
	Quantification approach	Quantification approach	hybrid	measure, model or hybrid	measure or hybrid	model	hybrid	measure / model / emission factors	measure / model / hybrid / emission factors	model only	measure / model / hybrid / emission factors	measure only	measure + model	measure + model
	Geographic coverage	Intended geographic coverage	global	country	country	country	country	global	global	global	global	country	country	country
		list regions or countries	NS	Australia	Australia	USA	USA	-	-	-	-	usa	france	france
	Active projects	Active projects	NS	110	N	9	Nov2021: not ARB eligible 2 projects	N	N	2	1	N (projects in planning)	1	N
		locations of active projects	-	Australia	-	USA	USA (numerous states)	-	-	India, Kenya	South Africa	-	France	France
		area covered (ha)	-	NS	-	NS	4.6 million (indigoag)	-	-	46000	96.8 million	-	NS	NS
PROJECT ELIGIBILITY, RULES AND ADMINISTRATION	Project Type	Project ownership	open	open	open	open - farmer preferred	project developer	farmer / project developer	farmers / landowner	farmer / land owner	farmer / land owner	farmer / land owner	farmer / project developer	farmer / project developer
		Project Land Relationship	NS	legal right	legal right	legal right	legal	legal	legal	legal	legal	legal	legal	legal
		Eligible land use	C+G+other (inc. agroforestry)	C+G+BF	C+G+BF	cropland (inc. orchards and vineyards)	C+G (including managed rangeland and/or pastureland)	C+G	C+G+rangeland	c+G	C+G	grassland (rangeland)	C+G	C+G
		Ineligible land use	Y	Y	Y	Y	Y	Y	Y	Y	Y	NS	NS	NS
		Eligible practice/intervention	categories	defined list	defined list	categories	categories	single (tillage)	categories	categories	defined list	open	categories	categories
	Rules	Additionality- 'common practices'	Y	Y (see Act 2011)	Y (see Act 2011)	n	detailed	detailed	detailed	brief	detailed	N	detailed	detailed
		Additionality - 'project practices'	detailed	Y	Y	Y	detailed	NS	detailed	brief	detailed	N	detailed	detailed
		Additionality: financial, legal, other	Y	N	N	N	Y	Y	Y	Y	Y	N	Y	Y
		Leakage rules	Y	Y	Y	Y	Y	Y	Y	Y - brief (biomass)	Y	N	Y	Y
		Permanence rules	8	25 or 100	25 or 100	10	100	other - fixed 20% pooled buffer	100	100	max. 100	10 years	other	other
		Reversal rules	Y	Y	Y	Y brief	Y	Y	Y - non-permanence risk	N	Y	N	Y - brief	Y - brief
		Compliance: laws or ethical	N	Y	Y	N	Y	Y	N	NS	NS	N	not obvious	not obvious
	Registration	Registration review process	NS	internal	internal	internal	independent	independent	independent	independent	independent	internal	internal	internal
		Registration costs	NS	NS	NS	NS	Y	Y	Y	Y	Y	y	NS	NS
		Associated Registry	NS	Australian National Registry of Emissions Unit	Australian National Registry of Emissions Unit	NRT Registry	CAR Public Registry	Gold Standard Impact Registry	VCS registry	VCS registry	VCS registry	Bcarbon - tbc	Ministry of Ecological Transition, French Government Registry	Ministry of Ecological Transition, French Government Registry
		Contract commitment duration	NS	permanence	permanence	project (10 years)	permanence (usually)	5 yr renewable	NS	project	project	min 10 years	min 5 yrs	min 5 yrs
		Who is the contract with?	NS	code owner-project owner	tbc	code owner-project owner	code owner - project owner	code owner - project owner	code owner - project owner	code owner - project owner	code owner - project owner	code owner - project owner	code owner - project owner - buyer	code owner - project owner - buyer
		Contract breach defined	Y - brief	Y - brief	tbc	Y - brief	Y	Y	Y	Y	Y	NS	Y	Y
		Project Boundaries definition	Y - brief	Y	Y	Y	Y	Y	Y	Y -brief	Y	Y	Y	Y
		Data Ownership addressed	N	N	N	Y	Y	n	n	n	n	NS	NS	NS
		Data Disclosure or Privacy addressed	N	N	N	non disclosure policy	partial disclosure	N	partial disclosure	partial disclosure	partial disclosure	N	partial disclosure	partial disclosure
		Changes allowed during project term	NS	Y	Y	Y	Y	Y	Y	NS	Y	Y	Y	Y
	Baselines	How many years of historic data are required in setting the baselines?	3-10	3-10	3-10	up to 5	min 3	min 5 yrs	NS	5 yrs for most	min 3 yrs	>10	4 yrs	3 yrs
