Spatial Prioritisation of Land Management for Carbon Dataset 2023

August 2025

Natural England Commissioned Report NECR510

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Foreword

The Nature and Climate crisis are closely inter-linked problems and need to be tackled in an integrated way. This challenge will require new policies, new technologies and action across all sectors. The natural environment plays an important part as healthy ecosystems, take up and store significant amounts of carbon in soils and trees. The large loss of habitat has resulted in a direct loss of carbon stored within them, restoring these for nature recovery will put back some of the degradation lost in the last century with the added climate benefit.

At present the land-based sectors 'Agriculture' and 'Land Use, Land Use Change and Forestry' (LULUCF) are responsible for approximately 11% of UK greenhouse gas emissions. How we manage our land significantly influences its role as a Greenhouse Gas (GHG) source or sink as habitats[1] still hold vast carbon stores in their vegetation and soils which need protection to avoid releasing this back into the atmosphere. Restoring ecosystems, particularly peatlands and native woodlands is essential to prevent the further loss of large amounts of carbon. Ecosystems recovery through Nature based Solutions (NbS) is the most cost-effective method of sequestering carbon currently available to us and the most reliable way of removing substantial amounts of carbon from the atmosphere.

To effectively understand carbon in nature and where to implement nature recovery we also need to understand this spatially and represent this in a mapped form to support integrated delivery. A targeted approach to the restoration and protection of nature and carbon not only safeguards biodiversity but can also help people adapt to the impacts of Climate Change along with sequestering and storing more carbon. We have developed effective habitat restoration techniques in the nature recovery sector and require clear targets, corresponding funding and resources to scale these up nationally and locally, through landscape scale delivery. With the advent of the Environment Land Management scheme along with future changes to agri-environment type support to land management and a renewed emphasis on the climate crisis, now is the opportune time to update this data set from the original 2014 version (see annex for 2014 report).

Land use can have a significant effect on the ability of land to store and sequester carbon. Management practices both directly, and indirectly, influence vegetation cover and soil carbon by altering the balance between carbon sequestration (e.g. in above ground vegetation and below ground organic matter) and carbon losses (e.g. soil respiration, dissolved organic carbon in waterways).

When considering Carbon mitigation spatially three key aspects are present; Carbon storage, carbon sequestration & carbon Loss. The storage element is the locations that have the most

[1] See Carbon Storage and Sequestration by Habitat 2021 (NERR094) http://publications.naturalengland.org.uk/publication/5419124441481216

carbon rich soils presently (generally peatlands) and through advances in present land management practices carbon storage can be maintained into the future. The Sequestration element highlights the areas where ecosystem restoration can once again increase carbon in vegetation and soils. Where the carbon loss highlights where inappropriate land use releases the greatest amount of carbon to the atmosphere. Consequently, through adjustments in land use to a lower emissions state, additional carbon can be stored through the application of changing land management through such mechanisms as the Countryside Stewardship options in these key locations.

The initial ‘Spatial Prioritisation of Land Management for Carbon’ datasets were created in 2014 (see annex 1 for methodology), to enable the targeting of agri-environment delivery and land use policy to maintain and enhance existing carbon stocks. It was a product designed to help deliver Biodiversity 2020 Outcome 1D. The datasets and maps were designed to enable advisers to identify:

1. High carbon habitats and land parcels where it is important to protect existing carbon stocks and keep in place management that supports continued retention of carbon in their soils and vegetation.

2. Sites and land parcels where a change in land management or land use would promote carbon sequestration/ abatement and storage in soils/ vegetation or reduce net carbon loss.

There is a large opportunity for agricultural land management to protect existing carbon stocks and enhance carbon storage, helping the English landscape to adapt to, and mitigate some of the effects of climate change. With the advent of the Environment Land Management scheme along with future changes to agri-environment type support to land management and a renewed emphasis on the climate crisis, NE have manged to get some funding to review and update this data set.

It is important to take a joined-up approach to climate, nature and the economy. Nature recovery is an important government policy that has recently been strengthened through the Environment Act & the 25-year plan; it can provide a wide range of economic and other benefits for people including a critical contribution to achieving net zero.

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Executive summary

Natural England (NE) is the Government's statutory adviser for the natural environment. They play a vital role in delivering the Government's 25 Year Environment Plan, supporting the ambitions for agriculture, fisheries and the natural environment as we leave the European Union, and responding to the Government's commitment to net zero by 2050. The twin challenges of biodiversity loss and climate change mean Natural England's work is more important now than ever.

Environment Systems Ltd, working with Natural England, have produced this report and associated data layers, and user guide (*'Spatial Prioritisation of Land Management for Carbon User Guide*'), to consider how the land of England is spatially contribution to preventing and mitigating climate change. This would be via the storage of carbon in the soil and vegetation, carbon sequestration of existing land cover, and where there may be abatement opportunities. The data layers that have been produced are aimed at assisting Natural England and other delivery bodies with strategic analysis for Sustainable Farming Incentive (SFI), Local Nature Recovery (LNR), and Landscape Recovery (LR). All of which underpin the 25 Year Environment Plan and the Environment Bill.

This work estimates that England has over four trillion tonnes of carbon stored, the distribution of which can be viewed in the Above Ground Carbon, and Below Ground Carbon data layers. These data layers, along with the Sequestration and Abatement layers, represent a strategic resource for England, that indicate the range of carbon storage values in tonnes per hectare (tC ha^{-1} yr), and sequestration tonnes of CO2 equivalent per year (t CO_2 e yr^{-1}) at a local scale (e.g., 1:50,000). They are presented as a series of data layers for use in GIS systems at a resolution of 25 m^2, with the aim of them of qualifying for an Open Government Licence.

In addition, an interactive spreadsheet has been created to prioritise sites for action when considering:

- Nature based management solution delivery.
- Meeting the Government targets for tree planting to assist carbon storage and sequestration.
- Peat restoration work.
- Management of other protected sites.

A user guide has been produced which accompanies the data and a Story Map has been created to allow access to those who wish to view the data in a more accessible format.

