How do soil properties influence carbon storage and sequestration in newly established woodland across the UK?

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1. Foreword

The UK government has committed to achieving net zero carbon emissions for the UK by 2050. To reach this target will require substantial emissions reductions across every area of the economy, including a transformation in land use across the UK. Policy changes include increasing woodland cover from 13% to at least 17% by 2050 by creating at least 30,000 hectares of woodland (90 – 120 million trees) each year (Committee on Climate Change, 2020). However, poorly planned woodland creation could increase CO_2 emissions and have negative consequences for biodiversity (di Sacco et al., 2021). Pre-afforestation soil properties are increasingly recognised as important factors to include in carbon sink projections (Hong et al., 2020). A key aim of this evidence review is to underpin Woodland Trust policy and practice on woodland creation. It is a companion piece to the evidence review: 'How do management interventions influence soil carbon storage and sequestration in UK woodland?' (Bavin, 2021).

Contents

Executive Summary

- Soils contain a large proportion of carbon in ecosystems. In UK woodlands, 75% of the total carbon stock is in the soil.
- The carbon content of soil prior to woodland creation has a strong influence on the carbon sequestration potential of new woodland. Soils which already have a high carbon content do not have the capacity to sequester large quantities of new carbon as a result of woodland creation. The highest carbon content is found in peat and organo-mineral soils. Mineral soils have lower carbon content.
- Afforestation of peat (organic layer >50cm in Wales, Scotland and Northern Ireland) is not permitted by the UK Forestry Standard because it is widely accepted that this leads to large net emissions of carbon from the soil for several decades, which may never be recovered by the trees. New guidance has recently been introduced for England that does not permit planting on depths of >30cm depth except in specific circumstances.
- Recent evidence suggests a review may be appropriate of depth of organo-mineral soils permitted by the UK Forestry Standard for afforestation. Tree establishment on organo-mineral soils (organic layer <50cm) may also lead to net carbon emissions from the soil for several decades.
- Studies of afforestation on organo-mineral soils have focused upon commercial forestry with coniferous species, predominantly Sitka spruce.
- The soil carbon impact of broadleaf afforestation on organo-mineral soils has only been measured in a single study to date. This highlighted the importance of not only considering the degree of disturbance when planting trees, but also the soil carbon loss due to biochemical changes in the soil (the priming effect) induced as trees grow.
- Woodland creation on organo-mineral soil is therefore a sub-optimal choice if an important aim of the project is to contribute to carbon sequestration over the appropriate time frame to meet the government's 'Net-Zero' by 2050 commitment. This does not rule out well-considered woodland creation on organo-mineral soils for biodiversity objectives, but it is important to understand the potential carbon trade-off of such projects to avoid false carbon-positive claims.
- Mineral soils usually have potential for greater soil carbon sequestration, particularly those previously used for arable agriculture, because their current carbon content is low.
- Afforestation on clay-rich mineral soils has the most potential for sequestering large quantities of carbon and for it to be stabilised and stored for the long term. Such soils are widely distributed across the UK and commonly used for both arable and pastoral agriculture.
- The outcome of the government's commitment to create 30,000ha of woodland per year could lead to very different levels of carbon sequestration depending on where those hectares are distributed.
- Stabilisation of accumulated woodland soil carbon is likely to be greatest in soils which are not too acidic to support an abundance of soil fauna, particularly earthworms.

2. Introduction

Soils contain substantial quantities of carbon. In the UK, as in most regions of the world, the largest terrestrial carbon stock is in the soil (Bradley et al., 2006). The carbon stored in UK forest soils accounts for almost 75% of total forest carbon stock (Forest Research, 2015). The carbon present in soils is mainly found in organic matter. The soil carbon stock is determined by the balance of carbon inputs and losses. Inputs include the below-ground growth of root and mycorrhizal biomass, soil fauna biomass and the addition of leaf litter to the soil surface. Soil carbon loss arises from microbial decomposition of organic matter to carbon dioxide (Morison et al., 2012). The balance of carbon input and outputs can be influenced by land-use change such as woodland creation, and the direction and magnitude of the change depends on the properties of the existing soil, which is highly variable across the UK.

Box: Soil properties

Soils include a mixture of rock particles and plant material in various stages of decomposition. The rock particles are referred to as the mineral fraction of the soil, and the decayed plant, fauna and microbe matter (living and dead) along with organic compounds, is referred to as the organic fraction. The mineral particles are described according to their size. Sand has the largest particles, while clay has the smallest particles and silt is intermediate. When a soil's mineral fraction is composed of a relatively balanced mixture of sand and clay particles it is called a loam. The ratio of organic to mineral fraction varies widely across soils. Soils tend to form in layers with different characteristics, these layers within the soil profile are termed 'horizons'. In most soils, organic horizons are present at the top of the profile (closer to the surface) and mineral horizons are present further down the profile. In broad terms, soils with relatively low organic matter content in the upper horizon are described as mineral soils, and soils with relatively high organic matter content in the upper horizon are termed organic soils. Peat is at the extremely organic end of the spectrum, the upper horizon being composed of mainly organic matter.

Carbon sequestration is one of many possible non-exclusive objectives for woodland creation. The aim of this is to increase the quantity of carbon in the soil, as well as increasing the carbon stock in above ground biomass (the trees themselves). Because of the significance of the soil carbon stock, it is crucial to understand the impact of woodland creation on the range of soil types in the UK, to enable effective decision making in terms of where to plant trees for the maximum sequestration benefits, as well as sound judgements on trade-offs with other ecosystem services.

The aim of this review is to synthesise the current evidence on how pre-afforestation soil properties can impact the carbon balance of an area of woodland creation, and to put this into context in terms of relevance for the Woodland Trust's work.