		what type of baseline is required	fixed	fixed	fixed	dynamic	fixed or dynamic ("matched" or "blended")	fixed average	fixed average	other (model equilibrium baseline)	fixed or dynamic ("matched" or "blended")	open	fixed average	fixed average
	Monitoring	Frequency of reporting : project / farm records	5-10	1-5	1-5	1-5	7 post last verification, 10years after data generated	annual and 5 yr	intervals of <5 years	annually	intervals of <5 years	yearly	5 yrs	5 yrs
		Frequency of reporting : measured SOC stocks	1-5	1-5	1-5	at least every 3 years	min 5 yrs	at performance certification, depending on approach	intervals of <5 years	-	intervals of <5 years	5 years	5 yrs	5 yrs
		Frequency of reporting : modelled GHGs / SOC stocks	1-5	1-5	1-5	at least every 3 years	yearly (one complete cultivation cycle?)	at performance certification, depending on approach	intervals of <5 years	5 years	intervals of <5 years	-	5 yrs	5 yrs
		Are reporting templates provided	n	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N
		Reporting bodies: Who must be involved with the monitoring and verification process?	independent	independent	independent	independent	independent	independent	independent	independent	independent	internal	independent	independent
	auditing and verification	Verification Responsibility	independent	independent	independent	independent	independent	independent	independent	independent	independent	independent (tbc)	independent	independent
		Verification Frequency	NS	defined intervals	defined intervals	defined intervals	defined intervals	defined intervals	defined intervals	defined intervals	defined intervals	defined intervals (tbc)	defined intervals	defined intervals
		certification bodies	NS	internal	internal	independent	independent	independent	independent	independent	independent	tbc	internal	internal
		standards for certification bodies	NS	ISO	ISO	ISO accredited	ISO accredited	Gold Standard Validation and verification body	ISO	ISO	ISO	tbc	ECOCERT Environment certification office; ISO	ECOCERT Environment certification office; ISO
		Transparency: are audits made public	NS	n	tbc	Y (summary)	Y (summary)	Y	Y (summary)	Y (summary)	Y (summary)	NS	NS	NS
	Complaints and disqualifications	Processes for dispute resolution and complaints	N	N	tbc	Y	Y	Y	Y	Y	Y	NS	NS	NS
		Disqualification conditions during a project contract	N	Y	Y	Y	Y	Y	Y	Y	Y	NS	Y	Y
	Other outcomes	co-benefits addressed	NS	N	N	Y (brief)	Y (brief)	Y (brief)	N	N	N	N	N	N
		co-benefit list	-	-	-	other ecosystem C benefits	ecosystem services stacking	NS	-	-	-	-	-	-
		Other environmental outcomes	N	Y	Y	N	Y	Y	N	N	N	N	Y	Y
		Social outcomes	N	Y	Y	N	N	N	N	N	N	Y	Y	Y

Table 3: Summary of determination of soil carbon sequestration and marketplace associated with reviewed soil carbon MRV methods

	Documentation	Review Method Abbreviation	GSOC_MRV (GSP FAO)	AU SOIL CARBON_1	AU SOIL CARBON_2	NORI	CAR SEP	GOLD STANDARD	VERRA VM0021	VERRA VM0017	VERRA VM0042	Bcarbon	LBC_Carbon Agri	LBC_Field Crop Method
DETERMINATION OF SOIL CARBON SEQUESTRATION	**Sampling for soil C stocks**	**Sampling strategies for soil C stocks defined**	Y	Y	Y	N	Y	Y	Y	-	Y	Y	Y	Y
	Minimum depth for soil C stocks	**Minimum depth for soil C stocks defined**	30	30	30	30	30	20	30	-	30 cm	open	NS	30 cm
		Consideration of soil below 30 cm for soil C stocks	up to 100	up to 100	up to 100	30	ideally 100	20-50 ICRAF; 30cm Verra+ 50 cm pits	ideally to 100 cm	-	ideally to 100 cm	open	NS	N
	SOC stock measurement	**soil C stock methods allowed**	open	dm / proxy	dm / proxy	modelling only	direct (not LOI or WB)/ proxy	dm / modelling / ipcc emission factors	dm	-	dm	dm	equation	dm
		soil carbon stock calculations defined	Y	Y	Y	N	Y	Y	Y	-	Y	Y	Y	Y
		How is soil bulk density estimated	dm	dm / proxy	dm / proxy	NS	dm	open	dm	-	dm	dm	NS	NS
	Modelling SOC stocks	**which soil C stock models are approved**	open	regression	calculation: change measured to baseline)	Soil Metrics Platform (inc. dCOMET, aycent / GGIT)	open	NS	-	RothC	NS	NS	-	AMG/ STICS/ MAELIA
		Requirements defined to add new information to soil C stock models	N	N	N	N	Y	Y	-	Y	Y	N	-	N