These new data will contribute to Natural England's vision of 'thriving nature for people and planet', by allowing policy makers and land managers to understand the terrestrial carbon resource. It will help protect and enhance existing carbon stores whilst also demonstrating opportunities to enhance carbon sequestration through changes in land use and management.

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Final report

April 2022

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Introduction

Natural England (NE) is the Government's statutory adviser for the natural environment. They play a vital role in delivering the Government's 25 Year Environment Plan, supporting the ambitions for agriculture, fisheries and the natural environment as we leave the European Union, and responding to the Government's commitment to net zero by 2050. The twin challenges of biodiversity loss and climate change mean Natural England's work is more important now than ever.

This report is produced to accompany spatial datasets which consider the lands contribution to preventing and mitigating climate change through storage of carbon in the soil and vegetation, carbon sequestration of existing land cover, and abatement. Environment Systems Ltd, working with Natural England, have produced strategic datasets covering the whole of England that indicate the range of carbon storage (t C ha^{-1}) and sequestration (t CO2 e ha^{-1} yr^{-1}). These maps are aimed at assisting Natural England and other delivery bodies with strategic analysis for the three schemes that will underpin the 25 Year Environment Plan and the Environment Bill:

- Sustainable Farming Incentive (SFI).
- Local Nature Recovery (LNR).
- Landscape Recovery (LR).

In addition, it is hoped that the work can be used to prioritise sites for action, including where best to help improve site condition or change land management use in:

- Nature based management solution delivery.
- Meeting the Government targets for tree planting to assist carbon storage and sequestration.
- Peat restoration work.
- Management of other protected sites.

This piece of work will contribute to Natural England's vision of thriving nature for people and planet, by allowing policy makers and land managers to understand the carbon resource in the land. This will help protect and enhance existing carbon stores whilst also demonstrating opportunities to enhance carbon sequestration through changes in land use and management.

Background

Carbon (in the form of carbon dioxide, CO_2) is removed from the atmosphere by plants through the process of photosynthesis, then stored in the stems or trunks and leaves above ground and in the root system below ground. This helps 'lock' carbon away from the atmosphere, therefore mitigating climate change.

Introduction to soil carbon

Over time in mineral soils, the carbon in the roots is broken down by soil fauna and flora. Soil organic matter comprises of the soil microbes and the decaying plant some soils hold more organic matter than others as the organic carbon components can bind to the mineral particles in the soil, this is then retained in the soil and not respirated by soil microorganisms. This builds up over time until an equilibrium is reached. The amount of carbon stored within a mineral soil depends upon the soil type, with clay rich and silt rich soils storing more carbon than sandy soils. This process can be influenced by a number of different factors including rainfall and temperature, habitat and land management. If the land use remains stable the soil carbon stored will eventually reach an equilibrium. Positive changes in management to enhance carbon include the use of farmyard manure rather than an inorganic fertiliser. Negative management practices, such as ploughing, allows oxygen to enter the system which can lead to carbon being released from the soil into the atmosphere as carbon dioxide.

Within peat soils, carbon storage operates by a different process. In a non-compromised state peat soils are fully saturated with water for most of the year, either from excess rainfall or from excess ground water. This leads to the continuous decomposition of plant biomass to form a very carbon rich layer of peat. This layer in blanket bogs, fens and raised bogs can become several metres thick as sequestration continues indefinitely, therefore making peatland soils a key carbon storage resource. However, if the peats dry out the soil microbial activity can re-start and as the carbon is utilised by the soil microfauna, carbon dioxide and methane are then released to the atmosphere, changing a carbon sink, sequestering carbon, into a source of greenhouse gas emissions.

Land use on peatland soils plays a very important role. Where peats have been drained, either for grazing or for afforestation, they will constantly release carbon dioxide to the atmosphere. Climate change itself is also having an impact on peatlands, with many being drier than they have been in the past 600 years. This is due to shifting weather systems, an increase in overall temperature, and a reduction in rainfall (Swindles *et. al.,* 2019). It is therefore very important that peat soils in the UK are conserved and restored in order to keep them as sinks of carbon.

Increasingly over the last 10 years, research has looked at the amount of carbon stored by various soil types under land uses. Natural England produced a report in 2021 reviewing this research and compiling different land use. approximate values in tons per hectare of carbon for a wide variety of habitats in England (Gregg et al 2021). Similar research has been done on soil carbon storage and sequestration.

This work has built upon the carbon storage and sequestration mapping carried out for Natural England in 2014, by suggesting approximate values of carbon stored and sequestration rates in vegetation and soils across England.

This report outlines the methodologies used to create the maps and the research that has been undertaken to create them. One of the key aims was for the maps to be issued under an Open Government Licence (OGL) to maximise impact. To achieve this the project only selected open access datasets. This means that there are some datasets that are more spatially accurate, but with greater licence restrictions that have not been used. To increase accuracy at scale, some of the OGL data were amalgamated.

The resulting maps are designed to allow Natural England policy makers and other stakeholders to identify:

1. High carbon habitats and land parcels where it is important to protect existing carbon stocks and keep in place management that supports continued retention of carbon in soils and vegetation.
2. Sites and land parcels where a change in land management or land use would promote carbon sequestration / abatement and storage in soils / vegetation or reduce net carbon loss.
3. Maximise sequestration potential through integrating higher carbon ecosystem restoration to appropriate areas.

The maps produced are designed to operate at the strategic scale national and regional scale. The methodology mainly utilised FME workbenches, which are also being made available so that the method can be adapted for use at a local scale where more detailed datasets could give more spatial precision.

Objectives

The project composed the following objectives:

- Objective 1: Review latest evidence especially with reference to the recently updated Carbon Storage and Sequestration by Habitat 2021 (NERR094).
- Objective 2: Using the result from the review, update the existing data Spatial Prioritisation of Land Management for Carbon Dataset.
- Objective 3: Using the Carbon abatement tool to link together nature recovery and climate actions by identifying areas where change in land use would benefit carbon and strengthen ecological networks.
- Objective 4: Create an indication of priority areas at several scales including national and regional levels.
- Objective 5: Create communication products to help disseminate this information to various audiences.

