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Understanding carbon sequestration from nature-based solutions

Baggaley NJ[1], Britton AJ[1], Sandison F[1], Lilly A[1], Stutter M[1], Rees RM[1], Reed M[2], Buckingham S[2]

[1]James Hutton Institute, [2] Scotland's Rural College

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1 Executive summary

1.1 Aims

This report examines the potential of nature-based solutions to contribute to Scotland's net-zero emissions target.

The International Union for the Conservation of Nature (IUCN) defines nature-based solutions (NBS) as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits".

Scotland is facing the twin challenges of a climate emergency and biodiversity crisis. Changing the way we use the land and sea is now essential to both store carbon and help society adapt to climate change. Doing so can also help to improve the state of nature, which is experiencing unprecedented threats.

Nature-based solutions feature prominently in the global biodiversity agenda. Vegetation growth and healthy soils, as well as sea floor integrity, provide a crucial way of locking away carbon emissions. However, it is the *additional multiple benefits* unique to nature-based solutions - addressing biodiversity loss, and adaptation to locked-in climate change - that makes them such a crucial part of a net-zero strategy. These are widely regarded as 'no-regret' actions to address climate change, but the evidence base to support their direct impact is complex. As such, further work is required to understand their practical application in Scottish circumstances.

In this study, we assess evidence for the greenhouse gas (GHG) mitigation potential of four nature-based solutions in Scotland (agroforestry, hedgerows, un-cultivated riparian buffer zones and the restoration of species-rich grasslands) and how these can help mitigate the impacts of climate change and reduce biodiversity loss. In addition, we provide a synthesis of the strength of evidence for including these as part of net-zero policy objectives and carbon codes.

1.2 Key findings

Evidence for greenhouse gas emissions and carbon stocks

- There is some evidence that above-ground carbon sequestration is increased by expanding tree and woody vegetation cover in agroforestry, hedgerows and riparian buffer zones.
- There is very limited evidence for species-rich grassland restoration increasing above ground carbon sequestration.
- Evidence for the effects of all four nature-based solutions on soil carbon sequestration is limited.
- The net GHG mitigation potential (the balance between sequestration and emission of all greenhouse gases) of the four nature-based solutions was found to be a function of local climate, soil type (particularly whether soils are mineral, have an organic surface layer or are deep peat), soil wetness and previous land use.
- Changes in carbon concentrations can act as an 'early warning' but the most robust way to assess changes in soil organic carbon (SOC) is to calculate soil carbon stocks to depth, which implies measuring the thickness of individual soil horizons (layers), carbon concentration, soil density and stone content.
- Where vegetation is deep rooting, such as agroforestry, hedgerows and riparian buffer zones, SOC stocks should be measured to at least the maximum rooting depth
- Vegetation carbon stocks are lesser than those in the soil but are more seasonally variable. Quantification of these stocks should take account of the longevity of different vegetation components (e.g. wood vs leaves) and whether there is removal of biomass as part of habitat management (e.g. hay cutting or hedgerow trimming).

Evidence for multiple benefits

- Agroforestry and other types of woodland planting, including hedgerows, help reduce soil erosion, decrease freshwater sedimentation and increase biodiversity.
- Increasing the area of species-rich grassland will increase terrestrial biodiversity.
- Achieving maximum benefits from nature-based solutions will require land to be managed at a landscape-scale, considering both the preservation of existing carbon stocks and habitats and the benefits of implementing nature-based solutions for carbon sequestration and climate change mitigation. This will ensure that the right measure is implemented in the right place.

Implementing nature-based solutions as part of Net Zero policy objectives

- There is a large amount of uncertainty regarding the GHG mitigation potential of the four nature-based solutions considered in this report.
- The inclusion of these nature-based solutions in new or current carbon codes requires further evidence to verify the potential carbon stock increases and their permanency, both within the soil and the vegetation.
- Changes in climate will impact on the ability of the four nature-based solutions considered here to sequester and store carbon.
- There is a need to ensure that offsetting GHG emissions and that implementing these nature-based solutions does not lead to offshoring of emissions or other damaging environmental impacts due to the displacement of land uses.

Table 1: Summary of the evidence found and the amount and agreement of the evidence for increasing carbon stocks, reducing greenhouse gas emissions and increasing biodiversity. Greater confidence in the science for decision making comes where there is a lot of evidence that shows good agreement.

Lots of evidence	Some evidence	Lack of evidence	
✚✚	✙✙	?	Good Agreement
✚	✙		Poor Agreement

	Parameters				
Nature Based Solutions	Vegetation C stock	Soil C stock	GHG emissions	Biodiversity	
Agroforestry	✙✙	✙	?	✙✙	**Agroforestry** has some evidence for an increase in vegetation and soil carbon stocks and improving biodiversity. However, there is a clear knowledge gap in evidence that demonstrates the implications of agroforestry on GHG emissions in areas with similar climate and soils as Scotland
Riparian buffer zones*/**	✙✙	?	?	✙✙	**Riparian buffer zones** have some evidence for an increase in vegetation and biodiversity but again, there are clear knowledge gaps relating to the impact of riparian buffer zones on soil carbon stocks, GHG emissions and biodiversity richness.
Hedgerows*	✙	✙	?	✚✚	There is good evidence that **hedgerows** lead to an increase in biodiversity and some evidence for an increase in soil and vegetation carbon stocks. Again, there is a clear gap in evidence showing the impact of hedgerows on GHG emissions.
Species-rich grasslands	?	?	?	✚✚	There are clear gaps in the evidence for the impact of restoration of **species-rich grassland** on soil and vegetation carbon stocks, and GHG emissions. There is good evidence for an increase in biodiversity after restoration.

*** Assumption that for buffer zones and hedgerows are assessed relative to adjacent managed agricultural land** Assumption that buffer zones include an increase in woody scrubs or trees**

Table 2: Summary of the evidence found and the confidence in the conclusions for increasing carbon stocks, reducing greenhouse gas emissions and increasing biodiversity for 4 nature-based solutions.

	Evidence	Confidence
Soil and vegetation carbon stocks		
Agroforestry	• Available studies show a positive effect of agroforestry on soil and vegetation stocks. • These impacts will be site specific depending on the yield and species of trees which are a function of soils, topography and local climate.	• Overall evidence is limited for Scotland and similar temperate regions. However, the evidence available is in good agreement.
Riparian buffer zones	• There is limited evidence for the change in vegetation carbon stocks in riparian buffer zones but where trees have been integrated into the buffer there is some evidence of increasing stocks. • There is a lack of evidence in the changes in soil carbon stocks from adding uncultivated riparian buffer zones	• There is much greater uncertainty for narrow buffer zones than for wider areas of tree planting.
Hedgerows	• There is no Scottish specific data or models for soil or vegetation carbon stocks in hedgerows. • Data from England or Wales are based on only a few empirical studies, based on a limited number of research sites • Modelled data is largely based on underlying datasets from agriculture or woodlands. • Evidence suggests there could be greater soil carbon sequestration potential in hedgerows in arable fields than for those in grasslands although the ranges in SOC change include no sequestration.	• There is a very limited number of studies and lack of agreement in sequestration rates in both vegetation and soils • Modelling results for carbon sequestration in vegetation are based on non-hedgerow specific data. •
Species-rich grassla	• The size of vegetation and soil carbon stocks in semi-natural grassland varies between grassland types and is influenced by soil type, climate and management regime. • There is very little evidence of the effects of increased plant richness on carbon stocks - a single study	• Differences in carbon stocks between the main grassland types are well established from national survey data, but Scottish evidence on the effects of management regimes on carbon stocks is lacking. • The evidence base on the effects of increasing plant richness in semi-natural grasslands is very limited, with no evidence

	suggests increased carbon storage. Reduction in grazing pressure to enable grassland restoration may enhance soil carbon stocks.	from Scotland. There is consistent evidence on the effects of grazing reduction/removal in upland semi-natural acid grassland, but no evidence for other grassland types.
•	• Evidence	• Confidence
• GHG emissions		
• Agroforestry	• Empirical data available is mainly for tropical and Mediterranean regions with limited data for GHG emissions from agroforestry in temperate zones. • Benefits of agroforestry in terms of GHG mitigation are inferred from forestry land use. • There is limited empirical evidence on the net GHG effect of agroforestry for Scotland-specific land uses, climate and soil types.	• No robust conclusion can be drawn on the effects of agroforestry on net GHG emissions in Scotland.
• Riparian buffer	• There is some research into GHG emissions in riparian zones and it shows that it is a function of soil wetness. • There is also some evidence of increasing nitrous oxide emissions where buffers become enriched in nitrogen from run-off.	• No robust conclusions can be drawn on the effects of introducing a managed buffer zone on net GHG emissions.
• Hedgerows	• There is no information at this time on potential GHG emissions from hedgerows in Scotland.	• A lack of data and evidence means no conclusions can be drawn.
• Species rich grasslands	• There is little evidence on the effects of increasing plant species-richness on greenhouse gas emissions from semi-natural grasslands. • Where reductions in fertiliser use and grazing intensity occur as part of management to increase grassland species richness, this would contribute to reduced emissions.	• Evidence on the effects of grassland plant species-richness restoration on greenhouse gas fluxes is lacking for semi-natural grasslands, with no data from Scotland.

	Evidence	Confidence
Biodiversity		
Agroforestry	Evidence available demonstrates agroforestry to have a beneficial influence on biodiversity.	Overall evidence is limited for Scotland and similar temperate regions. However, the evidence available is in good agreement.
Riparian	• Increasing native plant species in riparian zones can increase biodiversity with respect to the neighbouring agricultural land. • Stream shading can also improve in-stream biodiversity.	There is some Scottish evidence for this.
Hedgerows	Hedgerows are shown to have a strong positive impact on biodiversity.	Although the data is not Scotland specific, multiple studies utilising multiple indicators and species show a high degree of agreement.
Species rich grasslands	• Increasing plant species-richness in semi-natural grasslands has clear benefits for biodiversity, both of plants and of associated species (e.g. invertebrates, birds) both above and below ground. • Where grazing intensity is altered to achieve grassland restoration, there may be trade-offs between different species groups with both winners and losers.	• Data from a wide variety of sources show that restoration of plant biodiversity in grasslands has benefits for other elements of biodiversity. • Research on the effects of grazing reduction/removal includes Scottish studies on upland acid grassland, but there is little evidence from other Scottish grassland types.

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Appendices

2 Nature-based solutions

Scotland is facing dual challenges of a climate emergency and biodiversity crisis. Optimising land management practices is essential for the conservation and enhancement of soil carbon sequestration to contribute to climate change mitigation, ecosystem services and provide system resilience. It is vital for land practitioners to adapt to changes in climate that exist as a result of previous and ongoing emissions, and to contribute to the improvement of ecosystem health, which is currently experiencing unprecedented threats.

Vegetation growth and healthy soils, as well as sea floor integrity, provide a crucial way of locking away carbon emissions, but it is the *additional multiple benefits* unique to nature-based solutions (NBS) - addressing biodiversity loss, and adaptation to locked-in climate change - that makes them a crucial part of a Net Zero strategy. These are widely regarded as 'no-regret' actions to address climate change, but the evidence base to support their direct impact is complex.

Nature-based solutions now feature prominently in the global biodiversity agenda. This brief seeks to identify confident knowledge and key gaps for sustainable management practices in Scotland on a selection of priority habitats.

2.1 The concept

The International Union for the Conservation of Nature (IUCN) defines nature-based solutions as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits". 'Nature-based solutions' is an umbrella term for actions that achieve multiple objectives relating to sustainable land management, climate change mitigation, climate change adaptation and the preservation of biodiversity. The advantage of using such approaches to address major societal challenges is that they reinforce natural processes and are widely supported through public opinion to offer a valuable approach to sustainable land management. There are however many challenges associated with nature-based solutions. These include:

- Adequately defining NBS.
- Analysing trade-offs between the different ecosystem services offered through NBS based management practices.
- Defining circumstances in which NBS are additive to baseline conditions.
- Developing appropriate measurement, monitoring reporting and verification procedures which can quantify change in baseline conditions.
- Identifying appropriate biodiversity targets to which NBS can contribute.
- Accommodating NBS within an integrated land-use strategy framework in Scotland.
- Integrating NBS within new or existing funding mechanisms.