	Uncertainty in soil C stocks	**% used for buffer**	NS	5-25%, see GHGs	25%	Y	Y	n (20% fixed buffer)	Y (uses VCS AFOLU Non-Permanence Risk Tool)	NS	Y (uses VCS AFOLU Non-Permanence Risk Tool)	NS	y - discount applied	y - discount applied
	GHG Types	**What gases are covered**	all	all	all	all	all	CO2, maybe NO2+CH4	all	all	all	-	all	co2-n2o
		Are non-soil emissions sources covered?	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	Y
	Time periods for GHG modelling and reporting	**Period required for baseline emissions**	NS	10	5	3 years	min 2 years (not fixed, based on crop cycle)	NS	up to 5 yrs	NS	up to 5 yrs	-	tbc	tbc
		Timescale for scenario modelling	20	NS	NS	10 years	project period (e.g. 30 years)	NS	NS	NS	NS	-	tbc	tbc
	GHG Modelling	**emission factors allowed**	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	Y
		which models are approved	open	other	other	Soil Metrics Platform (inc. dCOMET, aycent / GGIT)	open	RothC and Century mentioned	NS	RothC	NS	-	CAP'2ER®	AMG/ STICS/ MAELIA
	Uncertainty in GHG emission reductions	**uncertainty in GHG reductions considered in buffer**	Y	5 or 25%	5 or 25%	Y	Y	n (20% fixed buffer)	Y (uses VCS AFOLU Non-Permanence Risk Tool)	NS	Y (uses VCS AFOLU Non-Permanence Risk Tool)	-	option of 10%	option of 10%
MARKET-PLACE	**Credit issuance**	**Crediting period for qualifying payments**	NS	25	25	10	30	10	20 to 100	20-100	20 to 100	10 yrs	5 yrs	5 yrs
		What defines the start of the crediting period	NS	after baseline	after baseline	switch date	start date	start date unless postponed	start date	NS	start date	verification of sampling results	project notification	project notification
		Retrospective crediting: Can past carbon capture be credited ?	N	N	Y	Y	N	Y	N	N	N	N	N	N
		What triggers payments to projects?	NS	after each report demonstrating carbon abatement	after each report demonstrating carbon abatement	verification report	outwith programme	outwith programme	outwith programme	outwith programme	outwith programme	after 10 yrs (use of modelling may support interim payments)	3 options	3 options
		Name of credit unit	NS	Australian Carbon Credit Units (ACCU)	Australian Carbon Credit Units (ACCU)	NORI token	Climate Reserve Tonnes (CRTs)	Gold Standard Verified Emission Reductions (VER)	Verified Carbon Unit (VCU)	Verified Carbon Unit (VCU)	Verified Carbon Unit (VCU)	NS	unnamed carbon unit	unnamed carbon unit
		Can the credit unit value change?	NS	Y	Y	Y	Y	Y	Y	Y	Y	NS	NS	NS
		Does uncertainty affect remuneration?	NS	Y	Y (see forward abatement estimate)	Y (quality score)	Y	NS	NS	Y (affects credits issued)	NS	Y	y in buffer	y in buffer
		Stacking: Payments interact with other payments (e.g. ES, subsidy)	NS	NS	NS	NS	Y	NS	NS	NS	NS	N	NS	NS
	Target buyers	**How are units sold in the market place**	NS	auction + secondary market	auction + secondary market	dutch auction	open	open	open	open	open	tbc	open	open
		Buyers identified	N	Y	tbc	Y	outwith programme	outwith programme	N	N	N	N	N	N
	Risk mitigation	**Are unintentional reversals handled**	N	Y	Y	NS	Y	Y	Y	N	Y	N	Y - buffer	Y - buffer
		Are intentional reversals handled	N	Y	Y	NS	Y	Y	Y	N	Y	N	Y- buffer	Y - buffer
		Are buffer funds required	N	Y	Y	Y	Y	Y (20% fixed)	Y	N	Y	Y	Y	Y
		Discounting arrangements in place	N	50%	25%	token quality score	N	N	N	N	N	N	N	N
		Are any carbon floor price guarantees given to farmers?	N	Y	Y	Y	N	N	N	N	N	N	N	N
	Market value	**Is there any information on carbon prices**	N	Y	Y	Y	outwith programme	Y	N	N	N	N	N	N
		Information on how carbon prices are determined	N	Y	Y	Y (via forward contract auctioNS)	outwith programme	Y	N	N	N	N	N	N
		Information on real value to project	N	Y	Y	N	N	Y (can be provided by project)	N	N	N	N	N	N
		Financial support available	N	Y (baseline soil sampling)	Y (baseline soil sampling)	N	N	n	N	N	N	N	N	N
		credit transaction fees	N	N	N	~10% transaction fee on sale price of each NRT	outwith programme	NS	N	N	N	N	N	N
		other costs	N	N	N	Y	Y other costs provided	Y e.g.review fees $900 / $1000	Y	Y	Y	N	N	N

Appendix 5
Mechanisms for integrating public and private payments

Mechanisms for integrating public and private peatland payments for ecosystem services in the UK (from Reed et al, 2021).