Rational

The factors that influence carbon storage were researched. Datasets that describe the factors were sourced and / or modelled. Four key data layers were created across the terrestrial area[2] of England:

- Below Ground Carbon storage.
- Above Ground Carbon storage.
- Carbon sequestration.
- Carbon Abatement.

The main factors that influence the amount of carbon stored or sequestered are:

- **The habitat type:** In mineral soils, broadleaved ancient woodlands store the most carbon (Figure 1). Unless careful management is undertaken arable land tend to store less carbon than land under permanent crops or habitat because the constant ploughing and aeration of the soil results in increased respiration of the plant materials by soil micro-organisms which decreases the overall carbon content. Carbon storage in farmland can be increased by specially tillage techniques and incorporation of additional organic matter as well as by integrating other natural habitats such as hedgerows, small shelterbelts or stands of trees and traditional orchards etc.
- In organic soils, raised bog peatlands store the most carbon, however if combined with damaging management practices (e.g. arable cropping, drainage) peatlands can become emission sources losing carbon over time to a rate of 0.86 – 0.60 kg / cm^2 yr (8,600 - 6,000 t ha yr) (Grønlund 2008).
- The influence of habitat type on carbon storage and sequestration was described by including data from Living England, the Priority Habitat Inventory (PHI) layers, and the National Forest Inventory.
- **Habitat condition**: Habitats that are managed to maintain the best ecological condition are likely to store and sequester the largest amount of carbon. It was not possible to source spatial data on habitat condition for the whole of England, however for woodlands the ancient woodland dataset was used as a proxy to indicate woodlands where conditions are likely to be good. These will hold more carbon than newly planted woodlands. Leaf litter and soil flora and fauna build up over the centuries leading to a very large store of carbon. Newly planted woodlands do not have this resource.
- **Habitat management**: Traditionally managed habitats, such as species rich hay meadows where a hay cut is taken followed by aftermath grazing (and the return of organic matter) hold a significant amount of carbon. However, there is little data across England on habitat management that is spatially explicit. In this study, protected sites boundaries were used to indicate areas that are likely to have more active appropriate management, but it is acknowledged that this is indicative as site management differs

[2] Marine areas store a large amount of carbon but this was out of scope for this study. Key factors contributing to carbon storage and Sequestration.

across sites and much land outside protected sites is managed to help maximised soil organic matter as it also has benefits to soil health and productivity.

- **Soil type:** Organic soils store more carbon than mineral soils. Clay and silt rich soils hold more carbon than sandy soils. This study used the Soilscape strategic soil data layer to give an indication of the soil type and its likely ability to store carbon; with soils higher in clay, silt and peat scoring high, and sandy soils and thin skeletal(?) soil scoring low.
- **Landform:** A woodland on a steep slope is likely to have formed on a thinner soil and thus would contain shorter trees than a woodland formed on deeper soils in valley bottoms. A digital terrain model or SRTM[3] was used to give slope thresholds to indicate when slope would begin to have an impact on the amount of carbon stored.
- **Hydrology:** Soils formed in areas with a high-water table support different types of vegetation than those on freely draining soils. Attributes were used from the soil dataset to identify soil likely to be permanently waterlogged.
- **Bioclimatic conditions:** Rainfall, temperature, wind gust and seasonality all have an impact on the habitats and the amount of carbon they store, however it was beyond the scope of this project to build bioclimate predictions into the model.

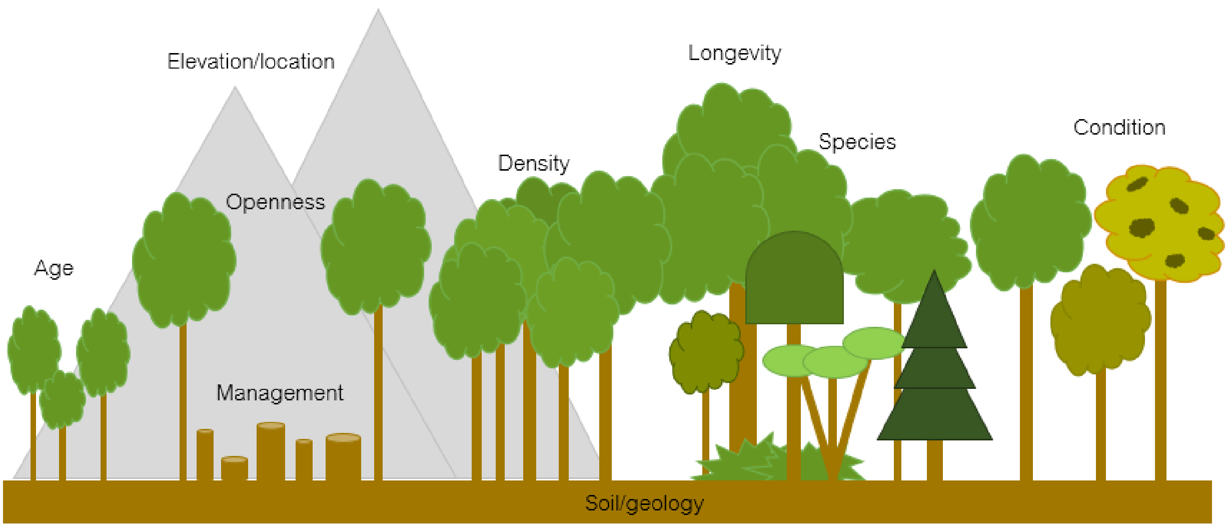


Figure 1. Factors affecting the amount of carbon stored in woodlands

[3] 30 m topographic data generated from NASA's Shuttle Radar Topography Mission (SRTM)

Review and update the existing evidence

Carbon values

The carbon values in this report have been compiled from the figures reported in NERR094. This resulted in a list of 31 evidence gaps which needed to be filled in order to characterise the carbon content of the habitats fully. The full list of evidence gaps is shown in Annex 1, the main habitat types for which gaps occur are outlined in Table 1.