3. Methods

A systematic literature search was conducted, including: The Woodland Trust Mendeley library and Google Scholar. Search terms: "soil" AND "carbon" AND "afforestation" along with modifiers such as "woodland creation", "tree planting", and "natural colonisation". Reference lists were checked to identify additional studies and included where relevant. All sources of relevant evidence were included, such as primary experimental studies, literature reviews, grey literature. Results were filtered by date to identify new literature dated 2019 or later which would not have been included in a previous Woodland Trust evidence review *The role of trees and woods in carbon sequestration and carbon balance* (Hornigold & Bavin, 2019).

4. How does the carbon content of soil influence carbon storage and sequestration potential of newly established UK woodland?

Peat and organo-mineral soils have a surface layer rich in organic matter overlying rock or mineral layers. The depth of this organic layer is used to define whether a soil is classed as peat or organo-mineral. In England and Wales, soils are referred to as peat when the organic surface layer is more than 40cm thick, and organo-mineral when the organic surface layer is less than 40cm. In Scotland, the threshold is defined as 50cm (Lindsay et al., 2014). New guidance has recently been introduced for England that does not permit planting on depths of >30cm depth except in specific circumstances. Organo-mineral soils are also referred to as 'shallow peats' particularly within the forestry literature. For consistency, throughout this report, the term organo-mineral will be used to refer to soils with an organic surface layer below the thickness threshold for the region in question. The term 'peat' will be used to refer to soils with an organic surface layer above the thickness threshold for the region in question. See the Appendix for a list of soil types and how these correspond with the broad categories discussed in this review: peat, mineral and organo-mineral.

Peats and organo-mineral soils are formed where relatively cold conditions and/or anoxic conditions resulting from permanent waterlogging have prevented the decomposition of dead plant debris from surface vegetation. This organic matter, and the carbon it contains, has therefore accumulated in these soils over time. As a result, peats and organo-mineral soils are particularly high in carbon content compared to mineral soils (Ostle et al., 2009). Organo-mineral soils are often managed prior to woodland creation to enhance tree growth, particularly where soil moisture is high. Ground preparation has included drainage to reduce the water table and ploughing to increase soil aeration. This increases the rate of organic matter oxidation resulting in carbon loss to the atmosphere (as CO_2), and to groundwater as dissolved and particulate organic carbon (DOC and POC) (Morison et al., 2012).

Peat

Peatlands are a globally significant store of carbon. In the UK, large areas of peat in the uplands were afforested during the second half of the 20th Century, particularly in northern Scotland, but also northern England, Wales and Northern Ireland (Sloan et al., 2018). Afforestation on peat presents a high risk of permanent net carbon loss from that ecosystem (as well as associated biodiversity loss). For this reason there is a presumption against woodland creation on peat (organic layer deeper than 50 cm) under the UK Forestry Standard (Forestry Commission, 2017). The 50cm threshold is arbitrary in relation to soil carbon loss (IUCN, 2020); it is not based on data indicating a clear increase in soil carbon loss after afforestation of soils with organic horizon deeper than 50cm compared to afforestation of soils with shallower organic horizons.

Organo-mineral soils

Current UK Forestry Standard guidelines do not advise against planting on organo-mineral soils (Forestry Commission, 2017), in fact organo-mineral soil (or shallow peat) is not specifically mentioned in the guidance. The UK Woodland Carbon Code is the voluntary standard for UK woodland creation projects where estimates are made about carbon sequestration (Woodland Carbon Code, 2019). Under this code, woodland creation on organo-mineral soils is accepted, despite no current requirement to monitor soil carbon (although a soil carbon assessment protocol is being developed).

Planting on organo-mineral soil can lead to substantial losses of carbon from the soil which may only be recovered after several decades or not at all (Friggens et al., 2020; Matthews et al., 2020; Vanguelova et al., 2019; Zerva et al., 2005).

A loss of ~50% of total soil carbon was reported 40 years after afforestation with Sitka spruce in a chronosequence study on organo-mineral soil in northern England (Zerva et al., 2005). This equates to a rate of loss of 3.3 t C ha^{-1} yr^{-1}. However, during the second rotation, despite disturbance from clear-fell and replanting, soil carbon began to re-accumulate, and after ~75 years since original afforestation (towards the end of the second rotation) soil carbon returned to levels similar to, though still lower than, adjacent unplanted grassland (Zerva et al., 2005).

Similarly, a chronosequence study in northern England, reported 30% losses of carbon from the peat horizon in the first 30 years after afforestation of heather moorland on organo-mineral soil (Vanguelova et al., 2019). The rate of loss equated to -3.14 t C ha^{-1} yr^{-1}; in line with that reported by (Zerva et al., 2005). After around 100 years (40 years into the second forestry rotation) the losses of carbon from the peat were compensated by carbon accumulation in the surface layers (fermentation horizon and litter layer). The overall influence of conifer afforestation on the carbon stocks of the organo-mineral soil was neutral over the span of a century (Vanguelova et al., 2019). The pattern of large initial carbon loss in the first few decades after afforestation was partly attributed to site preparation practices standard at the time of planting, such as drainage and deep ploughing (Vanguelova et al., 2019). However, neither chronosequence study was able to isolate the effects of these from any other impacts from the tree growth, such as soil priming (Liu et al., 2020).

Smaller losses of carbon have also been reported. On average, 37.5 years post afforestation there was a mean loss of 7.93 t C ha^{-1} from the peat layer at 20 organo-mineral sites across Scotland (Lilly et al., 2016). This was in comparison with archived samples taken prior to afforestation. The loss was not statistically significant because of the large variation in carbon change with afforestation reported between sites. This variation may reflect differences between the study sites such as tree species, peat depth, length of rotation (21-57 years) which were not accounted for in the study design. Lilly et al. (2016) concluded that direct comparison between pre- and -post planting at individual sites is not advisable due to insufficient sample size required to identify significant changes.