Description	Strengths	Weaknesses
1. Funds delineation Using public investment to fund a discrete menu of 'value-added' components within a package of nature-based solutions		
The concept here is to break out and use public funds for practical scheme components that are ancillary to privately funded ecosystem function delivery, and for which there is a clear public benefit justification. Designed-in and delivered from the start, these would ideally be spatially defined and discrete within a site.	– Clear 'lines of sight' between sources of funding and outcomes, help with transparency. – Helps boost scale and viability of projects. – Funds multifunctionality.	– May not realise the full potential for 'leverage' presented by more fully integrated payments and action. – Potential for funds to be mis-allocated – for example funding public access infrastructure that realistically will only be used for site management.
2. Trigger funds Setting up government funding that only 'triggers' when a certain level of private sector funding is achieved		
'Trigger funds' would be government funds (directed at carbon, and / or other site outcomes) that would only be released once a certain level of private payments was reached. A single universal percentage level could be used, or stepped trigger levels could be used based on site prioritisation (ideally determined regionally)	– Allows governments to co-fund ecosystem functions, without 'squeezing out' private sector finance. – The effect of private finance triggering public funds could assist in demonstrating additionality.	– Set too low, trigger levels may have the effect of capping the level of private sector funding. – Trigger funds would create organisational complexity
3. Establishing fund-matching or co-investment as a default principle		
An extension of 'trigger funds' in that it establishes a wider default that public funds should only be issued on the basis that a level of private sector funds are already in place for a package of nature-based solutions.	– 'Signalling' to build confidence within the marketplace – avoiding both demand and supply side players being caught in an 'opportunity cost dilemma'.	– Risk that public-benefit oriented projects, where there is little private sector demand, will be disadvantaged.
4. Using a transparent cost-benefit matrix to target public sector funds		
Public funds would be adjusted according to a matrix of public benefit versus private finance potential Stepped, or differential, rates of funding would need to be guided by a transparent set of tests.	– Creates 'smarter' funding, 'stepping up' funds for more difficult, or public-good oriented schemes or locations. – Provides a 'safety net' to fund valuable projects for which there is no private market	– Adds complexity, and requires a defensible and widely applicable set of tests.
5. Creating integrated systems for public-private implementation		
This is an organisational task; to enable public and private funding mechanisms to interact. It means	– System integration (or at least alignment) will be critical to avoiding public sector funds	– Depending on the level of integration, it could increase

Description	Strengths	Weaknesses
overcoming mismatches in organisation scales, timelines, terminology, definitions, and metrics. Integration could happen in various ways but is scale dependent; a funding synergy in East Anglia won't be the same as one in Cumbria. Our recommendation is that public funding shapes itself around emerging private sector markets.	neutralising potential private sector investment.	bureaucracy, and reduce the agility of private sector delivery.
6. Carbon guarantee mechanisms		
Public funds can be used to provide guarantee mechanisms for PES markets that can help de-risk projects and funds for private investors. For efficient use of public funds, guarantees can be awarded via reverse auction mechanisms to allow projects or funds to compete with each other, thus optimising value for money. Guarantees effectively act as an option to sell carbon units in the future for project developers and/or funds, if the market cannot offer a more attractive price. This certainty over future income streams can unlock impact investment in addition to carbon finance, and incentivises developers to put forward projects because they are able to retain carbon units for sale at higher prices than they can achieve by pre-selling pending issuance units prior to verification.	– Avoids risk of crowding out private sector as it provides a potential revenue stream rather than just capital – Value for money can be achieved through reverse auction mechanisms – Criteria for auctions can be used to direct support into targeted subsectors and regions – Ultimately if markets offer better prices, the guarantees may not be exercised thus freeing up public funds – Proven to be effective in unlocking private capital in the UK in renewable energy and woodland creation markets – Opportunity to create a profit capture mechanism to capture a proportion of market upside performance to recover capital for the public sector.	– Requires long-term public-sector commitments – Does not explicitly deal with supply chain issues. While growing the market will help supply chains to develop, they may still require additional public support.