Table 1. Summary of evidence gaps In NERR094 (Carbon storage by Habitat)

Evidence gap	Habitat	Evidence Gap
1 gap	Trees outside woodland	Carbon sequestration and storage and supporting important aspects of biodiversity in trees outside woodland.
6 gaps	Woodland	Understanding the carbon balance of naturally colonised or regenerated woodlands in comparison to planted ones. Together with understanding different management techniques on carbon values, and the value of wood pasture and parkland.
4 gaps	Hedgerows	There was little available data on hedgerows, types, density, and hedgerow trees.
2 gaps	Orchards	The carbon storage and sequestration potential of orchards and the impact of orchard management was not known.
2 gaps	Scrub	Significant gaps in the evidence on the carbon implications of scrub development in the UK together with changes in vegetation and soil carbon stock under scrub.
2 gaps	Heathlands	The carbon stocks in wet and dry heathland soils in response to management, grassland mosaics especially calcareous heaths.
4 gaps	Grassland	Carbon stocks and sequestration in semi-natural grasslands, especially calcareous grasslands together with the impacts of different management practices and the impact of different types of grassland on storing carbon at depth in the soil
2 gaps	Peatland under agriculture	The impact of management on subsoil and topsoil carbon under different conditions.
3 gaps	Blanket bogs and raised bogs	Improving accuracy in peat depth mapping to increase accuracy in peat carbon stock estimates together with difference in blanket and raised bog and measuring the impact of bogland restoration
2 gaps	Fens	Representation of the diversity of fen habitats across England and the rest of the UK and fens in upland situations.
1 gap	Rivers, lakes	Increasing understanding of the role of freshwaters in the carbon

Evidence gap	Habitat	Evidence Gap
	and wetland	cycle and carbon changes with restoration activity in wetlands
2 gaps	Saltmarsh Coastal and marine	Impact of grazing on carbon sequestration rates. Carbon stocks and sequestration rates of coastal and marine habitats

For each of the evidence gaps a review was done of recent scientific literature relating to the subject, and grey literature that might add to the knowledge base in terms of scoring. The search was conducted using Google Scholar and Government websites, using keywords for each evidence gap. Care was taken to select carbon storage and sequestration figures relating to the evidence gaps published after April 2021 to best identify any new evidence that might help fill these gaps. All new evidence is collated in the accompanying spreadsheet (Evidence_Gaps.xlsx). The new evidence collated was merged with the existing review work already completed to create a larger picture of the existing evidence available for each habitat.

Standardisation of data was required to ensure that consistent units are used throughout the project and that figures from different sources can be compared. There is considerable variation in the units of carbon storage and sequestration in published papers. For carbon storage, $t\ C\ ha^{-1}$ was chosen as the standard unit and $t\ C02\ e\ ha^{-1}\ yr^{-1}$ for carbon sequestration, all figures not presented in this unit are converted.

This section contains a summary of the new evidence found for each habitat based on the evidence gaps identified. Each evidence gap has been assigned a unique ID that can be used to link between this document and the spreadsheet.

Confidence was assigned to each value dependent on the number of papers reporting a figure, the comprehensiveness of the analysis and the exact match to the habitat type in question:

- High confidence was given where there was one comprehensive study, or many studies with similar results on the exact habitat type and within the UK.
- Medium confidence was given where there were several studies but few on the exact habitat type, or they were undertaken on temperate vegetation but not within the UK.
- Low confidence was given where values for a habitat had to be assumed from work on similar or related habitats.

Woodland

Table 2. New carbon figures for Woodland based on research for evidence gaps identified in NERR094.

Habitat	Evidence gaps research		Confidence	Comments/sources
	Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})		
UK ancient woodland		1.7 million t per annum	Medium	Reid et al 2021

Trends in Research and Evidence Gaps

- There is still a lack of quantifiable evidence for the gaps in woodland identified by NERR094.
- Forest Research have released a summary of statistics about woodland and forests in the UK, reporting that carbon stock in UK forests is estimated to have increased, from around 3.2 billion tonnes of carbon dioxide equivalent in 1990 to 4 billion tonnes of carbon dioxide equivalent in 2020 (Forest Research, 2021).
- It is important that more research is conducted to improve our understanding of carbon storage and sequestration in naturally regenerated woodlands.
- Evidence on the effects of specific management techniques is still lacking.
- Specific figures on whole net carbon flux measurements for all forest types and ages from recent research is difficult to come across.
- There is an evidence requirement to increase understanding of the synergies and trade-offs between carbon storage and sequestration, biodiversity and a range of other services provided by woodlands.
- There is insufficient evidence to determine carbon stock and flux of wood pastures and parkland and the impact of different regeneration techniques in wood pasture.

New Evidence

Table 2 is a summary of figures derived from recent research relating to carbon storage and sequestration in woodland. There is limited new research quantifying carbon storage and sequestration in woodland since the publication of the NERR094 report.

Understanding the carbon balance of naturally colonised or regenerated woodlands in comparison to planted ones. [Evidence Gap W-1]

Fletcher et al (2021) used the Native Woodland Model (NRW), created in 2004, to make estimations of carbon sequestration by large-scale native woodlands in Scotland established through natural regeneration. The full range of woodland types included in the model and their carbon sequestration values can be found in Fletcher et al (2021). They estimate that 3.9 million ha of native woodland could be established in the Scottish Uplands with a potential to sequester 696 million t CO_2 over a 100-year period, equivalent to an average of 6.96 million t CO_2 yr^{-1}.

Analysis by Fletcher et al (2021) contains a range of simplistic assumptions and estimates that do not account for potentially substantial changes in soil carbon as woodlands establish.

A report published by the Woodland Trust, State of the UK's woods and trees 2021 (Reid et al, 2021) states that annual sequestration by ancient woodland in Britain is around 1.7 million t C yr^{-1}, equivalent to 6.2 million t CO_2 e yr^{-1}.

Changes in soil depth or changing patterns of carbon storage at different depths. [Evidence Gap W-2]

Osei et al 2021 found that tree species identity on SOC stocks is more predominant in topsoil layers than deeper soil layers and attributed this to foliar litter influence. This finding is consistent with previous studies highlighted in the paper (Osei et al, 2021).

