ERAMMP Short Report-01

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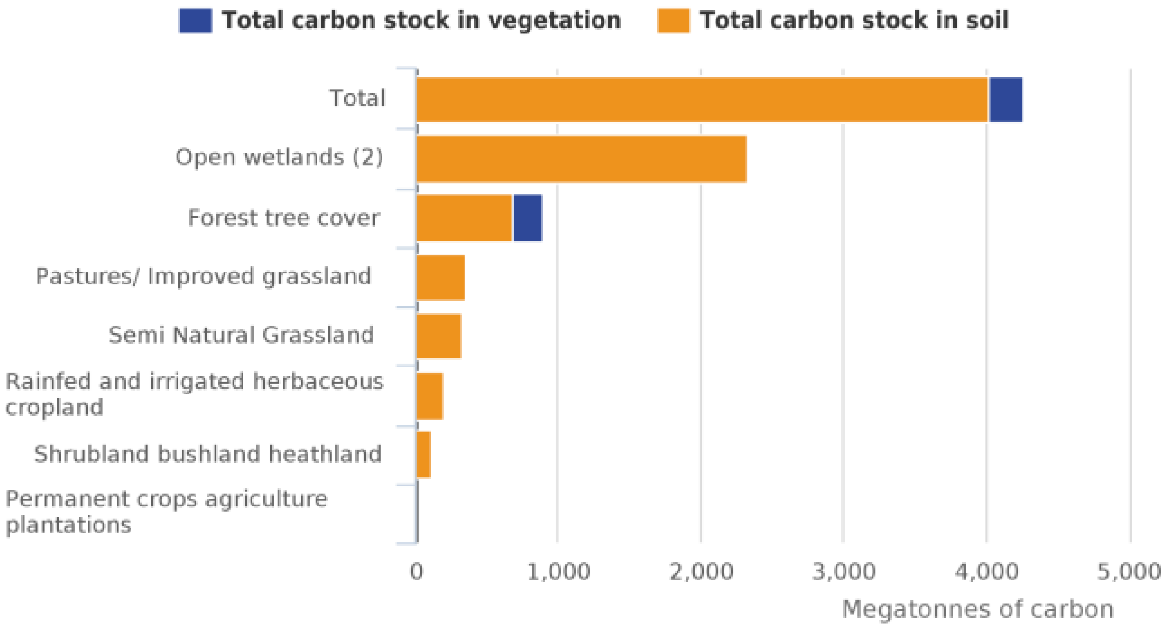
The opportunities and limitations of carbon capture in soil and peatlands

Credit Bruno Pereira on Unsplash

Soil as a carbon store

Soil stores more carbon than vegetation globally. Increasing this soil carbon pool through land-management change is considered one option to help balance emissions to achieve Net Zero – a process often called carbon sequestration.

Source: UK Centre for Ecology & Hydrology and the Office of National Statistics



In the UK, the carbon pool in the soil (including peatlands) represents approximately 94% of the UK terrestrial biosphere carbon stocks. This soil store has been built up over many 1000s of years and originally comes from plants which have captured carbon dioxide out of the atmosphere, using sunlight as an energy source. Plants transfer carbon to the soil through their roots when they are alive, by adding leaf and root material as they are continually renewed, and when they die and decompose into the soil. There are other forms of soil carbon derived from rocks and soil minerals but these are not considered further here.

It is important to recognise that these large stores of carbon in our soils which are derived from plants are often easier to protect than rebuild. This should be the first priority, as losses can be very large and fast compared to the very slow rates they can be accumulated again. Unfortunately, our soil monitoring programmes suggest we are not achieving this. Both arable mineral soils and organic (peat) soils are losing carbon due to historic and current intensive management activities. Overall in the UK, we lost an estimated 0.5% of soil carbon between 1998 and 2007[i,ii]

Soil and peatland carbon stores have been built up over thousands of years through the action of mainly natural processes.

The Welsh Government has prioritised protecting soil carbon and it is a national well-being indicator due to its contribution to both climate mitigation and overall soil health.

The activities which cause soil carbon loss include conversion of land to a less carbon-rich land use (usually arable) and land management activities such as drainage, tillage, removal of carbon via crop harvesting, over-grazing and excess fertilisation. Many of these activities can cause carbon captured over many 1000s of years to be released back into the atmosphere and therefore contribute to climate change. Soils can and should be helping prevent climate change, not contributing to it. What is also often forgotten is that soil carbon is also essential for overall soil health helping to maintain soil structure and stability and prevent erosion.