These issues are discussed within the report in the context of specific examples.

2.2 Current understanding

Interest in NBS as an approach to tackling environmental concerns in the land-based sector has expanded rapidly. Four recent reports provide a valuable assessment of the current capability and knowledge gaps on this topic and make a useful contribution here.

2.2.1 Natural England 2021

Natural England 2021 produced a report entitled "Carbon storage and sequestration by habitat: a review of the evidence"[1]. It set out to review the evidence supporting the role of carbon sequestration in semi-natural habitats in contributing to climate change mitigation. It concluded that "there is a need to be realistic: it is not possible to offset anything close to current UK emissions across the different sectors of the economy through better environmental management alone"[1]. Nature-based solutions were not considered as an alternative to deep cuts in greenhouse gas emissions across all sectors but as an option to complement them in mitigating the residual, "hard to-eliminate emissions"[1].

2.2.2 The Environment Agency 2021

Similar conclusions were reached by a recent report by the Environment Agency (Beechener et al 2021) [2]. The reports reviewed a wide range of terrestrial and aquatic approaches to carbon offsetting in the UK. Whilst strengths and weaknesses were recognised in different approaches, there was no silver bullet that could offer major opportunities for greenhouse gas mitigation by nature-based solutions. They also drew attention to the lack of accredited carbon offsetting standards within the UK which currently are limited to the 'Woodland Carbon Code' and the 'Peatland Code'.

2.2.3 House of Lords Science and Technology Committee

A recent report by the House of Lords entitled "Nature-based solutions: rhetoric or reality?"[3] analyses the role of nature-based solutions in contributing to climate change mitigation. They recognise opportunities in the management of peatlands, woodlands, agricultural land and marine environments in contributing to greenhouse gas mitigation, but they also identify a number of concerns. These include:

- Significant scientific uncertainties in the magnitude of the amounts of greenhouse gas mitigation that are possible.
- A lack of skills in the land-based sector to deliver potential benefits.
- Insufficient development of policies to support the delivery of benefits associated with NBS.
- A lack of research funding to improve our understanding of the opportunities available.
- Lack of the overarching land use strategy policy within which NBS would operate.

The report also argues that NBS should not be considered as an alternative to mitigation and suggests a more integrated approach together with other options to reduce greenhouse gas emissions in line with policy targets. Significant concerns were also expressed around the capacity for monitoring, reporting and verification of emissions reductions linked to the development of market-based solutions. They state "The market can incentivise investment in nature-based solutions. But the rush to develop new markets, with bottom-up initiatives, risks creating inconsistently regulated offsetting markets that do not deliver benefits to nature"[3].

2.2.4 British Ecological Society: Nature-based Solutions for Climate Change in the UK

The BES report[4] recognises the importance of nature-based solutions in tackling climate change. It identifies the benefits of nature-based solutions for human health and prosperity, the need for clear and appropriate policy in order to achieve the desired outcomes. This includes the identification of appropriate times and locations in which to implement NBS, and the generation of direct evidence to support policy development.

Carbon storage by habitat: Review of the evidence of the impacts of management decisions and condition of carbon stores and sources - NERR043 (naturalengland.org.uk)

[2] Beechener, G., Curtis, T., Fulford, J., MacMillan, T., Mason, R., Massie, A., McCormack, C., Shanks, W., Sheane, R., Smith, L., Warner, D., Vennin, S., 2021. Achieving Net Zero : A review of the evidence behind potential carbon offsetting approaches

[3] House of Lords, 2022. Nature-based solutions: rhetoric or reality? https://committees.parliament.uk/publications/8646/documents/87644/default/

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

2.3 This report

There are many land management practices that can contribute to NBS, however this report focuses primarily on four practical options that are applicable to Scottish agricultural and grassland sites. Therefore, this report will not include carbon sequestration potential through NBS that are likely to be applicable peatlands, wetlands or marshlands.

Based on agreement with the steering group, and the priorities of NatureScot for this report, this review is confined to four nature-based solutions. These are:

- Agroforestry
- Implementing un-cultivated riparian buffer zones
- Hedgerows
- Species rich grasslands

Our approach to the search for evidence is set out in Appendix 1.

3 Carbon sequestration through nature-based solutions: evidence review

3.1 Agroforestry

3.1.1 Introduction

Agroforestry systems are land use management systems in which trees are grown in combination with crops or pasture in the same field. In silvo-arable systems, trees are intercropped with arable crops, and in silvo-pastoral systems trees are combined with pasture for livestock (Cardinael et al 2017). Agroforestry systems take many forms including shelterbelts, widely spaced trees, groups of trees, hedgerows and woodland grazing (Perks et al 2018). The addition of trees in cultivated landscapes can contribute to carbon sequestration, greenhouse gas mitigation and Net Zero carbon targets through the photosynthetic removal of atmospheric carbon dioxide (CO_2), which is subsequently stored in biomass and soils.

Figure 1: Silvo-pastoral agroforestry at Glensaugh (A James Hutton Institute farm)
https://www.hutton.ac.uk/about/facilities/glensaugh/agroforestry

Using the Land Use/Cover Area frame Survey (LUCAS), Burgess et al (2018) estimated livestock agroforestry was, by far, the dominant type of agroforestry in Europe accounting for 15.1 million hectares. Agroforestry involving hedgerows covers about 1.78 million hectares (around 0.42% of the territorial area in the EU), with large areas in France, the UK, and Italy (Burges et al 2018). In Scotland, arable hedgerow length was reduced by half, from over 40,000 km in the 1940s to under 20,000 km in the 1980s (SNH, 2009) highlighting an opportunity for increasing biomass through agroforestry involving hedgerows (see Section 3.3). Modern commercial agroforestry systems such as silvo-arable and silvo-pastoral systems integrating trees into agricultural systems are in their infancy in the UK but becoming increasingly widespread across a number of European countries where policy support is available for establishing new systems (Lampkin et al 2015). The Committee on Climate Change (CCC) highlight that conversion of 0.6% of agricultural land area in the UK to agroforestry (the introduction of trees alongside crops and pasture-based land uses) could contribute significantly to meeting the fifth carbon budget target by 2030 (Soil Association 2018) although the extent of the land area of Scotland that could be converted to agroforestry, and where it occurs, was not explicitly specified. However, the CCC (2017) outline that the level of savings included in the assessment corresponds to around an additional 0.6% of UK agricultural land area on top of the 1% of land that is currently used for hedgerows and shelter belts and that this serves as a useful proxy for broader agroforestry activities in the absence of any official estimates. More recently the CCC (2020) state that planting trees on agricultural land, while maintaining their primary use (“agroforestry”), could deliver a further 6 Mt CO2e savings by 2050, however it is not clear where this value originates from. Agroforestry is not explicitly discussed in the Scottish Government’s forestry strategy or the CCC (2019) report outlining the UK's contribution to stopping global warming but is mentioned in Scotland’s Climate Change Plan (2018-2032) (Scottish Government, 2020).

3.1.2 Carbon storage potential in agroforestry systems

It is reported that significant carbon and greenhouse gas emission savings can be made through silvo-pastoral agroforestry systems in which woodlands or forests are integrated with forage and livestock production systems (Saunders et al 2016). In general, all forms of agroforestry have the potential to sequester carbon through increased photosynthetic activity, although the benefits will vary depending on soil type, species, planting density and location (Perks et al 2018). However, a key point to raise is that the majority of evidence available originates from tropical, Mediterranean or modelling studies. Few studies have assessed the impact of agroforestry systems on carbon storage in soils in temperate climates; as the majority of research has been undertaken in tropical regions (Cardinael et al 2017).

In relation to Scotland, evidence suggests that maximum carbon sequestration benefits on a per-hectare-basis might be achieved on the highly productive lowland areas, although potentially at a high agricultural opportunity cost (Perks et al 2018). Saunders et al (2016) outline outputs of a Scottish modelling exercise by Sibbald (2006) that showed the net carbon uptake of a low tree density silvo-pastoral agricultural system can be increased by between 55 to 107 t C ha^{-1}, over a 55-year period of growth, compared to a traditional pasture system depending on site productivity.

Beckert et al (2015) studied changes in the soil organic carbon (SOC) stocks beneath the trees at the Glensaugh agroforestry plots 24 years after planting and compared the stocks under the different tree spacings and between tree species. They found that total SOC stocks did not differ overall between treatments. Although stocks within the larch and Scots pine at 400 trees ha^{-1} density were greater than the stocks under the commercial-spaced woodland plots (2500 trees ha^{-1}), the opposite held for the Sycamore plots. The woodland spacings (2500 trees ha^{-1}) stored more carbon in the labile fractions and in the litter layers than the grassland control plots.

3.1.3 Multiple benefits of agroforestry

The incorporation of trees into agricultural landscapes is gaining more attention. Trees can help with soil stability, air quality, flood prevention and overall biodiversity. Trees integrated into arable settings have been proven to reduce soil erosion by up to 65% (Soil Association, 2018). The loss and degradation of soils in the UK is an important concern as a recent study showed an annual cost of £1.2 billion for soil degradation in England and Wales with almost half of the loss being related to the loss of soil organic matter, 40% due to compaction and 12% to soil erosion (Soil Association Handbook, 2019). Soil erosion in Scotland was estimated to cost around £50 million including the cost for the loss of soil carbon and essential soil nutrients (Nitrogen, Phosphorous and Potassium) and of bringing polluted waters up to drinking water standards (Rickson et al 2019).

Pardon et al (2018) outline the multiple benefits of agroforestry systems in combination with production and environmental enhancement and the delivery of ecosystem services. Benefits include greater carbon sequestration and erosion control. Agroforestry systems can provide multiple benefits, including diversification of farm income, shelter for livestock, fuelwood, carbon sequestration, nutrient management, reductions in soil erosion and leaching, biodiversity enhancement, and amenity value (Saunders et al 2016, Staton et al 2019, Cardinaela et al 2017). Several reviews and meta-analyses have demonstrated that temperate agroforestry systems generally enhance biodiversity and some ecosystem services compared with arable cropping. A meta-analysis (365 comparisons from 53 publications) by Torralba et al (2016) found an overall positive effect of agroforestry over conventional agriculture and forestry, with erosion control, biodiversity, and soil fertility enhanced by agroforestry.

Benefits of woodland on agricultural land can be the provision of shade and shelter for livestock (e.g. open woodland for poultry production), the reduction of agricultural ammonia emissions, enhancement of biodiversity, improved water management and the potential for an additional income stream from fuel and timber production (CIEL 2020). However, these benefits assume good woodland management practices, including the management of deer pressure (Perks et al 2018).

Padron et al (2018) state that the occurrence and magnitude of beneficial interactions appear to be strongly linked to the design and management of the agroforestry system, the prevailing environmental conditions (climate, soil type, etc.) and the in-field location, with variations in growing conditions (both among and within agroforestry systems) in turn affecting the yield and development of the cultivated intercrops. Torralba et al

(2016) conclude that agroforestry can enhance biodiversity and ecosystem service provision relative to conventional agriculture and forestry in Europe; this could be a strategically beneficial land use in rural planning if its inherent complexity is considered in policy measures. Staton et al (2019) outlined that silvo-arable systems can contribute to sustainable intensification by enhancing beneficial invertebrates and suppressing pests compared with arable, but future research should include measures of pest control and pollination and implications for productivity and economic value. However, they also outlined that the effects of silvo-arable systems on pest control and pollination services remain poorly understood in temperate regions, noting no comprehensive review, despite the importance of these services for sustainable intensification.