Soil carbon emissions under different management techniques, soil types, climates and weather conditions and the extent of inter-annual variation in soil carbon fluxes. [Evidence Gap W_3]

Hollands et al (2022) determine the carbon stocks from forest materials and assess the impact of management in a deciduous woodland in the UK. One plot was actively managed by thinning, understorey scrub and deadwood removal and the other plot that was not actively managed for 23 years. They found significant differences in the carbon stocks held by different forest materials that were dependent on site. The managed site had more carbon in the vegetation and fermentation layer, whilst the opposite occurred in dead wood and top mineral soils. This indicates that management affects the allocation of carbon stored and DOC released between different forest materials.

Whole stand net carbon flux measurements of the full range of forest types and ages. [Evidence Gap W_4]

The Woodland Carbon Code remains a good source for typical values of carbon storage and carbon sequestration by different species, timber yield classes, tree spacing and thinning. The latest version 2.4 was released in March 2021 which includes added Natural Regeneration for SP, YC 2,4 at 2 m spacing and Broadleaves (SAB) YC2,4 at 3 m spacing.

Trees outside woodland

Table 3. New carbon figures for Trees outside Woodland based on research for evidence gaps identified in NERR094.

Habitat	Study region	Evidence gaps research	Confidence	Comments/ sources
		Sequestration ($t\ C\ ha^{-1}\ yr^{-1}$)		
Trees in pasture	UK	1-4 (density of 50-100 trees/ha)	High	Reid et al, 2021
Silvopastoralism (integrating trees with pastures and livestock husbandry)	Range across different systems globally	-0.72 - 2.2	Medium	FAO and ITPS. 2021

Trends in Research and Evidence Gaps

- With the exception of hedgerows, research for carbon storage and sequestration in trees outside woodland remains more limited than the research for trees in woodland.

- The new research figures shown in Table 3 seem to have some consistency in the amount of carbon sequestered by trees in pasture / silvopastoralism, however more research is required to give confidence to these figures.

Hedgerows

Table 4. New carbon figures for Hedgerows based on research for evidence gaps identified in NERR094.

Habitat	Study region	NERR094 Figures		Evidence gaps research		Confidence	Comments/ sources
		Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})	Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})		
Hedges (aboveground)	Temperate climate zones	40.6 ± 4.47 trimmed to 2.7 m 32.2 ± 2.76 trimmed to 1.9 m	0.13–0.51 (based on understory woodland data)	52.2 ± 27.7		Low Medium	Blair, J., 2021. Value from mixture of peer review and grey lit. Drexler et al, 2021.
Unmanaged/minimally managed hedgerow vegetation		45.8 ± 12.26 42 ± 3.78					
Unmanaged **hedgerow** soil + vegetation		144.5 74–112 (SOC)					
Establishment of hedgerows on cropland (20 yrs transition time to equilibrium)	Temperate climate zones			17 in soil (additional)	SOC: 0.9 Veg: 4.3 Total: 5.2	Medium	Drexler et al, 2021
Establishment of hedgerows on cropland (50 yrs transition time to equilibrium)	Temperate climate zones				SOC: 0.3 Veg: 1.7 Total: 2.1	Medium	Drexler et al, 2021
Establishment of hedgerows on cropland (soil)	Temperate climate zones				0.7 (mean)	Medium	Drexler et al, 2021

Habitat	Study region	NERR094 Figures		Evidence gaps research		Confidence	Comments/ sources
		Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})	Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})		
Cropland to Hedgerow	Temperate climate				0.45 ± 0.40	Medium	Cardinael et al, 2018b
Established Hedgerow width 5m (established on cropland?)					Veg: 1.7 Soil:0.5	Low	Cardinael et al, 2018b
UK Hedgerow – regular trimming	United Kingdom				1 in biomass	Low-medium	Biffi et al, 2022.
Intensively managed Hedgerow		Managed: 67–95 (SOC)			Veg: 1.2		Biffi et al, 2022.
Hedgerow		Planted hedgerow: 76 ± 32 (above and below ground biomass)	New: 0.54 Old: 0.46	Above ground biomass: 47 ± 29 Below ground biomass: 44 ± 28 (high uncertainty) Total: 92 ± 40	Above & belowground biomass: 0.3-0.75		Drexler et al, 2021. Biffi et al, 2022.
Hedgerow (global temperate)	Temperate climate				Aboveground: 0.87 Below ground biomass: 0.23		Biffi et al, 2022.
Hedgerow (37 yr old)	England	Remnant hedgerow (38 yr old): 124 ± 21 (above and below ground biomass)			SOC rate: 1.48 (top 50 cm)		Biffi et al, 2022.
Hedgerow (SOC at 23 cm depth)		166 (55 cm depth. In		81.7 ± 28.8			

Habitat	Study region	NERR094 Figures		Evidence gaps research		Confidence	Comments/ sources
		Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})	Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})		
		vicinity to hedges)		Ghost hedgerow: 57.9 ± 14.1			
Hedgerow (stock in non-harvested biomass)	Western France			1.2 to 21.6 Mg C 100 m^{-1} above ground biomass 0.7 to 6.1 Mg C 100 m^{-1} in below ground biomass		Medium	Viaud and Kunnerman, 2021
Trees in hedgerows					0.7 – 4.3 t km^{-1} yr^{-1}		Van Den Berger et al, 2021

Trends in Research and Evidence Gaps

- Although the potential for hedge systems to store and sequester carbon has been acknowledged, there has been an increased interest in quantifying these values and their potential to contribute to net zero goals, especially for temperate regions.
- Recent studies have included more emphasis on the carbon sequestration benefits of establishing hedgerows on cropland.
- There is little new evidence on how species biodiversity within hedgerows impacts its carbon stock. Hedgerows studied by Biffi et al (2022) consist predominantly of hawthorn and blackthorn species and they do not discuss how these rates may vary beneath hedgerows dominated by different species and management regimes.
- There is a selection of papers that study hedgerows in the UK, mostly with the aim of quantifying carbon storage and sequestration. However, it remains that there is not sufficient research to represent the diversity of hedgerows in the UK.
- Recent studies investigating the carbon benefits of allowing hedgerow trees to become established generally conclude that trees in hedgerows have the potential to sequester significant levels of carbon, with some exceptions.

- Detailed information on the factors influencing carbon storage and sequestration remain unknown at a national level in the UK. These factors include management, age, width and height, species diversity, soil type, seasonal weather events, density.