Pre-afforestation soil carbon levels are important in determining the carbon outcome of woodland creation. The rate of soil carbon accumulation after afforestation was negatively correlated with the initial soil carbon density in a global meta-analysis of 154 published scientific articles (Wang & Huang, 2020). The emissions due to losses from soil carbon stocks can be so large that they can exceed sequestration in trees and litter for decades following tree establishment (Matthews et al., 2014). A modelled scenario of Sitka spruce afforestation on an organo-mineral soil predicted that after afforestation, carbon stocks initially decrease due to losses from soil. After about 20 years, the net balance reaches zero due to accumulation of carbon stocks in trees, and thereafter the forest becomes a net carbon sink (considering onsite carbon only, not harvested products). However, experimental studies (Zerva et al., 2005) have found soil carbon recovery to take much longer (up to 100 years).

A statistically derived estimate suggests 10.5 ± 0.17 kgC m^{-2} is the threshold soil carbon density above which tree planting will lead to a loss of soil carbon. The threshold value applies to the average carbon density across six soil depth ranges (0-5cm, 5-10cm, 10-20cm 20-30cm, 30-60cm and 60-100cm) (Hong et al., 2020) and was derived from 619 control-and-afforested plot pairs in northern China. The findings are considered representative of the northern temperate biome which includes the UK, but all forests sampled were monoculture plantations and <40 years old. The threshold value is an interesting starting point, but to be applicable in the context of UK conservation planting it requires validation against trial plots in the UK with mixed native woodland. Also, to produce a useful threshold value for guiding planting decisions in the UK context, the sampling and statistical methodology requires adjustment to ensure comparability of the threshold value against existing knowledge on UK soil carbon density of different soil types. For example, the data collected in the BioSoil Survey (Vanguelova et al., 2013).

Outputs from a spatial analysis (Figures 1 and 2) further demonstrate that tree planting on organo-mineral soils in Scotland could result in net carbon emissions for several decades (Matthews et al., 2020). Modelling revealed where net carbon surpluses and deficits are likely to occur, and how long they persist after afforestation. Importantly, it shows that excluding only the areas of peat >50cm from the potential planting area does not eliminate the risk of net carbon loss over the next few decades (Matthews et al., 2020). These model predictions are valuable as indications for where change may occur but need to be supplemented with field data.

In line with predictions (Matthews et al., 2020), downy birch *Betula pubescens* and Scots pine *Pinus sylvestris* plantations on organo-mineral soil in Scotland led to net loss in ecosystem carbon stock 12 or 39 years after planting (Friggens et al., 2020). Plots with trees had greater soil respiration and the loss of soil carbon from the organic layer cancelled out the carbon accumulation in tree biomass over the decadal timescales. It is very important to note that in this study, the soil was not cultivated for planting in any way; all trees were slot-planted with a spade, causing minimal disturbance to the soil profile. Friggens et al. (2020) suggests the mechanism behind the loss of carbon from the organic layer is that the presence of trees altered below-ground microbial and mycorrhizal communities and led to soil priming, enabling decomposition of pre-afforestation soil carbon stores (Friggens et al., 2020). This was the first UK field experiment which studied the soil carbon implications of afforestation with native tree species on organo-mineral soil. The findings are supported by a similar field study of native planting in the Scottish Highlands which also suggests reforestation may trigger carbon loss from areas with high initial soil carbon, even with low disturbance establishment, at least in the short term (20 years) (Warner et al., 2021). A limitation of both studies is that the mineral horizons (soil below the organic layer) were not sampled, therefore references to ‘ecosystem carbon stocks’ do not include mineral soil carbon. It is possible that tree roots may have inputted some carbon into the deeper mineral soil layers which was not accounted for. Further studies of native woodland creation with minimal soil disturbance, including natural colonisation, are required. Future work should consider the full soil profile in addition to above ground biomass. Measurements from a wide range of sites with different thicknesses of organic layer are required for refinement of these findings to quantify any relationship between depth of peat and soil carbon loss.