A number of improved, intensively managed grassland fields at Glensaugh hill farm in Kincardineshire were planted with trees in 1988 at three different densities. The intention was to investigate the effects of agroforestry systems on a range of environmental benefits and on livestock production systems. Three tree species (Scots Pine, Larch and Sycamore) were planted at densities of 100, 200, 400 and 2500 trees per hectare, the latter representing commercial woodland densities as a comparator (Sibbald et al 2001). No evidence on the effect of livestock production was found although both the tree density and height were found to have a marked impact on grass growth with the shortest and most dense Sitka spruce trees decreasing grass growth by up to 90% and the tallest, widest spaced trees (8m tall and 8m apart) reducing grass growth by only 15% (Sibbald et al 1991). This demonstrates the importance of tree density as a key consideration in the development of agroforestry and to be tailored to specific land uses across Scotland. The implications of tree density and height are that herbage production is less in the early years of tree growth. McAdam et al (2007) found an increase in invertebrates within the agroforestry system and a consequent increase in the number of birds (for further details see Appendix 2).

3.1.4 Considerations for agroforestry in Scotland

During the planting of trees or land use change to forestry, there is the potential for increased soil carbon (C) loss via soil disturbance, which can release carbon dioxide back into the atmosphere. All soils can release carbon when disturbed (such as that from tree planting or ploughing), however it is worth considering that there is a need to balance the conservation of high carbon content soils in Scotland (organic and organo-mineral soils) with the potential net soil carbon loss through agroforestry development. The extent to which carbon loss varies across all soil types during tree plantation has not yet been fully quantified and likely varies with original land use, soil type, planting method and the type of agroforestry (Lilly et al 2020). Saunders et al (2016) suggest 12 to 20 years (depending on yield class) are required for broadleaf systems to recover in terms of soil carbon lost during land conversion (from managed grassland to silvo-pasture).

There is a new (established March 2020) agroforestry site at SRUC Kirkton & Auchtertyre Farm comprising 100 trees per hectare including Alder, Downy Birch, Aspen, Gean, Pedunculate Oak and Rowan. The 0.5 ha area has been designed so that sheep will still be able to graze the pasture. This equates to trees being spaced 7.14m apart (i.e., 5 trees wide and 20 trees long). Clearly, as this site is newly established, there is limited data available, however this will allow for further Scottish-relevant empirical data to be collated in the future.

CIEL (2020) state that the strategy of applying agroforestry within the UK has high technological readiness, with sufficient knowledge and understanding for implementation and for carbon sequestration potential. They also argue that, compared to other strategies for mitigating greenhouse gas emissions in livestock systems, agroforestry has a relatively low cost. However, the uptake of agroforestry in the UK has been limited (Abdul-Salam et al 2022).

A key consideration is the additional financial commitments required. One study reports additional costs in the first 10 years, associated with the establishment, pruning, tree maintenance and insurance of forested areas which can result in an additional £30-70/ha/year (Burgess et al 2003). Lampkin et al (2015) outlined a commercially successful example of agroforestry in the UK through the production of ‘Woodland Eggs’ which involved organic and non-organic free-range eggs and chickens produced from approved ‘woodland farms’ where chickens have access to woodland.

Tree growth is dependent on soil, climate and topography meaning some land will be suitable for agroforestry and other areas will be less likely to support tree growth. A landscape scale approach to identifying sites suitable for agroforestry in Scotland is therefore needed. The Native Woodland Model shows that trees can grow over large swathes of Scotland (SNH., 2004). However, in a CXC report outlining Scottish agroforestry (Saunders et al 2016), the authors state that large areas of Scotland are unsuitable or unavailable for tree planting, such as the deep peat soils in uplands, prime agricultural areas or some of the land that has conservation or heritage status where tree expansion is not deemed desirable. Saunders et al (2016) also state that whilst heritage and conservation status land is likely to be excluded as an option for agroforestry in Scotland, the current perception for potential loss of productive land has led to a reluctance among land owners to convert agricultural areas exclusively to woodlands or forests (Duesberg et al 2013). Perks et al (2018) suggest that Scotland-wide, significant benefits are also possible on the less productive lands, by avoiding disturbance of organic soil layers.

Teklehaimanot (2002) showed that livestock productivity was unaffected by the presence of trees during a six-year establishment phase where trees were planted in a clumped pattern. The study also showed benefits for tree growth from maintaining livestock production while trees are established. Padron et al (2018) highlighted that a research gap exists in quantitative data about the performance (yield and quality) of crops (maize, potato wheat and barley) in temperate silvo-arable systems, which is likely due to wide variation in ability of crops to adapt to intercropping within an agroforestry system. At Glensaugh agroforestry experimental site, Scotland, by the time the experiment ended in 2001, there was no measurable reduction in sheep output, although production of grass in closed canopy plots of larch and sycamore has subsequently declined[1]. In addition, a new timber source had been created and a positive impact made on the landscape, and its biodiversity value.

Scottish Forestry (2020) outline forestry grant approvals for 2020/21 already cover 9,000 hectares, with a further 7,000 hectares of applications being worked on, however it is not noted what proportion of these relate to agroforestry. Therefore, the contribution agroforestry plays in Scottish carbon sequestration is unclear. Perks et al (2018) concluded that there is a lack of quantitative information on the extent of (and trends in) agroforestry in Scotland and that filling this evidence gap would provide a benchmark against which to judge future developments in Scottish agroforestry.

It is also worth noting that Torralba et al (2016) show that the available evidence for the societal benefits of agroforestry is fragmented and does often not integrate diverse ecosystem services into the assessment. Soil Association (2018) highlight that there is a lack of financial support as ‘agroforestry’ falls into a funding gap as the number of trees planted in agroforestry style systems fall below the minimum of 400 trees ha^{-1} required

[1] https://www.hutton.ac.uk/about/facilities/glensaugh/agroforestry

for woodland creation grants, and there is uncertainty as to whether eligibility can be sought under the Basic Payment Scheme as its interpretation lies with individual Rural Payment Agency inspectors. Soil Association (2018) state that there is a lack of knowledge, practical guidance and clarity on where to access advice on agroforestry within current farmer and forester advice networks; however for land managers interested in agroforestry there is useful practical guidance available in the Soil Association Agroforestry Handbook and the Highlands & Islands Woodlands Handbook. In addition, there are some grant schemes that land managers can apply to for financial support. Some of this is directly targeted at agroforestry, for example the Forestry Grant Scheme (FGS) to help create small-scale woodlands within sheep grazing pastures, with others being more directed at hedge or woodland expansion (Table 3).

Table 3: Advice and funding mechanisms available for Agroforestry in Scotland

Source	Funding mechanism	Details	Additional information
The Woodland Trust	**MOREwoods**	Anyone planting over half a hectare can speak to an expert advisor to get help designing a woodland. The Woodland Trust can cover up to 75% of the cost of this.	https://www.soilassociation.org/our-work-in-scotland/scotland-farming-programmes/resources-for-farmers/agroforestry/grants-and-guidance-on-agroforestry/
	MOREhedges	Through this programme, the Woodland Trust can subsidise up to 75% of the cost if planting more than 100 metres of new hedging allowing a large tree to grow every six metres.	
	Croft Woodlands	The Woodland Trust have four advisors who can assist with new planting proposals and assist with applications for funding.	
Scottish Forestry and Scotland's Farm Advisory Service (FAS)	In partnership with the **Scottish Tenant Farmers Association** and a Crown Estate Scotland tenant, FAS have produced a woodland creation case study to encourage more tenancy based businesses to consider growing trees. The case study is based on fully worked examples on a real tenanted farm.		https://forestry.gov.scot/support-regulations/farm-woodlands
	Financial support is available through the **Forestry Grant Scheme (FGS)** to help farmers create small-scale woodlands within sheep grazing pasture. The grant has two payment types:		Financial Support for Small-scale Woodland Creation within Sheep Grazing Pasture - Jun 2020

	• A capital grant for initial establishment • An annual maintenance grant that is paid for five years The rate of capital grant that can be claimed depends on the number of trees per hectare. Two stocking levels and grants are available. To be eligible for this grant one must own or lease the land the woodland will be created on.	

3.1.5 Evidence gaps

As mentioned, there is limited empirical data for Scottish-relevant agroforestry. Another issue to consider is that potential gains from agroforestry are often extrapolated or inferred from forestry and woodland expansion studies, which may not account for the complexities that multiple land usage may bring. In addition, some reports discuss increases in biomass more generally with agroforestry being integrated in estimates of overall biomass increase such as woodland, hedgerow or riparian zone expansion, without specifying data directly relating to agroforestry. This further compounds complications in determining specific carbon gains from agroforestry.

3.1.6 Confidence in the evidence available.

There is limited empirical evidence on temperate or Scotland-specific agroforestry. It appears that the majority of information relating to carbon sequestration or GHG mitigation potential is either a) inferred from empirical studies conducted in tropical or Mediterranean zones which does not account for soil types, land uses and climates relevant to Scotland; b) inferred from knowledge gained within the forestry and woodland sectors, which does not consider the complex interaction of agricultural management alongside tree plantation. This is reflected in the literature, where it is not always clear where statements about agroforestry have originated from i.e. whether they are based on agroforestry-specific studies or inferred from forestry/woodland knowledge and which climatic zones the underlying empirical data originates from. Therefore, the limited empirical evidence that directly relates to Scottish agroforestry results in limited confidence.

3.2 Riparian buffer zones

3.2.1 Introduction

Riparian buffer zones are a way of managing field margins along watercourses. Restoration of riparian buffer zones can increase tree and semi-natural scrub vegetation in intensively managed landscapes and sometimes includes managed hedgerows (Stutter et al 2019).

The proximity to watercourses means these measures are often associated with alluvial soils, fluctuating water tables and are at a risk of rapid inundation in the event of floods. The main focus of research into buffer strips has been on their application for improving water quality and increasing both terrestrial and aquatic biodiversity (Cole et al 2020) with more recent studies exploring the GHG emissions in riparian zones (Hadaway et al 2018). Buffer zones, are installed to protect water quality by intercepting runoff containing nutrients, particularly nitrate and particulate phosphorus. In Scotland, riparian buffer zones have been implemented as part of the EU Water Framework Directive where intensively-managed agricultural land has to be set back at least 2 m from water courses. However, they are often wider than this minimum width (sometimes 4->6 m) for funded schemes and some voluntary initiatives.

Figure 2: Left- Established riparian buffer in the Tarland catchment (Aberdeenshire).. Right - Example riparian area in the Tarland catchment (Aberdeenshire) prior to riparian buffer establishment (Bergfur et al 2012)

3.2.2 Carbon storage potential in riparian buffer zones

There is evidence (as with other nature-based solutions) for an increase in above ground carbon storage from both the increase in scrubby vegetation and trees and the removal of intensive cultivation from riparian areas (Greg et al 2021, Fortier et al 2010, 2013). In a review of the literature on the multiple benefits of buffer strips, Cole et al (2021) concluded there was a lack of evidence that the restoration of narrow zones (less than 5m width) had a positive effect on carbon storage. Adding trees to the mix of vegetation in a riparian buffer can increase above ground biomass carbon (Tefkioglu, 2003, Fortier et al 2010, Fortier et al 2013). However, although restored riparian zones were shown to have increased carbon, much of this was in the form of more labile carbon in the litter layer (Pulitano et al 2013) which is susceptible to losses due to runoff events or by riparian inundation. Continued carbon storage relies on the tree growth rate trajectories and there is a lack of evidence on the impact of riparian zone nutrient fluxes and water table dynamics on tree roots and soil carbon accumulation. The results of a global modelling study suggest that the restoration of riparian forestry could lead to increases in soil carbon, but that any increase would be greatest in warm and wet climatic conditions and lesser in a Scottish climate (Dybala et al 2019). Changes in soil carbon tend to occur over decades and evidence of long-term change in soils in riparian buffers is limited (Stutter et al 2021). Stutter et al (2012) used topsoil sampling across 57 Scottish sites, where it was anticipated that the buffers had been out of cultivation for 3-5 years or more, to compare established riparian vegetated (grass, shrub, trees), buffer zones and adjacent agricultural cropland and grassland. They found that buffer topsoils had significantly ($p<0.001$) greater soil organic matter concentrations (as measured by loss on ignition) and extractable Dissolved Organic Carbon (DOC), but significantly reduced soil bulk density ($p<0.001$) than the nearby cultivated agricultural soils. As a result, the areal Organic Matter stocks in topsoil (concentration * bulk density) did not differ. (for further details see Appendix 3).