New Evidence

Table 4 is a summary of figures derived from recent research relating to carbon storage and sequestration in hedgerows. Figures from the NERR094 report have also been included for comparison to see how new research compares to existing research.

Availability of data regarding carbon storage and sequestration in hedgerows representing the diversity of hedgerows found in the English landscape and the influence that vegetation management, different tree and shrub species, soil type and depth have on their ability to accumulate and store carbon above and belowground. [Evidence gap HR_2]

The biomass carbon stock figures in the Drexler paper (Total 92 ± 40 t C ha^{-1}) are independent of fluctuations occurring from hedgerow management. It has been reported that regular trimming hinders total biomass growth and sequestration estimates are around 1 t C ha^{-1} yr^{-1} (Biffit et al, 2022).

There is potential to increase carbon sequestration and storage of UK hedgerows by allowing them to become wider and taller. A hectare of hedgerows between 3.5 m and 6 m wide could sequester as much as 131.5 t C yr (CPRE and the Organic Research Centre, 2021).

Informing the need to boost biodiversity and climate change mitigation potential of hedgerows, including quantifying the carbon benefits of allowing hedgerow trees to become established. [Evidence Gap HR_3]

Viaud and Kunnegmann (2021) attempted to quantify the carbon storage potential of hedge agroforestry in France whilst Drexler et al (2021) conducted research on carbon sequestration in hedgerows in temperate zones. Biffi et al (2022) studied hedgerows in Cumbria, England on a dairy farm to quantify the soil carbon sequestration potential of planting hedgerows in agricultural landscapes.

Blair (2021) calculated a mean value of 52.2 ± 27.7 t C ha^{-1} for carbon stock in the aboveground component of hedgerows. This figure was derived from a literature search of both peer-reviewed and grey literature. There is some uncertainty associated with this; however this value is similar to figures reported in NERR094.

The need to quantify the carbon benefits of allowing hedgerow trees to become established had been identified as an evidence gap. Van Den Berger et al (2021) found that trees in hedgerows can sequester 0.7 to 4.3 t km^{-1} yr^{-1} (4,300 t m yr^{-1}) aboveground and conclude that trees growing in hedgerows should be included when biomass and carbon budgets are drafted. Litza et al (2022) found that numerous forest plant species can thrive in hedgerows in an agricultural landscape in Europe, with some exceptions of species that don’t. The species that thrive are likely thermophilic, tolerant against regular disturbance and able to disperse efficiently. Hedgerows in warm regions that are impacted by drought events contain fewer forest species. They also found that intensive adjacent land use had a negative impact on forest species richness, while the surrounding forest cover was not significantly important. Consistent with previous regional studies, they also found that wider hedgerows contain more forest species (Litza et al, 2022).

The Climate Change Committee (CCC) recommends that the extent of our hedgerow network should be increased by 40% to support the UK government’s goal of net-zero carbon emissions by 2050. A report by CPRE and the Organic Research Centre (2021) calculates there are 649,715 km of ‘managed’ hedgerows in the UK. Based on their knowledge of ratios of managed and unmanaged hedgerows and their suggestion that 30% of hedgerows in the new network be brought into management for biofuel, they have created a conservative estimate that a 40% increase in the UK’s hedgerows would have a sequestration potential of 1.9 million tonnes of carbon.

As identified in the NERR094 report, in the past woodland species have been used in data modelling to create estimations of carbon storage and sequestration in hedgerows. As hedgerows are typically more densely planted, this may lead to an underestimation of their carbon benefit potential. The ‘Hedge Fund’ report by CPRE and the Organic Research Centre (2021) describes how landscapes with a high density of hedgerows (200m per hectare of agricultural land) were found to have SOC stocks reaching 117 t C ha^{-1} with 38% of this effect being attributed to hedgerows (this translates to 44.5 t C ha^{-1}). In comparison to this, land with a density of 50 m of hedgerow per hectare had a mean SOC stock of 84 t C ha^{-1}, with hedges contributing only 13%.

Investigating how carbon storage in soils and biomass is offset by greenhouse gas emissions from trimming, flailing, disposal, laying, coppicing and cultivation methods and the role hedgerows can play in producing biomass for wood fuel, replacing fossil fuel emissions. [Evidence gap HR_4]

NERR094 identifies an evidence gap in the role hedgerows can play in producing biomass for wood fuel, replacing fossil fuel emissions. Whilst it is important to consider that woodchip production conflicts with long-term above ground storage of carbon and affects mitigation for climate change goals. A report by CPRE and the Organic Research Centre (2021) suggest that if 30% of the UK’s expanded hedgerow network is brought into small scale management for local and domestic woodchip biofuel, this would result in an innovative source of cleaner energy, as well as bringing an economic return on investment to the farmers.

Drexler et al (2021) found that, using Tier 1 default factors, for (net) calorific values and CO_2 emission factors, one hectare of harvested hedgerow biomass could substitute 1.6 tonnesnatural gas or 1.8 Mg light fuel oil per year. In carbon mitigation terms, this translates to 1.2 t C ha^{-1} yr^{-1} substituting natural gas or 1.5 t C ha^{-1} yr^{-1} substituting light fuel oil.

Orchards

Trends in Research and Evidence Gaps

- Most studies relating to carbon in orchards are based outside the UK. Of the few recent studies conducted on this topic, there seems to be a scarcity of those in temperate regions.
- There is insufficient evidence regarding the potential of orchards to sequester and store carbon, especially in the UK.
- There is a need for research into the management of orchards and the impact of this on carbon storage in the biomass and soil.

New Evidence

The impact of orchard management on carbon stored in the biomass and soils. [Evidence Gap O_2]

Granata et al (2021) measured the seasonal pattern of carbon sequestration over a year in two hazelnut orchards with traditional management in Italy. Orchard A had a training system of plants grown on a single trunk and orchard B had a bush like training system (stemmed plants with 4 to 6 separate stems). They sequestered values of 7 t C ha^{-1} yr^{-1} and 14 t C ha^{-1} yr^{-1} respectively. This demonstrates that the two training systems affect carbon sequestration potential. These figures are significantly higher than estimates highlighted in NERR094, emphasising the importance of further research, especially in the UK.