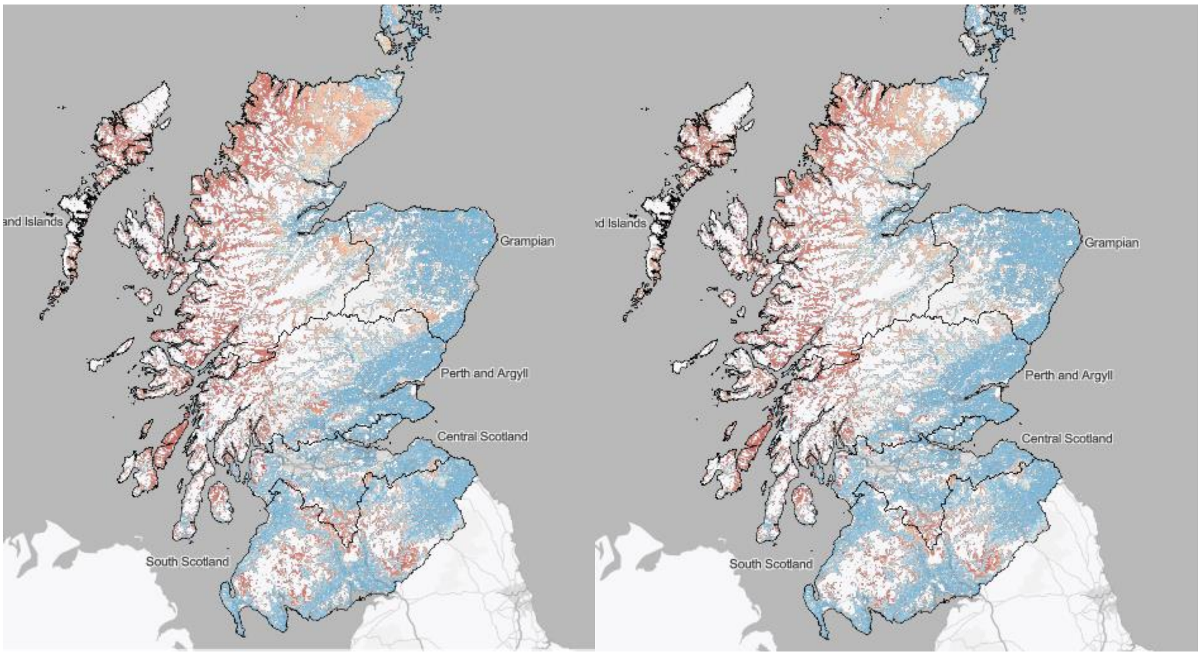

Figure 1. Tonnes of carbon stored per hectare, per year, 30 years after afforestation with native broadleaves. Darker shades of blue indicate the strongest carbon sinks, darkest shades of red indicate the strongest carbon sources. White areas indicate carbon neutrality. Map on the left includes areas of peat >50cm depth, map on the right excludes areas of deep peat. Outcomes of modelling by Matthews et al. (2020). Maps for other tree species and management regimes can be viewed on the interactive map at http://woodlandexpansion.hutton.ac.uk/

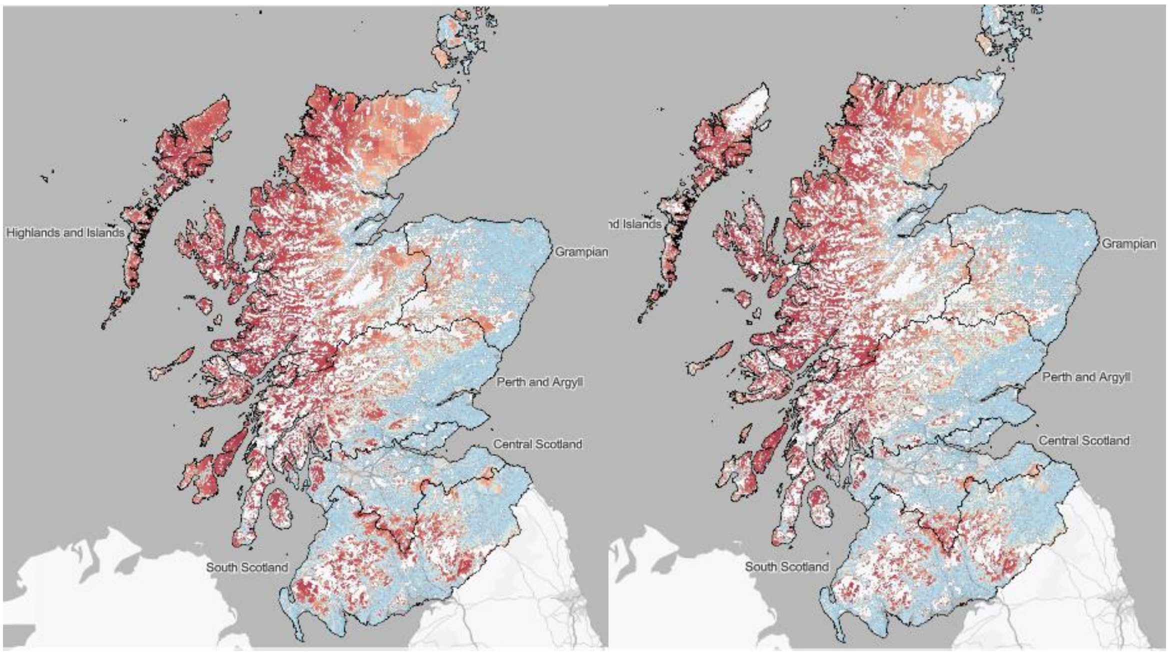

Figure 2. Tonnes of carbon stored per hectare, per year, 30 years after afforestation with native conifers (Scots pine). Darker shades of blue indicate the strongest carbon sinks, darkest shades of red indicate the strongest carbon sources. White areas indicate carbon neutrality. Map on the left includes areas of peat >50cm depth, map on the right excludes areas of peat >50cm. The mapping shows the results of whole ecosystem carbon stock modelling by Matthews et al. (2020). Maps for other tree species and management regimes can be viewed on the interactive map at http://woodlandexpansion.hutton.ac.uk/

To summarise, afforestation of organo-mineral soils causes a significant loss of soil carbon for around 30-40 years, before it begins to re-accumulate via inputs from the litter layer. Soil carbon is able to reaccumulate when uptake of carbon dioxide by the tree biomass, and its subsequent transfer into the soil, is greater than losses from soil decomposition (Vanguelova et al., 2018). Soil carbon stocks are not fully replenished until well into the second rotation of commercial forestry (around 75-100 years after afforestation (Vanguelova et al., 2019; Zerva et al., 2005). Some carbon will be sequestered above ground in the biomass of the growing trees. Therefore, a mature second rotation forest with a restored level of soil carbon could have more total ecosystem carbon than the previous non-wooded habitat and be considered a net carbon sink over this timeframe. Fast growing trees, such as the most productive yield classes of Sitka spruce are expected to reach this positive balance sooner than slower growing trees such as native broadleaves (Vanguelova et al., 2018). However, this is based on the assumption that the tree growth during the second rotation will not lead to loss of the re-accumulated soil C stock, which may be the case. To date, chronosequence studies have not sampled beyond 40 years into the second rotation. To avoid misleading conclusions, the longer term effects of planting in commercial forestry (beyond 100 years) require investigation. Unfortunately there are significant challenges attached to such work.