3.2.3 Considerations for riparian buffer zones in Scotland

Recent research on GHG emissions from riparian zones has focussed on short term studies exploring the processes and inherent landscape characteristics that may drive them. Changes in microbial community composition (Soosaar et al 2011) and earthworm communities (Bradley et al 2011) have been identified as drivers of these processes. Greater soil carbon in riparian soils has also been identified as a potential driver for an increase in nitrous oxide emissions compared to emissions from non-riparian soils (Roberts et al 2013). Shallow water table dynamics have also been shown to increase methane emissions from riparian soils (Pobladar et al 2017) and the dynamics of these emissions have been shown to change over time with vegetation growth and vary spatially depending on the geomorphological setting (Welsh et al 2021). Where riparian zones receive runoff from agricultural land, it has been suggested that they may become saturated with nitrate potentially becoming a source of emissions and lead to a deterioration in water quality over time (Haddaway et al 2018). Vidon et al (2018) identified that most riparian research has focussed on the removal of subsurface nitrates and concluded that there were no consistent benefits for GHG emissions but suggest that 2 stage channels (where artificially-steepened channel banks are reformed to give a shallower channel, then mini-floodplain stage) and short rotation forestry could be options for dealing with these and other issues.

Based on measuring methane and nitrous oxide emissions in riparian zones of forested headwaters in Vancouver, Silverton et al (2021) suggest regular harvesting of buffer vegetation could maintain a methane sink; however they highlight the importance of maintaining native forest without management for the protection of other ecosystem services. Stutter et al (2009) suggest that this kind of management may also be required for preventing phosphorus saturation and release.

3.2.4 Multiple benefits of riparian buffer zones

Riparian buffer zones have been shown to improve water quality and increase both aquatic and terrestrial biodiversity (Hadaway et al 2018, Stutter et al 2021). Cole et al (2020) suggest that, due to the interaction and flow of nutrients in agricultural landscapes, it is important to implement good in-field soil management practices to reduce nutrient inputs to riparian buffers and they shouldn’t be viewed as an “end of pipe solution”. Reducing the export of nitrates reduces the risk of nitrate saturation in buffers and the risk of re-release into the environment as nitrous oxide or into water courses as nitrate, contributing to issues of diffuse pollution. This review also suggests that zoned buffers (grass filter strip for trapping sediment-to native tree zones for assimilating nitrates and bank stability from field toward banks) address the trade-offs between the multiple ecosystem services that are expected from buffer zones. In addition, natural flood management can include the introduction of wetlands and ponds in riparian zones. However, Cole et al (2020) suggest that large buffers may not be accepted as a solution where they take a large proportion of cultivated land out of production, particularly with the likely associated loss of income. In a review of agri-environmental schemes, Clements et al (2021) suggest that cooperative agreements between farmers could be an effective way to achieve landscape scale objectives, however they identify that achieving this would be a complex process.

As part of a large-scale nature restoration approach, the Scottish “Riverwoods” project is an initiative that promotes riparian woodland planting for the primary purpose of improving biodiversity, including benefiting dwindling Atlantic salmon populations, and the creation of woodland corridors between areas of existing woodland.

3.2.5 Evidence gaps

Current research is focussed on *right measure, right place* approaches with different designs of buffers being considered to achieve multiple objectives of water quality, biodiversity and more recently carbon storage. Designs include the management of artificial subsurface flow and locations and widths that better intercept flow pathways (Zak et al 2019).

The gap in riparian-specific data is highlighted in a study assessing the cost-benefits of riparian restoration in New Zealand, (Daigneault et al 2017), where the assessment of the potential for tree planting was based on other soil and geomorphological settings. Research is lacking on the impact of riparian buffers on long term changes in soil carbon storage. There is also a lack of studies where buffer functioning, including carbon storage and GHG emissions, are quantified and compared to non-buffered areas in the same hillslope (Vidon et al 2018). Further research in this area would allow a better understanding of the relationship between inherent riparian soil and water dynamics and the potential for management to change GHG emissions and carbon storage.

There is also an overall lack of studies in the UK and in Scottish climates. In addition, many riparian areas in Scotland that are intensively managed for agriculture comprise wet soils and are likely to be artificially drained (Lilly et al 2012). The impact of the management of subsurface drains on net GHG emissions is an area where research is lacking.

3.2.6 Confidence in the evidence available

There is some evidence showing an increase in above ground carbon storage, particularly in buffer zones with trees. However, this is mainly inferred from studies assessing the restoration of larger extents of riparian forestry. In the case where areas of riparian forestry are restored, there is more evidence of the effect of tree planting on nitrogen and phosphorus cycles than carbon storage. Evidence on specific narrow restored zones for the protection of watercourses is limited. Studies have focussed on understanding the processes driving GHG emissions in riparian areas. There is a lack of evidence on the impacts of the management of riparian buffer zones on GHG emissions. Due to the lack of data specifically on the carbon sequestration potential of narrow riparian buffer zones, there is a lack of confidence in changes in carbon storage and GHG emissions. There is more empirical evidence for changes in vegetation carbon stocks. However, empirical data on changes in GHG emissions and soil carbon stocks is too limited to be able to draw conclusions as to whether changes are being driven by a change in management by not cultivating the area, or by the nature of riparian soils and water dynamics more generally. There is also uncertainty related to the long term stability of carbon in soils in riparian zones.

3.3 Hedgerows

3.3.1 Introduction

Hedgerows are actively managed linear boundaries in a farmed landscape. Hedgerows consist of wooded shrub and tree species, and act both as a physical barrier for livestock and as an indication of field boundary. They are associated with arable and pastoral systems, in both upland and lowland settings. Hedgerows can consist of a diverse range of plant species; in Scotland hawthorn (*Crataegus monogyna*) is the predominant species, occurring in 92% of all hedgerows, with smaller amounts of other species such as elder (*Sambucus nigra*, 19%) and ash (*Fraxinus excelsior*, 15%) (Barr et al 2000).

Hedgerows are generally 1–5 metres wide (Holden et al 2019), can be dense or have gaps in their structure, and may encompass the ground and vegetation beneath them, including associated ditches or earth banks (Wolton et al 2014). Hedgerows in Scotland are typically found as field boundaries in intensively managed lowland arable and pasture land. They are relatively rare in the islands and uplands, where fields are more likely to be bounded by fences or walls (Nature Scot 2020).

Figure 3: Examples of hedgerows from NatureScot BAP priority Habitat information sheet https://www.nature.scot/doc/priority-habitat-hedgerows

The decline seen in hedgerow condition is primarily attributed to changes in agricultural policy in the post war period (1945 onwards). During this period, the mechanisation of farming increased, which led to the loss of a large span of hedgerows in order to maximise field space and increase production. Further hedgerows were lost to neglect.

Multiple ecosystem services are provided by hedgerows, including the possibility to sequester carbon in their biomass. This aspect has gained increasing attention in line with concerns over climate change. It is suggested that hedgerows have an important role in meeting Net Zero targets with approximately 40% increase in hedgerow planting anticipated in the projected land use change scenarios in the UK (Committee on Climate Change 2020).

3.3.2 Carbon storage potential in hedgerow vegetation

Direct carbon sequestration is achieved in hedgerows by storing carbon in their biomass as they grow. Research into carbon sequestration by hedgerows in Scotland is absent at the time of this review; evidence across the UK is also limited. Recent empirical UK studies are restricted to works by Axe et al (2015, 2017, 2020), and Crossland (2015). Additional research on the topic has relied on models, based on data from alternative sources such as woodlands and agricultural sites e.g. (Falloon et al 2004; Follain et al 2007; Robertson et al 2012). While a case can be made for use of these proxies, other land use categories do not take into account the unique carbon cycles and management practices associated with hedgerows, which could result in large uncertainty in the modelled results. Hedgerow biomass carbon stock estimates in the literature (reported in (Gregg et al 2021)) were found to vary with hedge height, width management and hedgerow species, from 25 t C ha $^{-1}$ to 131.5 t C ha $^{-1}$.

Below ground biomass is thought to contribute a significant portion of overall hedgerow biomass but can be difficult to measure. Axe (2015) in Gregg et al (2021) correlated a positive relationship between the height and width of the hedge and stored carbon. Later work (Axe et al 2017) estimated the below ground biomass to be almost half that of the above ground though the authors have suggested that this may be an underestimation. It is suggested that the species mix in hedgerows can impact on overall carbon sequestered in the vegetation although the optimum mix of species is debated. Axe et al (2017) suggested that if bramble (*Rubus fruticosus*) were included in the shrub mix of the hedge, overall carbon stored could be increased by 3.8 ± 1.46 t C ha^{-1}. Crossland (2015) also supports this finding, reporting on a difference in sequestration rate in different hedge species. Beechner et al (2021) report that in a single study by Axe et al (2015) unmanaged hawthorn (Crataegus monogyna) potentially sequesters more than blackthorn, which in turn sequesters more than hazel (*Corylus avellana*), with hawthorn estimated to sequester 44.7 t C ha^{-1} yr^{-1}, blackthorn 33.7 t C ha^{-1} yr^{-1}, and hazel 10.5 t C ha^{-1} yr^{-1}. Axe (2018) also suggest that increasing hedgerow width could be the best opportunity to increase hedge carbon sequestration. In addition, the cutting and maintenance regime would have an impact on the amount of carbon stored in the hedgerow biomass.

There are additional studies that model carbon sequestration based on non-hedgerow data and these have reported a wide range of carbon sequestration rates, though these are often less than those reported in the empirical studies**.** For example, Robertson et al (2012) estimated sequestration rates of only 0.47-1.87 t CO_2e ha^{-1}yr^{-1} (0.13-0.5 t C ha^{-1}yr^{-1}). However, their model was based on woodland data in which the woody vegetation is typically much less dense in terms of biomass than that of a hedge. In contrast, Falloon et al (2004) based their model on data from agricultural set aside land and estimated greater sequestration rates of 3.67 t CO_2e ha^{-1}y^{-1} (1 t C ha^{-1}y^{-1}) between the soil and the biomass.

Healthy, managed hedgerows act as a physical barrier separating two adjacent areas. To remain functional, a dense structure is required, which relies on active management. Left unmanaged or pruned excessively, the shrubbery in hedges will progress into trees or the main stems will die, resulting in a loose 'gappy' structure which no longer acts as a practical barrier (e.g. see https://hedgelink.org.uk/). To keep structural integrity, pruning is required along with splitting branches or 'laying' as it is known. Without this regular management, it is estimated that within 40 years, the structure of a hedgerow will be lost and a technique known as 'coppicing' (occurring on a cycle of 15 years) where the hedge is cut back severely to encourage new growth, will be required (Staley et al 2015). Conversely over pruning can equally cause issues to the biodiversity (NERC, 2015a). It is estimated that over trimming has resulted in <50% of UK hedges being in good condition (NERC, 2015b). It is advised that hedgerows should be trimmed every three years to maximise these benefits (https://hedgelink.org.uk/). All maintenance activities remove biomass from the hedge, though coppicing is the most extreme. This loss makes it hard to quantify the net annual carbon sequestration achieved by managed hedges, and it has been suggested that unmanaged hedges may show greater sequestration rates due to the absence of this loss (Crossland, 2015). In contrast, the pruning of managed hedges may in turn result in a greater sequestration rate in their below ground biomass (Beechener et al 2021). This difference between the two hedge management levels is one of the contributing factors to the wide variation found in estimated carbon sequestration rates found in the literature.