Scrub

Trends in Research and Evidence Gaps

- Recent studies that include scrub habitats also highlight the fact that there are very few studies on carbon cycling in scrub (Thom and Doar, 2021)
- There is an evidence need in the carbon implications of developing scrub, specifically in the UK.
- There are few studies on the changes on scrub vegetation and soil carbon stocks in the UK.

Heathlands

Table 5. New carbon figures for Heathland based on research for evidence gaps identified in NERR094. Note some cells have been left blank.

Habitat	Study region	NERR094 Figures	Evidence gaps research	Confidence	Comments/ sources
		Storage (t C ha^{-1})	Storage (t C ha^{-1})		
Heathland vegetation	UK	Dwarf shrub heath various figures from papers: 2, 2 – 17.5, 9, 49	0.5 - 49	Medium - High	Stafford et al, 2021
Heathland soil	UK	Dwarf shrub heath various figures from papers: 88, 50.7 – 196, 94	82 - 103	Medium - High	Stafford et al, 2021
Scotland Upland dry heathland (soil samples to 100cm)	Scotland		Min = 47 Mean = 205 Max = 648		Baggaley et al, 2021
Upland heathland		Unmanaged vegetation: 49			

Habitat	Study region	NERR094 Figures	Evidence gaps research	Confidence	Comments/ sources
		Storage (t C ha^{-1})	Storage (t C ha^{-1})		
Scotland Wet heathland (soil samples to 100cm)	Scotland		Min = 114 Mean = 313 Max = 784		Baggaley et al, 2021

Trends in Research and Evidence Gaps

- Whilst there are a number of studies quantifying carbon storage and sequestration in heathland, there remains a need for further studies to compare mineral and organic soils across a range of geographical locations in the upland and lowlands (Stafford et al, 2021).
- There is a requirement for more experimental research on the impacts of management interventions on the carbon stocks in wet and dry heathlands.
- There is an evidence gap on the impacts of higher scrub and tree cover on the carbon fluxes and trade-offs with specialist species which require open niches.
- Generally, studies conclude that planting trees and scrub on heathland does not directly result in gains in carbon stocks. There remains a gap in quantifiable evidence of the impacts of higher scrub and tree cover on carbon fluxes in heathlands.

New Evidence

The carbon stocks in wet and dry heathland soils respond differently to management interventions. More experimental research on the impacts on different types of heathlands would help when providing tailored advice and management. [Evidence Gap HL_1]

The British Ecological Society have gathered and analysed results from existing papers in their 2021 report 'Nature-based solutions for climate change in the UK' therefore some of the figures have already been quoted in the NERR094 report and may explain similarities between the comparison with new evidence data.

Baggaley et al, 2021 present figures on soils carbon storage to 100 cm depth at 19 sample points for upland dry heathland and wet heathland. The figures are from the National Soil Inventory of Scotland data (2007-2009), therefore they cannot be considered new research.

The impacts of higher scrub and tree cover on carbon fluxes and particularly trade-offs with specialist species which require open niches are not clear. [Evidence Gap HL_2]

The general trend of research shows that planting trees on heathland does not directly lead to significant gains in carbon stocks and can even potentially reduce carbon sequestration and increase emissions (Thom et al, 2021). Restoring heathland by reversing past succession to scrub and tree cover is likely to lead to GHG emissions (Thom et al, 2021).

Grasslands

Research Trends and Evidence Gaps

- All evidence gaps identified in the NERR094 report have not been investigated in depth since the report was published in April 2021.
- There are significant evidence gaps with carbon stocks and sequestration in semi-natural grasslands, especially for calcareous grasslands.
- There are insufficient amounts of carbon flux datasets from grasslands and those which assess changes with different management practices or grassland restoration from arable sites.
- There are gaps in our understanding of the synergies and trade-offs between the potential for grasslands to store and sequester carbon on and specific management interventions, such as cutting, liming and burning.
- There's a need to quantify grassland carbon stores at depth and their interaction and sensitivity to grassland intervention. There is also an evidence gap in understanding how past management can continue to influence grassland's carbon storage potential.

New Evidence

There are few carbon flux datasets from grasslands and very few which assess changes with different management practice or grassland restoration from arable sites. [Evidence gap GR_2]

One significant research paper by Chang et al (2021) conclude from their findings that net global climate warming caused by managed grassland cancels the net climate cooling from carbon sinks in sparsely grazed and natural grasslands. In their study, global trends and regional patterns of the full greenhouse gas balance of grasslands are estimated for the period 1750 - 2021. They found that grasslands worldwide are found to have no warming effect on climate, thanks to the presence of intensified carbon sinks, especially over sparsely grazed grasslands.

In terms of specific management practices, Brown et al 2021 found in their study that deep non-inversive and minimum tillage led to 6.5 and 1.6 t C ha^{-1} greater SOC than conventional plough sites under rotation systems. In a monoculture system in Scotland, conventional plough had 25.3, 21.6 and 17.7 t C ha^{-1} greater SOC than plough compaction, minimum tillage and zero tillage, respectively.

Peatland under agriculture

Research Trends and Evidence Gaps

- There is an evidence requirement for further investigations at scale and under field conditions.
- There is insufficient data on the impact of management on subsoil carbon.

New Evidence

A report by the British Ecological Society (2021) discusses the climate change mitigating and adoption potential and biodiversity value of peatlands, however as the report is a review of existing literature it does not offer any new information. The evidence gaps in peatlands remain an information need.

Peatlands are now emitting greenhouse gases at a rate of about 3,400 kt CO_2 eq yr^{-1}, with about 31% of this being attributed to agriculture or forestry UK peatlands (Thom and Doar, 2021)

Blanket bogs and raised bogs

Research Trends and Evidence Gaps

- The improved accuracy in peat depth mapping to increase accuracy of carbon stock estimates remains an evidence need.
- For emissions from ombrotrophic bogs there is insufficient data to differentiate between blanket bog and raised bog. There is a need for site-based studies to support quantification of the potential benefit for carbon emissions that restoration interventions may have on peatland habitats.
- There is an evidence gap in quantifying the co-benefits of raised bog restoration for biodiversity and climate change mitigation.