Although the total quantity of carbon in the organo-mineral soils is unchanged over 100 years, the location of the carbon within the soil profile is moved from the organic layer into the surface fermentation layer, where it is potentially more vulnerable to future disturbance (Laganière et al., 2010). Further research is needed on the long-term stability of this soil carbon. The evidence regarding how afforestation affects the deeper mineral layers of organo-mineral soils is inconclusive; more studies are needed that focus on this aspect (Vanguelova et al., 2018).

Cultivation for afforestation disturbs soil; the loss of soil carbon during the first rotation on organo-mineral soils has been attributed to this physical disturbance (Vanguelova et al., 2018). This has led to the assumption that moving to low disturbance methods will help to substantially reduce soil carbon loss. However, there is little evidence of the magnitude of the potential benefits because few chronosequence studies of plantations established using the newly recommended low-disturbance cultivation techniques are available. Significant soil carbon losses have been measured decades after native trees were manually slot-planted on organo-mineral soils with zero cultivation (Friggens et al., 2020; Warner et al., 2021). These findings show there are additional complex ecological and biochemical mechanisms behind the release of carbon from organo-mineral soils post-afforestation, which cannot be prevented by avoiding cultivation. The effects of these mechanisms must be better quantified and understood before we can be assured that large-scale tree planting in regions with considerable pre-existing soil carbon stocks will have the intended climate change mitigation outcomes. Furthermore, in many areas of the uplands, organo-mineral soils are in close proximity to peat. Due to hydrological connection between these soils, afforestation of organo-mineral soils in these locations is likely to impact the hydrology of the peat (Berdeni et al., 2020). This highlights the need to use meaningful ecological scales when undertaking land use change, such as expanding Environmental Impact Assessments beyond the area being planted.

In the context of afforestation to meet the UK 'Net Zero' emissions target by 2050 the widespread planting of organo-mineral soils would clearly not lead to meaningful carbon sequestration on the timescale required. Recent recommendations to the Scottish Government's Woodland Expansion Advisory Group include organo-mineral soils in the land area considered suitable for afforestation (Sing & Aitkenhead, 2020), which risks jeopardizing soil carbon stocks on the extensive heather moorlands and heathlands with peat <50 cm in depth (Friggens et al., 2020; Warner et al., 2021). According to model predictions, the arbitrary figures used for peat depth classification across the UK are not sufficient to eliminate the risk of afforestation resulting in net carbon emissions over the next few decades (Matthews et al., 2020). Field research in the UK to ground-truth these model predictions, plus the threshold carbon density at which afforestation leads to carbon loss (Hong et al., 2020) will be important avenues of future work. Other priorities are to more accurately map soil carbon stocks to inform future woodland creation and further understand the mechanisms for carbon loss following afforestation. In order to meet the urgency and scale of climate change and biodiversity obligations we need restoration of both peatlands and trees/woodlands in the UK, without compromising one for the other (IUCN, 2020) and without overlooking the importance of preserving the vast soil carbon stocks in organo-mineral soils, much of which falls outside of areas identified for peatland restoration.

Mineral soils

There is substantial variation in the carbon content of mineral soils, although it is much lower than that of organo-mineral soils (Vanguelova et al., 2013). To a lesser extent, the risk of soil carbon loss after afforestation also exists for mineral soils, though it may be recovered relatively quickly (Rytter, 2016). However, woodland creation on mineral soils usually increases soil carbon content (Forest Research, 2021) due to the addition of leaf, branch and root litter, and root exudates (Morison et al., 2012). The magnitude of this increase varies substantially depending on the original carbon content of the mineral soil (Rytter & Rytter, 2020). This is because a portion of the organic carbon in mineral soil forms bonds with the fine mineral particles. This portion is known as the mineral-associated carbon pool (Lavallee et al., 2020). The quantity of fine particles in a soil is finite, therefore there is an upper limit to the amount of carbon which can enter the mineral-associated pool. This is the carbon saturation concept. The maximum quantity of carbon that can enter the mineral-associated pool per volume of soil is referred to as the soil's carbon saturation point. If the existing carbon content is low, there is greater potential for additional carbon sequestration before the soil becomes saturated (Chen et al., 2019).

The original carbon content of mineral soils is highly dependent on the previous land use. Soils which have been relatively undisturbed over long periods such as those under semi-natural grasslands or scrub tend to already be highly saturated with carbon, whereas soils which have been altered during use for arable agriculture, horticulture or improved grazing pasture tend to have lower carbon stocks due to soil disturbance (Emmett et al., 2010). Thus on these soils there is great potential for woodland creation to deliver immediate carbon sequestration both above and below ground with very little risk of any significant amount of carbon being lost in the process of afforestation (Baddeley et al., 2017). Soils which have been subject to other forms of disturbance, such as artificially constructed substrates on brownfield sites are also likely to have low carbon content and therefore high potential for carbon sequestration.

The consensus across several recent meta-analyses at regional and global scales is that afforestation on former cropland results in an increase in soil carbon stocks over 100 years, whereas following afforestation of grasslands, mean soil carbon stocks may increase less, remain unchanged or even decrease (Mayer et al., 2020). This can also be the case with natural forest succession of grasslands on mineral soils. For example, spruce regeneration on abandoned Alpine meadows led to a decrease in mineral soil carbon stocks which reached a minimum (80% of the meadow stock) 15-60 years after the onset of forest development. Thereafter a new soil carbon stock level was attained which tended to be lower than that of the original meadow. However, with above ground biomass, total ecosystem carbon stock was greater in forests compared to the meadows, despite the losses from the mineral soil (Thuille & Schulze, 2006).