What is soil carbon sequestration and why is it so often mis-reported?

Soil carbon sequestration is the amount of carbon added to the soil store each year and converted into stable forms of organic carbon, mainly by the actions of soil organisms. If we either remove too much plant material, or encourage soil carbon loss, no carbon sequestration will occur and we may lose carbon from the existing soil carbon store. It is important to emphasise that the rate of soil carbon sequestration is typically very slow and the carbon stocks that have been increased can be reversed.

Unfortunately, exaggerated rates of carbon sequestration are often reported. This comes from a mixture of issues including:

- Confusing the very large soil carbon stores built up over thousands of years (carbon stocks) with the very slow and small annual carbon increase (annual carbon sequestration rates). Mature soils can contain very large carbon stocks but (with the exception of peat, which can accumulate carbon continuously) have low / zero carbon sequestration rates.
- Measurement of soil carbon after adding manures and other plant materials without allowing time for the decay process to happen and stable soil carbon to form. Recently added organic matter will mostly not form stable soil organic carbon.
- Confusing the physical accumulation of existing organic carbon with new carbon sequestration, notably in the case of saltmarsh restoration where soils may have very high rates of carbon accumulation due to organic-rich sediments being washed in on the tide.
- Extrapolating sequestration rates in highly degraded soils to all soils. Degraded soils often have rapid initial rates of accumulation which then slows to the more typical very slow rates of accumulation. The processes which create stable soil organic carbon essentially become full-up or saturated over time. That is not to take away from the value of restoring degraded soils.

Carbon sequestration in soil is slow and is not always permanent.
Tillage, drainage and excess fertilisation can all reverse the process and release soil carbon back into the atmosphere.

What is the realistic potential to increase soil carbon sequestration in the UK?

Many claims have been made about the potential for increasing soil carbon sequestration. These include actions such as conversion of land from one land use to one which is more carbon-rich; creating a more diverse and mixed landscape; habitat restoration and changes in management practices which maintain or increase soil carbon within an existing land use.

Land use change

In most situations, conversion of any arable system to grassland or woodland will cause soil carbon sequestration until a maximum is reached. The effect of planting grassland with trees is more variable, depending on the soil and woodland type, and how it is managed so it may not result in increased soil carbon sequestration initially, in fact there may be losses during the early stages of woodland establishment. This may be surprising, as tree planting is often stated as one of the most effective approaches for capturing carbon, but actively changing land use from grassland to woodland involving tree planting can lead to initial losses of soil carbon e.g. from ground-preparation practices, after which soil carbon will usually accumulate with the growth of the trees.

Potential range of mean soil carbon sequestration rates associated with land use change (excluding urban) until a new stable state is reached (tCO_2 ha^{-1} yr^{-1}) to 1m depth. Negative values indicate soil carbon lost back to the atmosphere.

Land Use	From Cropland	From Grassland	From Woodland
To Cropland		-0.04 to -0.40	-0.08 to -0.65
To Grassland	0.04 to 0.40		-0.04 to - 0.28
To Woodland	0.08 to 0.65	0.04 to 0.28	

Sources: Figures are estimated mean rates of soil carbon sequestration for UK non-organic soils 0-100 cm depth, calculated from carbon stocks observed under different land uses derived from the study of Bradley et al. (2005) [Table 6], and assuming 100 years to reach a new stable state following land-use change. Ranges indicate variation in mean rates when estimated separately for England, Wales, Scotland and Northern Ireland. The values for cropland and grassland change are included in calculations of soil carbon stock changes reported in the UK's national GHG inventory.

One risk of land use change to increase carbon sequestration is the potential for displacing or 'offshoring' our carbon emissions if overall agricultural production is reduced. This can occur due to a total reduction in farmed area or if the efficiency per unit area for production is reduced. This displacement outside of our national boundaries goes against national policies in all 4 nations of the UK, and could effectively negate any local carbon gains in terms of the overall impact on atmospheric CO_2 at a global scale.

Habitat restoration & changes in management practices (including regenerative agriculture)

With agricultural land use, a wide range of actions have been proposed to improve soil carbon sequestration. These include actions such as: organic amendments, moving to more diverse rotations, mob grazing; use of legumes, increasing the number of trees in the farmed system and addition of soil improvers (e.g. biochar; basic silicate rock material). Some of these actions do increase soil carbon on some soil types and most are likely to help improve overall soil health, however the rates are highly variable.