The classic 'box hedge' shape is not optimal for carbon sequestration or for its other nature-based benefits. Axe (2018) estimated a potential 2.0 million tonnes of carbon could be sequestered in England and Wales alone by increasing hedgerow width. The addition of trees placed periodically within a hedgerow will increase sequestration rates further. Warner et al (2011) estimated the potential increase in sequestration to be 1.6 t CO_2e ha^{-1} (0.432 t C) if assuming 2 trees per 100 metres of hedge. There will be a direct trade-off between the number of trees established and maintaining the function of the hedge as a barrier as trees can cause gaps within the hedgerow as they grow.

3.3.3 Carbon storage potential in soils under hedgerows

In addition to sequestering carbon within their biomass, hedgerows can increase sequestration of carbon in the surrounding soils. This outcome is a combined function of deeper rooting systems than surrounding vegetation, and by the addition of falling leaves and other organic matter which enriches the soils beneath it (Thiel et al 2015). Holden et al (2019) found that soil organic carbon (SOC) concentration in an arable field was only around 40% of that found under the surrounding hedgerow. The meta-analysis by Drexler et al (2021) reported an average increase in SOC stocks under hedgerows established on cropland of 32 ± 23 %, but no significant differences noted with establishing them on grassland. Gregg et al (2021) conclude that soil under hedgerows is likely to have greater SOC stocks than the surrounding fields, but this will only extend to a narrow band around them and the limited areal extent needs to be accounted for in carbon stock assessments. Ford et al (2019) have suggested the difference in SOC between hedgerows and adjacent fields is equal only to that of any other barrier such as stone walls. It should be noted that if this is the case, then while protection of original SOC stocks beneath hedgerows is still beneficial, it may not count towards sequestration goals, and highlights a potential danger of overestimation of net hedgerow sequestration potential. This study and Ford et al (2021) also highlight that the soil under hedgerows can alternate between being a net sink in non-drought conditions, and a net carbon emitter under drought pressures.

Modelled results from Crossland et al 2015 showed that SOC under unmanaged hedgerows was greater (74-112 t C ha^{-1}) than under managed hedgerows (67-95 t C ha^{-1}) along the same stretch and showed a wide range of modelled soil and vegetation sequestration rates (2.74-12.19 t C $ha^{-1}yr^{-1}$). Modelling by Robertson et al (2012) has suggested that planting hedgerows may result in long term soil carbon sequestration and that it may take longer than 750 years before soils becomes saturated, but they reported much lower sequestration rates than predicted by Crosslands et al (2015) and suggested that the rate of sequestration decreases over time. However, both models are likely to have a large amount of uncertainty associated with them, with Robertson et al (2012) relying on woodland data, while Crossland (2015) used hedgerow-specific data but is reliant on a small number of observations (8 sites in total).

A recent study by Biffi et al (2022) on 5 farms in Cumbria reported a SOC sequestration rate in the upper 50cm beneath mature (37 year old) hedgerows of 1.48 t C $ha^{-1}yr^{-1}$ and by increasing hedgerows in England by 40%, 6.3 Mt CO_2 could be removed from the atmosphere and stored as SOC over a 40 year period. They also found that the difference in SOC stocks between the adjacent grassland field and beneath the hedgerow varied with the age of the hedgerow from 3.3% greater for young (2-4 year) hedgerows to 45.2% for hedgerows > 37 years old. In addition, Thiel et al (2015) highlight that hedgerows planted to increase biodiversity may show greater SOC stocks than those of traditional hedgerows.

3.3.4 Multiple benefits of hedgerows

The benefits of hedgerows are numerous and well documented. They have even been suggested as the first example of nature-based solutions (Collier, 2021). One of the key benefits often highlighted in hedgerows is the role they play in protecting biodiversity. Acting as green corridors, they allow pathways or linkages between areas of refuge for wildlife, and can even act as a refuge themselves, for animal species ranging from insects to birds, small mammals and reptiles (Puth and Wilson, 2001; Roy and de Blois, 2008; Wehling and Diekmann, 2009; Boughey et al 2011; Lecq et al 2017). In addition, they can act as a reproductive source population for plants, allowing dispersal into new areas (Vanneste et al 2020) and act as genetic reserves for species (Dover, 2019). As well as increasing biosecurity in general (Montgomery et al 2020), they can offer agricultural benefits by enhancing biological pest control through the increase of predatory mite populations (Gavinelli et al 2020). Further detail on hedgerow biodiversity benefits is summarised by Collier (2021), and these range from acting as biodiversity repositories, habitats for plants, animals and birds (including migratory), supporting pollinators, over winter shelter for predators, supporting insect life and supporting fungi.

There are additional benefits associated with hedgerows, including improvements in infiltration (Coates and Pattison, 2017), natural flood management (Pattison and Coates, 2016), intercepting pesticide drift from aerial applications (Hancock et al 2019), and helping to significantly reduce loss of key nutrients (nitrogen and phosphorus) from agricultural practices on sloping land (Oshunsanya et al 2019). The protection against soil erosion is also well documented (Follain et al 2007; Ford et al 2019). In addition, they have been shown to prevent snowdrift (Walter et al 2004) and improve the microclimate (Sánchez et al 2009). Finally, it has been suggested that hedgerows may also offer economic incentives for upkeep, as they require periodic coppicing; the harvested wood could be used for woodchip or woodfuel, offering additional income to the farmers or those responsible for their management (Smith et al 2021). This was found to be cost effective and resilient to changes in prices if the correct management options and machinery are used (medium scale being optimal, such as tree shears). Furthermore, the benefits increased if woodchip was used on farm in place of heating oil or purchased woodchip, and if farm labour were utilised rather than contractors (Smith et al 2021).

3.3.5 Considerations for hedgerows in Scotland

In general hedgerows are at low risk with regards to increasing temperatures, as there is little direct threat (Gregg et al 2021). However, they still have vulnerabilities to extreme weather conditions such as drought which may put stresses on hedgerows and damage their long -term resilience and carbon sequestration potential. As with any threat, climate change-induced or otherwise, correct management will be key in helping maintain hedgerow health and its ability to withstand negative pressures. Selection or introduction of species with high tolerances, for example to drought, could be one management decision to increase resilience.

3.3.6 Evidence gaps

There is an absence of empirical data for carbon and SOC sequestration by hedgerows in Scotland. Available information on carbon and SOC sequestration mainly comes from the rest of the UK and modelled results are often parameterised by data from woodland or agricultural vegetation, with the exception of Crossland (2015) and studies by Axe and associates (Axe, 2015, Axe et al 2017, 2018, 2020). There are large differences highlighted between empirical studies and the modelled data based on alternate data sources; this suggests a strong need for more field-based measurements of carbon storage with an emphasis on Scottish specific data.

A better understanding of carbon sequestration in hedgerows is needed to better inform management decisions. Given the importance of management on carbon sequestration, the lack of evidence also suggests further research is required into the ramifications, and relative pros and cons of each management decision including incorporating trees into the hedgerow and different species mixes. A balanced carbon assessment is required to determine the true offset potential of hedgerows after accounting for the GHG emissions associated with their management, as greater management may lower the net benefits in terms of carbon sequestration. There is also a lack of data for the socio-economic drivers behind establishment and maintenance of hedgerows in a Scottish context. There is a new NERC funded project by the Game and Wildlife Conservation Trust to develop a pilot 'Hedgerow Code', however, it is clear that some knowledge gaps will need to be addressed as a priority before reliable sequestration estimates can be factored into a code.

3.3.7 Confidence in the evidence available

Currently, there is no Scottish specific data or models for soil or vegetation carbon stocks in hedgerows. Data exists from England and Wales, but only based on a few empirical studies and utilising only a couple of research sites. Modelled data for the UK is largely based on datasets from agriculture or woodland. Though some studies are detailed, there is a very limited number and they show a lack of agreement in sequestration rates (in biomass) or whether SOC changes occur at all. Furthermore, modelled studies based on non-hedgerow data would appear to be unreliable indicators when contrasted against hedgerow-based data due to the large discrepancies. In conclusion there is a small amount of evidence available and what there is shows poor agreement for both soil and vegetation carbon stocks. At this time, there is no information on the direct interaction between GHG emissions and hedgerows in Scotland.

Although the data is not Scotland specific, multiple studies utilising multiple indicators and species would suggest there is a good quantity of evidence with a high degree of agreement to indicate that hedgerows have a strong positive effect on biodiversity.

3.4 Species rich grasslands

3.4.1 Introduction

Collectively grasslands are one of our most extensive habitats, covering around 36% of land in the UK (Ostle et al 2009) and 30% of Scotland (Norton et al 2009). These grasslands vary greatly in intensity of management, from fertilised and improved agricultural grasslands with low biodiversity value, to semi-natural grasslands with high value for biodiversity. Changes in management to improve the species richness and biodiversity value of intensively used or degraded semi-natural grasslands may also influence carbon storage in vegetation and soils and thus provide a nature-based solution for biodiversity and climate.

Figure 4: Species rich grasslands in Scotland Left - Calcareous Grassland Right - Neutral grassland (NatureScot: Guide to types of species-rich grassland, https://www.nature.scot/doc/guide-types-species-rich-grassland)

Several different types of grassland are present in Scotland. Intensively used agricultural grasslands are farmed for a grass crop which is either used for intensive grazing or silage production. Some of these grasslands form part of a rotational system with arable crops and so are temporary, while others have permanent grassland cover. Intensive grassland productivity is improved by reseeding with low-diversity high-productivity species mixes (often only 1-3 species) and fertilisation, liming and drainage. Semi natural grasslands cover a range of grassland types, from those which may have been semi-improved by liming or fertilisation in the past to those which have never been improved, but are maintained as permanent grasslands. Semi-natural grasslands are typically used for extensive grazing or, less commonly, hay production. Grassland species richness typically declines with intensity of use – the most species-rich grasslands are those with no fertiliser or lime inputs and a low intensity of grazing or cutting. The potential for increasing carbon sequestration in intensively managed grassland is reviewed by Gregg et al (2021). In this review we focus on extensively managed semi-natural grasslands. Semi-natural grasslands occupy around 18% of

Scotland (Table 4, Norton et al 2009). Much of this area comprises degraded, species-poor upland acid grassland while a much smaller area is species-rich grassland prioritised for conservation (Aspinall et al 2011).

Table 4 The extent of different grassland types in Scotland circa 2007. *Data from Norton et al (2009) and **Data from Aspinall et al (2011). Note: The Biodiversity Action Plan priority grassland category includes a subset of the acid, neutral and calcareous semi-natural grassland categories which are most important for conservation.

Grassland type	Area in Scotland (hectares)	% Scottish Land area
Improved*	**907 000**	**11.2**
Semi-natural acid*	983 000	12.3
Semi-natural neutral*	461 000	5.8
Semi-natural calcareous*	26 000	0.3
Total semi-natural grassland *	**1 470 000**	**18.4**
Biodiversity Action Plan priority types *	*17 893*	*0.2*

Semi-natural grasslands include acid, neutral and calcareous grassland, upland and lowland hay meadows, all of which differ in their plant species richness, species composition and associated soils (Bullock et al 2011, Lake et al 2020). The size of their associated carbon stocks and the potential for carbon sequestration is influenced by soil type, climate and management regime, and is very variable (Soussana et al 2004). Based on data from the Countryside Survey, the National Soils Inventory of Scotland (for further details see Appendix 4) and smaller-scale studies, carbon stocks appear to be larger in acid grasslands than in neutral grassland (88.4 vs 73.9 t C ha^{-1} in the top 15 cm of the soil, Emmett et al 2010). When considering carbon stock to 1m depth, reported values for grasslands (mainly acid grasslands) vary from 185.2 -281.7 t C ha^{-1} (Chapman et al 2013, Zerva et al 2005, Razauskaite et al 2020).

Restoration of biodiversity in semi-natural grasslands can be achieved by changes in management (e.g. reduction in grazing and fertiliser use) and by direct intervention to increase plant species richness (e.g. seed addition). Both interventions have the potential to alter carbon cycling and stocks in grasslands by changing the amount and type of carbon entering the soil (plant and root litter), physical conditions in the soil (through trampling and erosion) and interactions with other nutrients (nitrogen, phosphorus).