The Forest Research CARBINE forest carbon accounting and large-scale scenario analysis model predicts no initial loss of soil carbon for trees planted on mineral soil, meaning the stand becomes a carbon sink immediately. Trees planted on organo-mineral soils were predicted to become carbon neutral after approximately 20 years. By this time, trees planted on mineral soils were predicted to have sequestered 50 tonnes of carbon per hectare (Matthews et al., 2014).

The spatial analysis by Matthews et al., (2020) (Figure 1 & 2) showed that afforesting mineral soils in Scotland could deliver even greater carbon storage than anticipated by the country’s emissions reduction plans. This is in stark contrast to the findings for planting on organo-mineral soils.

5. How does the texture (clay/silt/sand) of mineral soil influence carbon storage and sequestration potential of newly established UK woodland?

It is important to make a distinction between carbon accumulation in soil and carbon stabilisation. Forest floors accumulate carbon quickly, but most of it is in an unstable form and residence time is short (Jandl et al., 2007). Any gains in the soil carbon pool through woodland creation must be protected from subsequent losses over the long term, so understanding the mechanisms of stabilisation of the soil carbon pool is crucial (Lal, 2013). The carbon in soil organic matter can be stabilised in 4 ways:

- It can form part of aggregates (lumps of soil) which protect the soil organic matter by forming physical barriers against microbes and enzymes (Six et al., 2002).
- It can form chemical associations with mineral (silt and clay) particles (Six et al., 2002).
- It can be physically protected from disturbance by deep placement in subsoil horizons via the growth of plants with deep root systems (Lal, 2013).
- Some of the molecules in soil organic matter are inherently stable because their complex chemical composition is resistant to decomposition (e.g. lignin in wood) (Six et al., 2002).

Of these stabilisation mechanisms, the two which are affected by the type of soil present at a site are the formation of aggregates, and the chemical bonding with clay and silt mineral particles. Soil organic matter associated with mineral particles is particularly stable over long timeframes (decades-centuries), but the quantity of organic matter which can be stabilised in this way is limited by the finite surface area of minerals within the soil. In clay soils, the particles are small, so there is a lager total surface area, giving clay soils a higher saturation point than sandy soils (Eldor, 2016; Lavallee et al., 2020; Tew et al., 2021).

Therefore, soils with higher clay and silt content have greater potential to stabilise a larger quantity of carbon (Six et al., 2002). Within the minerals defined as clay, there are 2 further groups described as 1:1 clay minerals or 2:1 clay minerals. Soils dominated by 2:1 clay mineral have a greater protected carbon pool than 1:1 clay mineral dominated soils (Six et al., 2002).

The importance of clay content for long term sequestration is supported by the findings of two global meta-analyses which both indicate that clay content is one of the main factors that contributes to restoration of soil carbon stocks after afforestation. Soils that are more than 33% clay have a greater capacity to store soil carbon than soils which are less than 33% clay (Laganière et al., 2010; Wang & Huang, 2020). Research on UK woodland soils also confirmed that on mineral soils with high clay content, most of the carbon (70%) will be of stable form (Villada, 2013). Knowledge of carbon stabilisation is developing rapidly (Gabriel et al., 2018). However, there remains much uncertainty on the mechanisms of soil carbon stabilisation following afforestation; this is a priority for future research.

6. How does soil pH and soil moisture affect carbon sequestration by newly created UK woodland?

Soil moisture and pH do not feature heavily in the literature as key factors predicting the impact of afforestation on soil carbon. Generally, very wet, acidic soils tend to be already high carbon because these conditions slow decomposition so are conducive to the accumulation of organic matter (the formation of peat). However, the carbon content of such soils is the variable which tends to be discussed in the literature in relation to the impact of afforestation, rather than moisture or pH.

In the cool temperate climate zone, which includes most of the UK, the rate of soil carbon accumulation after afforestation is negatively correlated with mean annual precipitation (Wang & Huang, 2020). This is according to a global meta-analysis; the UK was not represented in any of the samples, so the relationship is based on the broad pattern across the wider climatic zone. According to these findings, the highest rate of soil carbon accumulation after afforestation would be expected in drier parts of the UK, and lowest rate of accumulation would be expected in the wettest parts. This trend fits with the distribution of organo-mineral soils and peat which are associated with areas of high rainfall. Research is needed to examine whether soil moisture *per se* has an influence on the response of soil carbon to afforestation.

Acid and calcareous soils both have the ability to stabilise soil carbon within the mineral associated pool, despite differing chemical mechanisms (Rowley et al. 2018). The effect of pH on soil carbon accumulation after afforestation was insignificant in a global meta-analysis by Laganière et al., (2010), although there was a trend toward increased carbon accumulation in less acidic soils. The accumulated soil carbon in very acidic soils may be less likely to be stabilised in aggregates because low soil pH can negatively affect the activity of soil fauna which contribute to the formation of stable aggregates. After 120 years of broadleaf natural regeneration on the Rothamsted experimental farm in England, Poulton et al., (2003) observed the formation of a litter layer at the acidic site but not at the calcareous site. This was attributed to the fact that the common earthworm *Lumbricus terrestris*(L.) cannot survive in acidic soils (pH<4.5). The acid site gained 0.38 t C $ha^{-1}year^{-1}$ in litter and soil to a depth of 69 cm, while the calcareous site gained 0.54 t C $ha^{-1}year^{-1}$ in the soil. A similar pattern was found in a chronosequence study of natural spruce forest succession on former grassland in the Alps (Thuille & Schulze, 2006). Carbon stocks in the organic litter layer of plots on acid soils accumulated linearly at a rate of 0.34 t C $ha^{-1}year^{-1}$. In contrast, the organic litter layer of plots on calcareous soil increased at 0.24 t C $ha^{-1}year^{-1}$ and stopped increasing after forests were around 60 years old (Thuille & Schulze, 2006). The lower abundance of earthworms at the acid sites explained the continuous build-up of the organic litter layer due to less mixing of the organic material into the deeper mineral soil. Since carbon stored at the surface in an organic litter layer is more vulnerable to disturbance, this would suggest acid soils are less favourable for woodland creation for long-term carbon sequestration than neutral or calcareous soils. However, the type of trees can have a substantial impact on the pH of soils, and litter pH is a more important determinant of the rate of litter decomposition than soil chemistry (Tao et al., 2019).