Current robust evidence sources suggest long term, realistic rates of soil carbon sequestration (excluding avoided emissions) within farmland are shown in this table. These numbers need to be considered alongside the average emissions from UK farmland of ca. 2.67 tCO_2 ha^{-1} yr^{-1}. This is calculated from 2020 UK agricultural greenhouse gas emissions (44.8Mt CO_2 ha^{-1} yr^{-1}) corrected for total farmland area (16.8M hectares). This rate varies significantly by farm type, soil and climate. For example, in Wales due to the dominance of the livestock sector, the rate is 3.75 tCO_2 ha^{-1} yr^{-1}.

Current rates of GHG emissions from UK (and Wales) agriculture, status of current soil carbon stocks and the potential range of observed carbon sequestration rates to new stable state ($tCO_2\ ha^{-1}\ yr^{-1}$) due to habitat restoration and changes in management practices.

2020 GHG emissions from UK agriculture = 2.67 $tCO_2\ ha^{-1}\ yr^{-1}$ (Wales = 3.75 $tCO_2\ ha^{-1}\ yr^{-1}$)		
Potential soil C sequestration within an existing land use	**Current status of GB/UK soil carbon stocks**	**Range of potential rates to new stable state ($tCO_2\ ha^{-1}\ yr^{-1}$)**
Arable	Declining	Values are for cool moist systems
Organic amendments		2.79 (-0.62 to 6.2)
Low and min till		0.51 (0 to 1.3)
Cover crops		0.88 (0.51 to 1.25)
Ley-arable		3.04 (1.17 to 4.91)
Improved fertilizer management		0.55 (0.01 to 1.10)
Agroforestry		0.51 (0 to 1.3)
Grassland (permanent)	Maintained / Increasing	Values are for cool moist systems
Improved grazing and fertilizer management		0.81 (0.11 to 1.50)
Woodland	Maintained / Increasing	Conversion from grassland, 80 year time horizon
Woodland creation with broadleaves (planting)		0.25 (0.1 – 0.4)
Woodland creation with broadleaves (natural recolonisation)		0.65 (0.4 – 0.9)
Woodland creation with conifers (planting, moderate-fast growth rate)		0.27 (-0.1 – 0.5)
Woodland creation with conifers (planting, very fast growth rate)		1.3 (0.7 – 1.7)
Woodland creation with mixtures (planting, moderate-fast growth rate)		1.65 (1.5 – 1.8)
Wetlands	Declining	
Peat		0.6 – 5.0 (note increased emissions of methane may limit climate mitigation)
Saltmarsh		2.6 – 5.2
Mixed systems	Unknown	Adjusted for area of hedges to cover estimated 2.5% of productive land area
Hedges		0.1 (0.01 – 0.76)
Estimates following the addition of basic silicate rock and biochar across a wide range of land use systems are less well tested but current estimates range from 2-6 $tCO_2\ ha^{-1}\ yr^{-1}$ for basic silicate rock (assuming 20 t/ha application) and 4.2-27.5 $tCO_2\ ha^{-1}\ yr^{-1}$ for biochar.		

Sources: Countryside Survey Soil report (2010); GHG removal methods and their potential UK deployment (2021; A report for the Dept for Business, Energy and Industrial Strategy by Element Energy and the UK for Ecology and Hydrology, Smith et al (2008); A report for Scottish Forestry, Forestry Commission, Welsh Government and Northern Ireland Forest Service by Forest Research, Matthews et al. (2022).

Potential contribution of soil carbon sequestration to balance current national and overall UK GHG emissions (tCO_2/ha)

Within the UK, the 4 nations have very different total area, soils, climate and land uses. This means they have very different soil carbon stores and soil carbon sequestration potentials. Each country has to develop their combination of strategies to both protect their soil carbon stores and develop strategies to increase rates of soil carbon sequestration and achieve the overall UK target without creating competition and displacement within the UK or displacing emissions outside of the UK. Unfortunately, currently net fluxes of carbon into soil and vegetation in the UK contributes to, rather than helping to offset, agricultural emissions[1].

Moving forward, there are land management practices that could sequester carbon to compensate for the emissions from agriculture, but the options available have lower rates of carbon sequestration, when compared with the emissions from agriculture on a per-hectare basis. As an example, in grassland systems, between 1.8 to 24.3 hectares of improved grazing and fertiliser management would be needed to sequester the carbon emissions from 1 hectare UK agriculture assuming no other change in agricultural activity. This increases to between 2.5 to 34.1 for Wales. A change of land use from farmland to woodland assuming no net loss of agriculture emission rates would typically require between 1.5 – 26.7 hectares of new woodland in the UK depending on woodland type to sequester into woodland soils the carbon emissions from 1 hectare of UK agriculture. This increases to between 2.1 – 37.5 hectares for Wales. These results assume that woodland options that would lead to losses of soil carbon are avoided. Also note that carbon captured in the trees is not included in these numbers. When carbon captured in trees is included, the area required to sequester agricultural carbon emissions decrease to less than 1 hectare for the UK and less than 2 hectares for Wales.