Plant-species richness should not be considered in isolation, as all grasslands require some form of grazing or cutting management to maintain them and to prevent succession to scrub. The nature of this management will affect outcomes for both carbon stocks and biodiversity.

3.4.2 Carbon storage potential due to increasing plant richness

There is very little evidence of the direct effects of restoration of grassland biodiversity on carbon sequestration. Increased diversity of plant species can alter the amount and quality of plant inputs to the soil, with deep rooted species delivering carbon to deeper soil layers (Ostle et al 2009). However, evidence in semi-natural grasslands is limited to one study in northern England which found that cessation of fertiliser input and addition of seed mix to previously intensively managed grassland increased plant species richness, led to an increase in soil carbon storage and was associated with high rates of carbon sequestration (De Deyn et al 2011). However, at this study site the soil was a brown earth over limestone, which is not common in Scotland, and more studies on typical Scottish soils are needed to confirm the results. Reduction in fertiliser use as part of management to increase grassland diversity would also contribute to greenhouse gas reductions, though this was not quantified in the English study. Introduction of legumes and deeper-rooted species has also been shown to increase carbon sequestration in intensively managed improved grasslands (Gregg et al 2021).

3.4.3 Carbon storage potential due to changes in grazing management

Maintenance of grassland biodiversity requires a grazing or cutting regime tailored to the environmental conditions and type of grassland present. Both under grazing and overgrazing may reduce grassland plant diversity and hence either reductions or increases in grazing pressure may be needed for restoration.

Impacts of grazing on grassland carbon stocks appear to be variable. Globally, across many types of grassland, both positive and negative effects, or no effect of changes in livestock stocking density on soil carbon stocks have been reported and impacts of grazing appear context specific (McSherry & Ritchie 2013, Eze et al 2018b).

Positive impacts of grazing can occur when grazing stimulates the growth of plants and increases biomass production below ground (Eze et al 2018b). Around half of biomass removed by grazing animals is redeposited as faeces and the carbon in this may subsequently be incorporated into the soil (Forster et al 2021). Too much grazing however may reduce plant productivity and carbon inputs to the soil and result in carbon loss through erosion of bare soil (Eze et al 2018b). Grazing animals themselves are also an important part of the carbon balance of grazed grasslands, as some of the carbon they consume is released as carbon dioxide and methane, offsetting gains from increased plant productivity (Sozanska-Stanton et al 2016).

When looking specifically at grasslands experiencing moist, cool climatic conditions (similar to Scotland), a review by Abdallah et al (2018) found that all studied levels of grazing intensity reduced soil carbon stocks, by an average of 19%. This suggests that typical grazing regimes in this climate zone are generally having a negative impact on carbon sequestration. This result agrees with modelling studies (Chang et al 2016) which suggest that recent reduction in grazing intensity across Europe has enhanced soil carbon sequestration and reduced carbon dioxide and methane emissions. The detailed relationships between grazing regimes and carbon sequestration, particularly in semi-natural grasslands remain a key area of uncertainty.

Most studies on the effects of grazing changes on grassland biodiversity and carbon stocks in the UK have been in degraded upland semi-natural acid grasslands dominated by mat-grass and purple moor-grass (Medina-Roldan et al 2012, Smith et al 2015, Smith et al 2014). These studies included sites in Scotland and in very similar habitats in northern England. In these grasslands grazing removal or reduction increased above ground biomass and benefitted cover of dwarf-shrubs at the expense of grasses. Effects on soil carbon stocks were small and difficult to detect, but modelling suggests an increase (Medina-Roldan et al 2012, Smith et al 2014). Comparison of grassland and heathland habitats also suggests a larger carbon stock and greater sink strength in heathlands (Medina-Roldan et al 2012, Quinn et al 2014, Smith et al 2015, Quinn et al 2015). These grasslands are likely derived from dwarf-shrub heath, blanket bog, or wetland vegetation, due to long-term over-grazing, burning and drainage (Bullock et al 2011). Reduction in grazing pressure could result in restoration of these habitats, providing both a biodiversity and carbon benefit (Sozanska-Stanton et al 2016, Field et al 2020). Similar evidence for the effects of grazing changes on carbon sequestration in lowland species-rich grasslands is currently lacking and is a key knowledge gap.

3.4.4 Multiple benefits of species-rich grasslands

Evidence for multiple benefits of increases in species richness of grasslands come from a variety of sources, but few studies have considered effects on both carbon stocks and other ecosystem services, and there are a limited number of Scottish examples. Restoration of grassland plant diversity increases biodiversity, both of plant species and of associated species above and below ground, including invertebrates and fungi (Millard & Singh 2010, De Deyn et al 2011, Van vooren et al 2018). Soil biodiversity is positively associated with soil organic matter (Lal 2008, Canedoli et al 2020) so increases in soil carbon storage would be expected to benefit biodiversity below ground. Effects of grazing reduction/removal on above ground biodiversity are likely to be positive in the short-term as previously suppressed plant species are able to grow and flower but may become negative in the long-term if competitive species become dominant, and plant diversity is reduced (Su & Xu 2021). In upland grasslands, reduction of grazing to benefit carbon storage may have trade-offs with wider biodiversity including invertebrates and birds (Smith et al 2014). Evidence suggests the optimum solution may be reduced grazing rather than complete cessation (Smith et al 2014). Where grazing reductions result in a restoration of heathland on grassland, a shift in the suite of species present will occur and the impacts of these shifts in biodiversity need to be considered at a landscape scale, to ensure positive outcomes for biodiversity overall (Sozanska-Stanton et al 2016, Field et al 2020). Given that the Scottish uplands are currently extensively grazed by both wild and domestic herbivores, visions for future habitat mixes should not be limited just to those currently present. Changes in grazing management also provide an opportunity to restore a more diverse mixture of upland habitats including wetland, scrub and woodland which could contribute to maximising both carbon sequestration and biodiversity in upland landscapes (Field et al 2020).

Restoration of grassland species richness may have other benefits depending on the methods used to achieve restoration and the effects on soil carbon. Broadly speaking, increased soil carbon content decreases nutrient and water loss from ecosystems, enhances water use efficiency and purifies water by retaining and removing pollutants (Lal 2008). Increased soil carbon also has positive effects on soil structure and ecosystem resilience (Lal 2008). If restoration is achieved by reduction of fertiliser use, this could benefit surface water quality through reduction of nutrient leaching (van Vooren et al 2018). Reduction of grazing intensity can reduce soil compaction and erosion and increase water infiltration and may benefit soil health (Eze et al 2018b, Su & Xu 2021). Grazing reduction may also reduce nitrogen mineralisation, reducing potential for nitrogen leaching into surface waters (Medina-Roldan et al 2012).

3.4.5 Considerations for species-rich grassland in Scotland

Grassland carbon stocks are principally in the soil and are generally stable while soils remain undisturbed and management intensity is constant. Grassland is not a perpetual sink for carbon and increases in carbon sequestration resulting from changes in management will be temporary, with a new equilibrium carbon stock being reached after 50-100 years (Smith 2014). Additional carbon stocks gained through changes to management are vulnerable to loss, and physical disturbance of soils such as ploughing or re-seeding of pasture species can lead to rapid loss of soil carbon (Soussana et al 2004, Godde et al 2020).

Semi-natural grasslands are vulnerable to climate change which could impact on soil temperature and moisture and therefore on species composition, plant productivity and decomposition of soil carbon. European-scale studies suggest that grasslands on mineral soils would remain carbon sinks with low levels of warming (1.5-2 °C) but greater warming (3.5 °C) could cause them to become a net source (Chang et al 2016, 2017, Smith et al 2005). An experiment in English upland grassland suggested that warming and drought could reduce carbon sink strength in grassland, but this might be offset by a longer growing season (Eze et al 2018c). Cold and wet upland soils may be most at risk from climate change effects, with warming and drought being important drivers of increased emissions (Ostle et al 2009, Thomas et al 2020).

Reduction in grazing to enhance carbon sequestration in above ground biomass and soils could lead to increased fire risk in extensive upland semi-natural grasslands. Large upland fires can lead to significant carbon losses from vegetation but if occurring on organic soils could also lead to loss of soil carbon stocks through combustion and subsequent erosion of burned areas (Baggaley et al 2021).

3.4.6 Evidence gaps

There are large evidence gaps around the relationship between grassland species richness and carbon sequestration in semi-natural grasslands and around the effects of direct biodiversity restoration activities, such as seeding, on carbon stocks. Information on the effects of management on carbon sequestration in semi-natural grassland is also limited, particularly for grasslands on organic soils and under Scottish climatic conditions. There are particular gaps in knowledge around the effects of management actions in calcareous and neutral semi-natural grasslands and in species-rich lowland acid grassland. Studies are needed which assess impacts of management and restoration on a variety of ecosystem services (e.g. biodiversity, soil health) alongside carbon sequestration, to ensure that trade-offs can be identified and perverse outcomes avoided.

Information on the spatial variation of carbon stocks in semi-natural grasslands on organic and organo-mineral soils is limited with rarer grassland types being particularly poorly studied. Additional data are needed to address this knowledge gap and increase understanding of how carbon stocks relate to grassland species composition and richness. Most current carbon stock assessments consider only the upper 15 cm of the soil, and more work is needed which assesses carbon stocks over the full soil profile.

Biodiversity and long-term stability of carbon stocks in grassland soils will be impacted by climate change, but at present there is limited evidence on what the net effects will be for Scottish grasslands. More studies are required to assess the effects of drought and increasing temperatures on whole ecosystem carbon balance in a variety of Scottish grassland types.

3.4.7 Confidence in the evidence available

There is little evidence on the direct carbon benefit of restoring plant diversity in semi-natural grasslands, with no evidence from Scotland. The single study that we found is, however, consistent with studies looking at use of more diverse species mixes in intensively managed improved grassland which have found improved carbon sequestration. In terms of multiple benefits to biodiversity and ecosystem function, restoring plant diversity enhances biodiversity by definition. There is also evidence from a range of sources that demonstrates improved biodiversity in other groups and improved ecosystem function in more diverse, carbon-rich ecosystems, though few specific studies of the effects of restoration in Scotland. While there is general agreement on the relative carbon stocks in grassland versus other habitats, there is significant variation between studies in the carbon stocks reported for semi-natural grasslands. Variation in sampling depth compounds this issue as sampling to 1 m verses 15 cm depth gives a different picture.

There is broad agreement that reduction or removal of grazing on upland acid grassland will lead to increased biomass carbon stocks and in the long term also soil carbon stocks, as well as reduction in emissions from livestock. There is also consistent evidence that reduction or removal of grazing favours dwarf-shrub dominated vegetation over grassland. Direct evidence for effects of grazing removal/reduction on Scottish grassland habitats is limited to acid grassland. There is also broad agreement from studies including Scottish sites that restoration of heathland on upland acid grassland increases carbon sequestration and, in the long-term, carbon stocks. This is consistent with measurements of carbon stocks under existing heathland and grassland habitats.

3.5 Metrics for assessment of soil carbon stocks

Soil carbon concentration is probably the most straightforward metric to assess change over time due to the implementation of nature-based solutions. Often the concentration is measured over a fixed depth, for example, the Countryside Survey sample to 15 cm (Henrys et al 2012) and LUCAS (Land Use and Cover Area frame Survey) implemented by the European Soil Data Centre (JRC, Ispra) measured carbon concentrations to a depth of 20cm. However, carbon concentration alone and sampling to these shallow depths is generally a poor measure of change over time as shown by Chapman et al (2013) and Lilly & Chapman (2015). They measured the carbon concentration, horizon thickness, stone content and the dry bulk density and found that a decrease in soil carbon concentrations in Scottish soils over time was offset by an increase in soil horizon thickness resulting in no change in carbon stocks overall. Thus, in order to fully assess changes in soil organic carbon over time, it is important to take into account changes in dry bulk density and horizon/soil thickness. Sampling at fixed, shallow depths is unlikely to be able to take account of changes in the carbon-rich topsoil thickness.