7. Conclusion and recommendations

The UK Government has committed to creating 30,000 hectares of woodland per year by 2025 to combat climate change through carbon sequestration (Committee on Climate Change, 2020). The size of the UK soil carbon stock is substantial. Therefore, the impact of afforestation on soil carbon is an important factor in determining where woodland creation will result in genuine net carbon sinks and contribute to climate change mitigation. Targets based on number of hectares as an indicator of carbon sequestration do not take into account different soil types.

There is strong evidence that the higher the existing carbon content of a soil, the lower the carbon sequestration benefit that can be achieved through woodland creation, and the higher the risk of overall carbon emissions for a significant period of time. Afforestation of organo-mineral soils can lead to substantial overall emissions for 30-40 years because of carbon loss from the soil. Woodland creation on organo-mineral soils for carbon sequestration is at best sub-optimal or ineffective, at worst counter-productive on the relevant time scale. The current policy against afforestation on peat >50cm (Forestry Commission, 2017) should be reviewed in light of recent evidence on the significance of organo-mineral soils for carbon storage and the risk of soil carbon loss (Friggens et al., 2020; Matthews et al., 2020; Vanguelova et al., 2019; Warner et al., 2021) during the decisive next few decades for action on the climate emergency (IPCC, 2021). A more nuanced approach to an evaluation of soil carbon stocks prior to planting is warranted.

The reduction of carbon emissions at source must be a priority with trees contributing to offsetting unavoidable and historic carbon emissions. Nevertheless, woodlands created for meaningful sequestration as recommended by the Committee on Climate Change (2020) must act as a carbon sink as soon as possible and then store carbon for the long term. Importantly, we are also in an ecological emergency, and therefore potential trade-offs between carbon sequestration and biodiversity need careful consideration in order to achieve positive outcomes for both climate and nature.

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9. Appendix

Definition of organic, organo-mineral and mineral soils taken from The Woodland Carbon Code website https://www.woodlandcarboncode.org.uk/standard-and-guidance/1-eligibility/1-2-eligible-activities#whatareorganic.

Organic Soils/Peat/Deep peat: In Scotland and Northern Ireland, organic soils are those with an organic layer of at least 50cm. In England and Wales they are have an organic layer of at least 40cm. The Forest Research classification suggests an organic layer of > 45cm. These organic soils can also be known as peats in Scotland and Northern Ireland and deep peats in England and Wales.

Organo-mineral Soils/shallow peat: In Scotland and Northern Ireland, organo-mineral soils have an organic layer of 50cm or less, and in England and Wales 40cm or less. Forest Research's classification, suggests an organic layer of < 45cm. These can include humus-iron podzols, peaty podzols, surface and ground water peaty gleys, peaty rankers and podzolic rankers.

Mineral soils : Not defined as having an organic layer (primarily composed of decaying plant material) although they do contain an organic horizon (with higher organic content than underlying horizons). Forest Research classifies mineral soils as having an organic layer of less than 5cm. These can include brown earths, brown rankers and rendzinas, cultivated podzols, surface water and ground water mineral gleys.

A comparison of the soil classifications used in the soil surveys of England & Wales, Scotland and the Forest Research classification, and which of these soil types are organic (peat), or organo-mineral (shallow peat). All other soil types not mentioned in this table are considered mineral soils.

Organic soils/peat/deep peat

FC Soil type and phase code	**England and Wales Soil Survey MSSG Code and wording**	**Soil Survey of Scotland MSSG Code and wording**
8, 8a, 8b, 8c, 8d Juncus bogs (basin bogs)	10.14 (Raw peat soils) 10.24 (Earthy eutro-amorphous peat soils)	5.1.4 (Dystrophic peat)
9, 9a, 9b, 9c, 9d, 9e Molinia bogs (flushed blanket bogs)	10.11 (Raw oligo-fibrous peat soils), 10.13, (Raw oligo-amorphous peat soils) 10.21 (Earthy oligo-fibrous peat soils), 10.23 (Earthy peat soils)	5.1.4 (Dystrophic peat)
10, 10a, 10b Sphagnum bogs (flat or raised bogs)	10.11(Raw oligo-fibrous peat soils), 10.21 (Earthy oligo-fibrous peat soils)	5.1.4 (Dystrophic peat)
11, 11a, 11b, 11c, 11d *Calluna, Eriophorum, Trichophorum* bogs *Calluna*, (unflushed blanket bogs)	10.11(Raw oligo-fibrous peat soils), 10.21 (Earthy oligo-fibrous peat soils)	5.1.4 (Dystrophic peat)
14, 14h, 14w Eroded bogs	10.11(Raw oligo-fibrous peat soils) 10.21 (Earthy oligo-fibrous peat soils).	5.1.4 (Dystrophic peat)