In conclusion, all authoritative reports now recognise the potential for soil and peatlands to contribute to climate mitigation through reducing carbon emission or increasing carbon removal is important, but realistically may be limited to no more than ca. 5-10% of the total needed at the UK level. Higher rates of carbon capture may be achievable through other land-based greenhouse gas removal methods such as enhanced rock weathering associated with the application of basic silicate rock and/or the use of biochar, but these are yet to be fully tested, and will be challenging to scale up to the levels required by 2050 to meet net zero targets. With respect to soil carbon sequestration, the co-benefits of changes in soil management practices for overall soil health are perhaps of even greater importance for policy support due to the extremely slow rates of soil renewal (estimated at 100 years to build just 0.5cm).

The potential for carbon sequestration in soil and peatland to contribute to climate change mitigation is limited to no more than 5-10% of the total needed at the UK level

Most management and land use change options have lower soil carbon sequestration than the carbon/GHG emissions from agriculture in UK (and Wales) when compared on a per hectare basis

[1] Current UK GHG emissions (2021) from agriculture are 43,090 kt CO2e. Net emissions from Land use, Land use change and forestry (LULUCF) are 1,164 kt CO2e, but note that this represents the balance of a number of emission sources (notably drained peatlands), and the current net carbon sink into trees and soil of -22,858 kt CO2. Combined, these emissions represent 10.3% of total UK GHG emissions.

Why is some soil organic carbon more stable and what are the wider benefits of soil organic carbon for soil health?

Not all soil organic carbon derived from plants is the same. During the first stage of plant matter decomposition by soil organisms, partially decomposed plant material is visible as dark coloured humus and peat. If conditions are suitable, additional decay processes can follow forming a wide range of carbon-rich compounds attached or fixed onto soil minerals. These soil minerals are a mix of sand, silt and clay which have been formed from the breakdown of underlying rock by many natural processes. Soil minerals with these attached carbon-rich compounds are critical for creating soil structure, holding water and providing many plant nutrients. These carbon-rich compounds attached to soil minerals are more stable than humus and peat due to the physical protection and chemical bonds provided by the soil minerals.

Peatlands are dominated by this partially decomposed plant material because oxygen is limited due to waterlogging. While this partially decomposed plant material (i.e. peat) is inherently vulnerable to decomposition, this waterlogging restricts the availability of oxygen to soil microorganisms and therefore greatly reduces decomposition, allowing peat to build up layer by layer over many years (potentially over millennia) at rates or around 1 mm/year. However, this means peat is highly vulnerable to drainage, which can lead to very rapid carbon loss as well as land subsidence of 10mm/yr or more.

Outside of peatlands, some soil carbon is also at greater risk of being lost because it is more exposed to our management actions. For example, soil nearer the surface is considered more vulnerable to carbon loss because it is the layer we manage most intensively. It also has a greater concentration of the more vulnerable partially decomposed plant material.

Soil organic carbon in all its forms is one of the key indicators of soil health. The typical amount in topsoil based on a nationally representative sample varies from 2-3% organic carbon for a mineral arable soil to ca. 45% for a peat soil[4]. Any loss of soil organic carbon is considered unhealthy as organic carbon helps create good soil structure reducing erosion risk, provides space for roots to grow and habitat for soil biodiversity, contributes to nutrient supply for plants as well as storing carbon contributing to climate mitigation[5]. Maintaining and increasing soil carbon to protect soil health which takes so long to renew should be a key priority for all four nations irrespective of its role in climate mitigation.

[4] Emmett et al (2010) Countryside Survey: Soils report from 2007. UKCEH.
[5] Soil Structure and its Benefits: An evidence synthesis (2020). The Royal Society.

ERAMMP is developing insight into Sustainable Land Management (SLM) of the Welsh landscape through championing collaboration with a large consortium of partners bringing the best of their expertise and ongoing activities across the monitoring and modelling community.

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[i] UK Natural Capital Accounts (2016) Experimental carbon stock accounts, preliminary estimates. Office of National Statistics.
[ii] Emmett et al (2010) Countryside Survey: Soils report from 2007. UKCEH.