However, while changes in carbon concentrations are not the most robust ways of measuring changes in SOC over time, they are relatively easy to measure compared to calculating stocks and, as such, could be used as an early warning system to trigger more detailed investigation. However, any sampling scheme beyond an ‘early warning system’ should take horizon thickness, dry bulk density, stone content and carbon concentration into account to assess stocks (Lilly and Baggaley et al 2020).

The timescale over which changes in soil organic carbon can be robustly measured remains uncertain (Lilly & Baggaley 2021). Various national, regional and local studies have attempted to quantify the change in SOC over time ranging from 9 years (Countryside Survey, Emmett et al 2010) to over 50 years (Lilly, Baggaley & Edwards 2020). The changes observed in soil organic carbon stocks or topsoil concentrations in Scottish soils over time through these studies are complex with some datasets showing no change whilst others show a decline in concentration but no statistically significant change in stocks. However, none were looking specifically at changes in land use due to the implementation of NBS. Thus, there remains evidence gaps on the potential changes in soil organic carbon concentrations and stocks associated with planting hedgerows ,establishing agroforestry or riparian buffer zones and increasing species richness in grasslands.

3.6 Metrics for vegetation carbon stocks

Vegetation carbon stocks are smaller but more dynamic than those in the soil and exhibit measurable changes over relatively short time scales (1-10 years). Measurement of vegetation carbon stock uses standard biomass harvesting and carbon measurement techniques as reviewed by Dumitru and Wendling (2021) or forestry allometric measurements for determination of tree biomass. Measurements of vegetation carbon stock should take account of the longevity of different vegetation components; trees and woody species provide longer term sequestration of carbon, while grassland management (e.g. mowing or grazing) will determine whether the vegetation contributes to carbon stocks beyond the current growing season.

3.7 Review of carbon codes for implementing nature-based solutions

Carbon codes are being developed to provide frameworks by which private investment and government subsidies can be allocated for the purpose of funding environmental activities that contribute to offsetting GHG emissions.

Currently, there are two regulated codes in place in Scotland (and the UK) that provide private investors the opportunity to buy carbon credits from the planting of woodlands (‘Woodland Carbon Code’, WCC) and the restoration of peatlands (‘Peatland Code’, PC). There are also other mechanisms for blending public and private funding.

The four NBS covered in this report can provide multiple ecosystem services such as improving water quality, reducing erosion and increasing biodiversity. However, the inclusion of NBS as part of a regulated carbon offsetting scheme requires robust scientific evidence demonstrating the benefits in terms of offsetting GHG emissions, a means of verifying additional carbon stocks and an assurance of permanency. There is some evidence that increasing trees and woody vegetation in agroforestry, hedgerows and riparian buffer zones will increase above ground carbon sequestration but a lack of evidence for species-rich grasslands. The evidence on increasing soil carbon sequestration is much more limited and uncertain for all four NBS. In addition, both buffers and hedgerows have challenges over the depth at which changes should be quantified to demonstrate a change in soil carbon stocks over time. The implementation of code approaches that require land to be taken out of production (for example woodland creation under the ‘Woodland Carbon Code’), could also lead to increased reliance on imports and the risk of offshoring of emissions; both of which need to be addressed in the development of market-based approaches to carbon sequestration.

Changes in land use driven by carbon markets are sometimes referred to as “land sparing”, because land is taken out of production, and put aside or “spared” for carbon sequestration. This is very different to the “land sharing” approach, where land is “shared” for its ability to sequester carbon and other functions, for example by continuing to use a peat bog for sustainable levels of grazing and hunting after it has been restored under the ‘Peatland Code’ or moving to more regenerative agricultural practices in anticipation of payments for soil carbon under, for example, a future UK ‘Farm Soil Carbon Code’. Because land sparing approaches are typically associated with changes in land use and ownership, they pose unique risks and opportunities for the land use sector (See Elliot et al (2022) and Reed et al (2022) for recent reviews of land sharing approaches in the UK and McMorran et al (2022) for a review of risks and opportunities from land sharing versus land sparing approaches in the UK.)

The potential for achieving the maximum benefits from NBS requires land to be managed at a landscape scale that considers both the importance of protecting existing carbon stocks and habitats and the benefits of implementing NBS for carbon sequestration and other benefits. A strategic approach needs to consider the wider impacts of changing land use to provide a required range of ecosystem services (see Appendix 5 for further details) with the House of Lords Report (2022) calling for a strategic land use strategy for the UK. The British Ecological Society report (Stafford et al 2021) also outlines the importance of right measure right place approaches to land use planning.

There is currently a discussion about the potential to include agroforestry within the 'Woodland Carbon Code'. In addition, two pilot codes currently being explored include biodiversity metrics as part of their offsetting (The 'Wilder Carbon Code' being developed by the Kent Wildlife Trust the and the 'Hedgerow Code' as part of the Game and Wildlife Conservation Trust's Allerton Project). The 'Wilder Carbon Code', in contrast to the WCC and PC, on which it is built, also requires buyers to have done everything possible to reduce emissions before they can offset their residual emissions and addresses concerns about permanency by requiring minimum contract lengths of 50 – 100 years.

Riparian buffer zones are too narrow to qualify under the 'Woodland Carbon Code'. The Scottish Wildlife Trust's Riverwoods project is exploring the potential to finance the creation of riparian woodland via carbon markets. However, it is likely that riparian woodland planting would need to be done as part of a wider floodplain afforestation programme, which may be designed to attenuate flooding, or improve biodiversity rather than as part of individual edge of field buffers designed to mitigate diffuse pollution, to be eligible under the code. There are existing examples of riparian woodland planted as part of wider adjacent planting schemes already financed under the 'Woodland Carbon Code'.

Although there are no UK domestic carbon markets that focus on species-rich grasslands, there are a number of international voluntary carbon markets that have developed methodologies that could in theory be adapted for use in the UK (e.g. Verra's methodologies for Sustainable Grassland Management (VM0026) (Food and Agriculture Organization of the United Nations, 2021) and Improved Agricultural Land Management in the UK (VM0042) (Schoch & Swails 2020)). The UK 'Farm Soil Carbon Code' could also be extended in future beyond its current arable focus to include conversion to species-rich grasslands, if there is robust evidence of soil carbon benefits from conversion or changes in nutrient management.

Where private investment to facilitating nature-based solutions to climate change is sought there is a requirement for a policy framework to be in place to support this investment and mitigate some of the unintended negative consequences to communities and the environment (Appendix 5).

4 Conclusions

This review sets out an assessment of the evidence for the GHG mitigation potential of four NBS i.e. agroforestry, hedgerows, riparian buffer zones and species-rich grasslands. It also addresses the additional multiple benefits that can help to mitigate the impacts of climate change and reduce biodiversity loss. Agroforestry has some evidence for an increase in vegetation and soil carbon, stocks and improving biodiversity. However, there is a clear knowledge gap in evidence that demonstrates that agroforestry can reduce net GHG emissions in temperate regions such as Scotland. Similarly, studies of riparian buffer zones provide some evidence for an increase in vegetation and biodiversity but again, there are clear knowledge gaps relating to the impact of riparian buffer zones on net GHG emissions and biodiversity richness. The review highlights that there is good evidence that hedgerows lead to an increase in biodiversity and some evidence for an increase in soil and vegetation carbon stocks. Again, there is clear a gap in evidence showing the impact of hedgerows on GHG emissions. There is good evidence for an increase in biodiversity in species-rich grassland, but there are clear gaps in evidence for the impact on soil and vegetation carbon stocks and GHG emissions.

The measurement of soil carbon stocks needs to consider soil horizon thickness, carbon concentration, density and stone content. Considering the changes of soil carbon at depth, it is particularly important in assessing stock changes in systems that include deep rooting vegetation such as trees in agroforestry, hedgerows and riparian buffer zones. Methodologies to reflect this have been developed in the 'Woodland Carbon Code'.

Vegetation carbon stocks are smaller but more dynamic than those in the soil and assessments should take account of the longevity of different vegetation components and whether the carbon stocks are retained on site or removed, for example by grazing or cutting of vegetation.

The inclusion of NBS in carbon codes requires further evidence to verify carbon stock change potential and its permanency both within the soil and the vegetation. There is a lack of accredited carbon offsetting standards within the UK - currently limited to the 'Woodland Carbon Code' and the 'Peatland Code'. Any policies that are put in place should ensure that those investing to offset GHG mitigations have done everything they can to reduce emissions and ensure that implementing these practices does not lead to offshoring of emissions or other damaging environmental impacts. The potential for achieving maximum benefits from NBS requires landscape-scale land management that considers both the conservation of existing carbon stocks and habitats as well as the multiple benefits of implementing NBS with a "right measure, right place" approach. A strategic land use strategy is required to achieve this.

This review summarises the existing evidence for carbon sequestration in Scotland through the implementation of 4 NBSs and where there are gaps in knowledge. We have identified a need for additional data relevant to Scottish conditions for all four NBSs. There is a lack of empirical data on hedgerows and further work is needed to understand soil carbon losses due to hedgerow establishment to implement the approaches used in the WCC. For agroforestry, we have noted key differences to wider woodland planting, which means this measure may not be compatible with existing funding mechanisms. With riparian buffers as a NBS, we have noted that there is considerable complexity in GHG balances and permanency of carbon stocks, and for species-rich grasslands there is a lack of evidence in general with regards to carbon sequestration in soil or vegetation.

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6 Appendices

Appendix 1: Review methods

Key review papers highlighted by Natural England, Environment Agency and NatureScot were used to track relevant publications. In addition to this, other primary and grey literature were sources via internet searches conducted through Google and Web of Science and Google scholar.

Publications and reports were selected based on pre-defined criteria which included studies that described agroforestry, hedgerows, buffer strips and species-rich grasslands in Scotland or locations relevant to Scotland.

Therefore, papers from sites that did not relate to Scottish climate and land uses were excluded. Modelling studies were included only where they demonstrated how primary data had been used to draw wider conclusions and the uncertainty in this.

The compilation of publications provided a quantitative assessment of evidence of knowledge gaps.

Additional information was added based on reports from agroforestry trials at the James Hutton Institute's Glensaugh farm.

The publication of the House of Louse of Lords report came to our attention while writing the report.

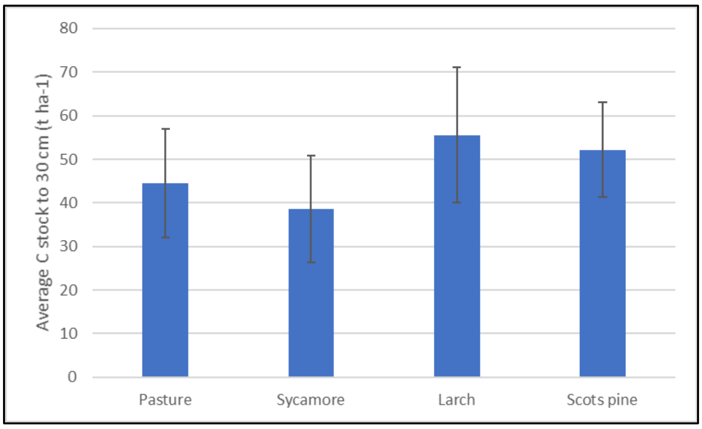
Appendix 2: Glensaugh agroforestry

There are few datasets available in Scotland from which soil carbon (C) stocks can be calculated for each of the 4 proposed Nature-based solutions. Of the 4, there is a limited number of measured stocks for agroforestry from one site in Scotland (Glensaugh) and data from the National Soil Inventory of Scotland (NSIS) 2007-9 and the related sampling of specific iconic /rare Scottish soils.

A number of improved, intensively managed grassland fields at Glensaugh were planted with trees in 1988 at three different densities to investigate the effects of agroforestry systems on livestock production systems. Three tree species, Scots Pine, Larch and Sycamore were planted at densities of 100, 200, 400 and 2500 trees ha^{-1}, the latter representing commercial woodland densities (Sibbald et al 2001). Some of the lower density plots have subsequently had the trees removed. A detailed soil survey was undertaken of the agroforestry plots prior to planting (50m grid spacing plus 10 m transects giving 190 profiles in total at 2 depths (generally 0-15 and 35-45 cm)) but, as no bulk density measurements were made, SOC stocks cannot be directly calculated (a retrospective calculation of bulk density is possible via spectroscopy, e.g., see Chapman et al 2013).