Organo-mineral soils/shallow peat

FC Soil type and phase code	**England and Wales Soil Survey MSSG Code**	**Soil Survey of Scotland MSSG Code**
3p Peaty podzol (peat depth 5cm - 45cm)	6.3.1 Humo-ferric podzols 6.3.3 Ferric podzols	3.3.2 Humus-iron podzols, 3.3.4 Peaty podzols, 3.3.5 Subalpine podzols, 3.3.6 Alpine podzols
3pg Peaty podzol (peat depth 5cm - 45cm), gleyed	6.3.1 Humo-ferric podzols 6.3.3 Ferric podzols	3.3.4 Peaty podzols
3ps Peaty podzol (peat depth 5cm - 45cm), stony	6.3.1 Humo-ferric podzols 6.3.3 Ferric podzols	3.3.4 Peaty podzols
3p(x) Peaty podzol (peat depth 5cm - 45cm), indurated	6.3.1 Humo-ferric podzols 6.3.3 Ferric podzols	3.3.4 Peaty podzols
3mp Hardpan podzol, peaty	6.3.1 Humo-ferric podzols 6.3.3 Ferric podzols 6.3.4 Paleo-argillic podzols	3.3.1 Humus podzols 3.3.4 Peaty podzols
4 Ironpan soil	6.5.1 Ironpan stagnopodzols	3.3.4 Peaty podzols

4a, 4c, 4e, 4g, 4s, 4se, 4x, 4xg, 4xse Ironpan soils, shallow/cultivated/ericaceous/gleyed/stony/indurated	6.51 Ironpan stagnopodzols	3.3.4
4p Peaty ironpan soil (peat depth 15cm - 45cm)	6.51 Ironpan stagnopodzols	3.3.4
4px, 4pxg Peaty ironpan soil (peat depth 15cm - 45cm), indurated/gleyed	6.51 Ironpan stagnopodzols	3.3.4
4z Podzolic ironpan soil	6.52 6.5.2 Humus-ironpan stagnopodzols	3.3.4
4zc, 4ze, 4zg, 4zp, 4zp(x), 4zs, 4zx Podzolic ironpan soil, shallow/cultivated/ericaceous/gleyed/peaty/stony/indurated/humose	6.52 6.5.2 Humus-ironpan stagnopodzols	3.3.4
5h Ground-water gley, humose	8.1 Alluvial gley soils, 8.2 Sandy gley soils, 8.3 Cambic gley, 8.5 Humic-alluvial gley soils, 8.6 Humic-sandy gley soils 8.7 Humic gley soils	1.3.2 Mineral alluvial soils, 4.2.3 Humic gleys
5p Ground-water gley (peat depth 5cm - 45cm)	8.1 Alluvial gley soils, 8.2 Sandy gley soils, 8.3 Cambic gley, 8.5 Humic-alluvial gley soils, 8.6 Humic-sandy gley soils 8.7 Humic gley soils	1.3.3 Peaty alluvial soils, 4.2.4 Peaty gleys
5pf Ground-water gley (peat depth 5cm - 45cm), flushed	8.1 Alluvial gley soils, 8.2 Sandy gley soils, 8.3 Cambic gley, 8.5 Humic-alluvial gley soils, 8.6 Humic-sandy gley soils, 8.7 Humic gley soils	1.3.3 Peaty alluvial soils, 4.2.4 Peaty gleys (surface water)
6 Peaty gley (peat depth 5cm - 25cm) 6a, 6c, 6e, 6f, 6s, 6l, 6la, 6le, 6lf, 6lfs, 6lp, 6lpe, 6s, 6x, 6xe, 6xse Peaty gley (peat depth 5cm - 25cm), shallow/ cultivated/ ericaceous/flushed/loamy/stony/loamy/peaty/indurated	7.2 Stagnohumic gley soils 7.21 Cambic stagnohumic gley soils, 7.23 Paleo-argillic stagnohumic gley soils	4.1.6 Peaty gleys (Ground water) 4.2.4 Peaty gleys (surface water)
6p Deep peat, peaty gley (peat depth 25cm - 45 cm) 6pf Deep peat, peaty gley (peat depth 25cm - 45 cm), flushed	7.2 Stagnohumic gley soils 7.21 Cambic stagnohumic gley soils, 7.23 Paleo-argillic stagnohumic gley soils	4.1.6 Peaty gleys (Ground water) 4.2.4 Peaty gleys (surface water)
6z Podzolic peaty gley (peat depth 5cm - 25cm)	6.43 Stagnogley-podzols	4.1.6 Peaty gleys (Ground water) 4.2.4 Peaty gleys (surface water)

6za, 6ze, 6zl, 6zlp, 6zp, 6zs, 6zx, 6zxe, 6z(x), 6zxse Podzolic peaty gley (peat depth 5cm - 25cm), shallow/ ericaceous/loamy/loamy/peaty/ indurated	6.43 Stagnogley-podzols	4.1.6 Peaty gleys (Ground water) 4.2.4 Peaty gleys (surface water)
7h Surface-water gley, humose	7.11 Typical stagnogley soils, 7.12 Pelo-stagnogley soils, 7.13 Cambic stagnogley soils, 7.14 Paleo-argillic stagnogley soils	4.1.5 Humic gleys
12h Calcareous soils (soils on limestone rock), humose	3.14 Rankers. 3.42Grey rendzinas 3.43 Brown rendzinas, 3.44 Colluvial rendzinas	2.2.1 Brown calcareous soils
13p Rankers and Skeletal soils (rankers = shallow soils < 30 cm to bedrock, skeletal = excessively stony)	3.11 Humic rankers	1.4.4 Peaty rankers
15w Sand very shallow water table	8.2 Sandy gley soils 8.6 Humic-sandy gley soils	4.2.2 Noncalcareous gleys