In 2016, Beckert et al compared the stocks under the 400 trees per hectare spacings and pasture land in the Glensaugh agroforestry plots, which was 24 years after planting. They found that both the Larch and the Scots pine plots had greater C stocks in the top 30cm (55.55 t C ha^{-1} and 52.17 t C ha^{-1}) than pasture (44.53 t C ha^{-1}) which had greater C stocks than the Sycamore plots (38.6 t C ha^{-1}). The sample size varied between 8 and 9. The differences in the mean value were just on the threshold of being significantly different ($p=0.051$).

Figure A2: Bar chart showing the mean and standard deviation of SOC stocks (t C ha^{-1}) in the Glensaugh agroforestry plots by tree species.



Appendix 3: Mechanisms for carbon storage in riparian buffer zones

Mechanistically increasing Soil Organic Matter (SOM) storage is the product of supply of decomposing plant matter or deposition of incoming sediment OM from upslope at a greater rate than decomposition and losses to the atmosphere as gases or leaching as Dissolved Organic Content (DOC). Despite greater litter inputs and moist soil conditions under permanent vegetation in buffer zones (relative to field land cover), the observed enrichment of buffer zones in an agricultural field edge context with available nutrients N and P (Stutter et al 2009; 2012) will drive microbes to greater C acquisition to balance C:N:P stoichiometry and favour growth (Stutter et al 2018). Stabilising influences of mineral surfaces then become important for retaining C and limiting further degradation and leaching losses of C. In Scottish acidic soils, Fe and Al phases control leaching and stabilisation of organic matter anions. Since Fe, Al (and Ca in neutral soil) also control phosphate anion retention, soil amendments (e.g. Fe compounds and gypsum) have been studied in buffer zones (Uussi-Kamppa et al 2012; Habibiandehkordi et al 2014). The effects on SOM and DOC fate were not studied but are likely controlled by similar mechanisms. However, metal additions to soils (especially near rivers) need balancing with other eco-toxicological implications. The timescales of such biogeochemical processes relative to land use change is important. Stutter et al (2009) found significant increases in SOM concentration in riparian buffers converted from cropland eight years before (relative to that adjacent cropland) that were not different for 3-year buffers. However, biogeochemical factors microbial respiration and extracellular enzyme activities indicating organic C turnover were also heightened in the 8-year buffers. Longer term, the processes of C retention may be more reliant on woody vegetation. There is a moderate body of literature for this, specific to field edge management zones. The continued storage relies on the tree growth rate trajectories and potential for biomass removal and regrowth. However, riparian zones, where processes (e.g. water table, nutrient fluxes) are distinct, a system understanding of interactions of tree roots on soil carbon necessary for holistic understanding of C change, is lacking.

Appendix 4: National Soil inventory Data

During the resampling of the National Soil Inventory in 2007-9 and the additional sampling in 2010 of the more rare soil types found in Scotland, 18 sites were visited, and the soils sampled where the vegetation community could be described as species-rich according to Robertson (1984). The soil C stocks to 100 cm (where the soil reached this thickness) ranged from 55.5 t C ha^{-1} to 264.4 t C ha^{-1} with a mean value of 119.7 (± 52.3). These calculations ignored the samples taken from machair soils due to the presence of calcium carbonate which increases the total C concentration. The mean carbon stock in the top 30 cm of soil (roughly equivalent to plough depth) was 89.5 ± 43.8 t C ha^{-1}. There is a wide range in the amount of carbon stored in the soil under these vegetation communities (see table 4.2.1) depending on the vegetation community itself and the thickness of both the organic-rich topsoils and soil thickness to rock.

Table 4.1: Vegetation communities assumed to be species-rich grasslands based on the Birse and Robertson classification (Robertson, 1984).

Code	Community Latin name	Community Common name
A1A	Lolio - Cynosuretum	Permanent & old ley pastures of rye-grass and crested dogs-tail
M1B	Potentillo - Juncetum acutiflori	Species-rich sharp-flowered rush pasture
N3A	Achilleo - Festucetum tenuifoliae	Herb-rich bent - fescue grassland
N3B	Achilleo - Festucetum tenuifoliae	Upland bent - fescue grassland
N4A	Junco squarrosi - Festucetum tenuifoliae	Heath grass - white bent grassland
N6	Cirsium palustre - Nardus stricta	White bent - tussock-grass grassland
A3A*	Galium saxatile - Poa pratensis	Common meadow-grass - bent pasture
A3C*	Galium saxatile - Poa pratensis	Sweet vernal - Yorkshire fog pasture
BE1*	Polygono - Helictotrichetum pratensis	Rockrose - fescue grassland
BE2*	Galium verum - Koeleria cristata	Crested hair-grass grassland
GP8*	Scilla verna - Festuca rubra	Vernal squill maritime pasture

* Species-rich grassland communities not sampled in the NSIS 2007-9 or Rare soils (2010) sampling campaign.

Appendix 5: Codes, markets and policy

There is growing interest and funding from private investors aiming to reduce emissions from the land use sector and offset residual GHG emissions from other sectors. Carbon and other ecosystem markets are driving changes and providing opportunities for farmers and land managers to develop new income streams. There is also growing awareness of the large funding gap between public funding available and the funding needed to meet Scottish Government policy ambitions from land use. The Green Finance Institute has recently estimated that there is a c.£20 billion funding gap for nature in Scotland over the next decade in order to deliver our policy ambitions for climate change, clean water, biodiversity, sustainable soil management, flood risk management.

Broadly speaking, there are three types of markets for investors that want to offset or inset emissions:

- **Carbon markets** including international compliance (Article 6, Paris Agreement), international voluntary markets (e.g. Gold Standard, Verra) and national voluntary markets (e.g. 'Woodland Carbon Code' and 'Peatland Code'). Carbon credits must be verified against a relevant standard to be additional and permanent.
- **Ecosystem markets** pay for other public goods (which may also provide direct private benefits to investors e.g. reduced water treatment costs). These outcomes may be paid for alongside projects funded by carbon markets, as long as it can be demonstrated that these are additional benefits being paid for by these ecosystems.
- **Green finance** mechanisms are designed to provide a return on investment by funding projects that deliver public goods (including via carbon and ecosystem

markets). Common mechanisms include green bonds, loans and insurance products.

The UK participates in compliance markets such as the Emissions Trading Scheme and can engage with international voluntary carbon markets to meet its obligations under the Paris Agreement (the rule book for this was agreed under Article 6 at COP26). The majority of voluntary carbon market transactions take place via the 'Woodland Carbon Code', with the 'Peatland Code' now rapidly scaling its operation. A number of initiatives are underway to develop new pilot codes which if implemented could expand the domestic voluntary carbon market in the UK, including:

- The Wilder Carbon standard has been developed by Kent Wildlife Trust and is due to be launched and piloted in March 2022. It will enable the generation of carbon credits from rewilding activities including woodland creation, peatland restoration and other forms of restoration, using metrics developed by the 'Woodland Carbon Code' and 'Peatland Code', and requiring the collection of biodiversity data using Defra's biodiversity offsetting metric. In contrast to other UK domestic carbon markets, it requires buyer checks to ensure those investing in projects have done everything possible to reduce emissions at source before offsetting their residual emissions. It also has unusually long minimum contract lengths of 100 years, or 50 years with conservation covenants that would ensure projects are effectively permanent;
- The development of a 'Hedgerow Code' is being led by the Game and Wildlife Conservation Trust's Allerton Project. While its initial development will focus on carbon in above ground biomass and soils, projects will monitor biodiversity benefits for potential use in Biodiversity Net Gain and similar programmes. There is no date set yet for the launch of the code;
- As with the 'Woodland Carbon Code', there is a discussion with a team applying for NEIRF funding to explore the potential to extend the scope of the code to include agroforestry, or develop a stand-alone agroforestry code.
- Development of a pilot 'Farm Soil Carbon Code' is being led by a consortium managed by the Sustainable Soils Alliance with FWAG South West, SRUC, University of Leeds and others funded by the Environment Agency's Natural Environment Investment Readiness Fund (NEIRF). It will focus initially on arable regenerative farming practices; Potential delivery in late 2022.

Policy development

An important part of this market development will be consideration of how public investment and policy (regulations, advice) can best support responsible private investment. There is a range of policy options that could be explored to develop high-integrity markets and mitigate some of the unintended negative consequences of a market-based approach to facilitating nature-based solutions to climate change (McMorran et al in prep.).

Carbon markets:

- <u>Creating new carbon markets</u> - high quality codes accredited by UKAS to relevant ISO standards, could be developed for a range of ecosystem services, habitats and land uses, to provide assurances to both buyers and sellers that GHG reductions and other ecosystem services are real, additional and permanent.
- <u>Project pipeline</u>: there is now significant demand for land-based carbon projects in the UK, but the 'Peatland Code' cannot supply enough projects to meet this demand and there are constraints on the availability of land for afforestation. Therefore, in addition to developing carbon codes and ecosystem markets for new land uses and habitats, it will be important to co-design these with inputs from the

landowner and manager community to ensure there is a sufficient pipeline of projects to supply demand.

- High-integrity investment – To further increase the integrity of these markets, it may be necessary to incorporate buyer checks to ensure land is only used for carbon offsetting to offset residual emissions when a buyer has done everything that is technically and economically feasible to reduce emissions at source. There is work underway by SG and the Scottish Land Commission to develop an interim statement on the type of responsible investment that we want to encourage in Scotland.

Market integrity:

- Market Design - There is a need to develop a policy framework in Scotland for the design, governance and operation of high-integrity carbon and ecosystem markets that support future farming incomes and deliver policy goals.
- Public policy design –future policy such as the agriculture bill and post-CAP funding for land management are exploring the potential for private investment to achieve environmental goals.
- Regulation – There is a requirement for regulation to ensure that carbon credits are verified, measurable and permanent.
- Regional markets - Place-based models that integrate multiple services and buyers may need to be further explored, for example via Regional Land Use Partnerships, to avoid conflicts between investment in different land use policy objectives and take into account potential trade-offs between flows of ecosystem services, and between stocks of natural, social, financial, physical and human capital.
- UK Co-ordination - Co-ordination of policies may be needed across the UK to secure the scale of market development and standardisation.

Just transition considerations:

- *Community benefits* - Mechanisms need to be developed to ensure that investment in Scotland's natural capital creates benefits that are shared fairly between public, private and community interests. This could include direct financial returns for local community benefit, for example via Community Wealth Building to reinvest in local economies and deliver long-term benefits. Scottish Government and Scottish Land Commission are working on the options to secure appropriate community benefit from investment in land.
- *Impact Assessments* - Mechanisms need to be developed (within the scope of human rights legislation) to ensure all major land acquisitions leading to land use change include an assessment of potential dependencies with neighbouring and downstream land uses, impacts on local communities, and meet expectations for responsible practice in the Land Rights and Responsibilities Statement, and where relevant engaging with Rural Land Use Frameworks or the National Planning Framework to ensure co-ordinated land use change in the public interest.
- *Community Engagement* - Public consultation and stakeholder engagement may need to be built into the design of future markets, for example following Scottish Government's Guidance on Engaging Communities in Decisions Relating to Land, to ensure projects respond to local circumstances, and communities and tenants actively engage in land use decisions that affect their interests.
- *Capacity building* - it will be necessary to build skills and capacity across all the components and contributors to ecosystem markets – farmers, land managers, investors, brokers, contractors, advisors.

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Scotland's centre of expertise connecting climate change research and policy

info@climatexchange.org.uk
+44(0)131 651 4783
@climatexchange_
www.climatexchange.org.uk

ClimateXChange, Edinburgh Climate Change Institute, High School Yard, Edinburgh EH1 1LZ