New Evidence

UKCEH Countryside Survey are currently conducting a new rolling survey which continues sampling in the same locations as their 2007 survey, reporting on findings on soil carbon from this survey will begin in 2022., results of the full survey will be published in 2025.

It has been projected that each hectare of active raised bog that is restored could sequester c. 1.85 t CO_2 ha^{-1} yr^{-1}, with a reduction of 6 t CO2 ha^{-1} yr^{-1} if the bog is restored from a very degraded condition. This translates to c. 0.51 t C ha^{-1} yr^{-1} and 1.6 t C ha^{-1} yr^{-1} respectively.

Fens

Research Trends and Evidence Gaps

- Based on the evidence gaps identified, no new evidence has been found on fen habitats.
- There is a need for further work to create an evidence base which represents the diversity of fen habitats in England and the rest of the UK.
- There is still a knowledge gap on the current extent of fen habitats, especially in the uplands.

Rivers, lakes and wetland

Table 6. New carbon figures for Rivers, Lakes and Wetlands based on research for evidence gaps identified in NERR094. Note some cells have been left blank.

Habitat	Study region	Evidence gaps research		Confidence	Comments/ sources
		Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})		
Natural pond in arable vegetation	UK	30		High	Thom and Doar, 2021
Natural pond in pasture vegetation	UK	47		High	Thom and Doar, 2021
Natural pond in dune vegetation	UK	59		High	Thom and Doar, 2021
Wetlands	European Union		0.49 – 6.5	Medium	Malak et al, 2021
Riparian, fluvial and swamp forest - EU	European Union		0.9 – 5.63 (90 – 563 g C m^{-2} yr^{-1})	Medium	Malak et al, 2021
Inland marshes	European Union		1.73 ± 1.18 (173 ± 118 g C m^{-2} yr^{-1})	Medium	Malak et al, 2021
Boreal Mires, bogs and fens	European Union		0.34 ± 0.57 (34 ±28 g C m^{-2} yr^{-1})	Medium	Malak et al, 2021
Rest of EU mires, bogs and fens	European Union		0.57 ± 0.34 (57 ± 34 g C m^{-2} yr^{-1})	Medium	Malak et al, 2021

Research Trends and Evidence Gaps

- New carbon storage and sequestration figures have been included in **Error! Reference source not found.** to aid better representation of key freshwater habitats, however there still remains an evidence gap in this area.
- There is a need for increased consideration of the linkages between terrestrial-based solutions and freshwater.
- There is also a need for assessment of the carbon benefits of restoring human-modified habitats to their natural state.

New Evidence

Although the figures do not address the specific evidence gaps, Thom and Doar (2021) present new figures of carbon stocks in varying standing water environments (see **Error! Reference source not found.**) in their literature review. Another source reports carbon sequestration rates for wetlands as 0.49 – 6.5 t C ha^{-1} yr^{-1} (Malak et al, 2021). The sequestration values for more specific wetland classification of terrestrial wetlands are shown in **Error! Reference source not found.**, the values were given as g C m^{-2} yr^{-1} and have been converted to t C ha^{-1} yr^{-1}. The carbon sequestration potential of healthy EU Wetlands per year is calculated to range between 24,352 - 143,719 kt CO_2 eq yr^{-1} (Malak et al, 2021)

Saltmarsh

Table 7. New carbon figures for Saltmarsh based on research for evidence gaps identified in NERR094. Note some cells have been left blank.

Habitat	Study region	Evidence gaps research		Confidence	Comments/ sources
		Storage (t C ha^{-1})	Sequestration (t C ha^{-1} yr^{-1})		
Saltmarsh	European Union		1.66 - 2.82 (166 – 282 g C m^{-2} yr^{-1})	Medium	Malak et al, 2021
Natural saltmarsh	UK and NW Europe	90.6 (± 92.5)	1.18 (UK), 2.24 (Northern Europe)		Mason et al, 2022
Natural saltmarsh (1m depth)	UK and NW Europe	461.8 (± 852.8)			Mason et al, 2022
Restored Saltmarsh	UK and NW Europe	138.85 (± 64.94)	3.63 ± 4.09		Mason et al, 2022
Restored Saltmarsh (1m depth)	UK and NW Europe	506.29 (± 237.93)			Mason et al, 2022
Saltmarsh (Sediments)	UK	59 [20 to 134]			Corrected figures from Beaumont et al (2014)
Saltmarsh (Vegetation)	UK	13			Corrected figures from Beaumont et al (2014)
Coastal wetlands and lagoons – (EU saltmarshes	European Union		2.82 ± 0.99 (282 ±99 g C m^{-2} yr^{-1})	Medium	Malak et al, 2021
Coastal wetlands and lagoons – (Mediterranean saltmarshes)	European Union		1.66 ± 0.83 (166 ±83 g C m^{-2} yr^{-1})	Medium	Malak et al, 2021

Research Trends and Evidence Gaps

- The impact of grazing on carbon sequestration rates remains an evidence gap.

New Evidence

The paper released by Beaumont et al 2014 has since released corrections for carbon storage figures in saltmarsh. See Table 7 for the updated figures.

There are not many new studies that quantify the effects grazing has on carbon sequestration in saltmarsh, new research tends to be more focused on how grazing management can increase erosion resistance in saltmarshes (Marin-Diaz et al, 2021; Zhang et al, 2021), although they acknowledge that intensive and long -term grazing can have a negative effect on soil carbon content.

Graversen et al (2022) found that significantly larger aboveground biomass and vegetation height in non-grazed salt marshes than in grazed salt marsh in study sites in Denmark did not lead to significantly enhanced overall carbon accumulation rates. Detailed model analyses of sediment profiles even indicated higher carbon densities in the surface layers at grazed sites. The results of the research showed carbon sequestration rates of 17-45 g C m^{-2} yr^{-1} (0.17 - 0.45 t C ha^{-1} yr^{-1}).

The figures published by Malak et al (2021) are based on a meta-analysis of 34 peer reviewed studies and they have assigned low confidence.

Since conducting the literature search for the carbon evidence gaps new research has been released. Mason et al, 2022 conducted their own literature review to synthesise data for developing the metrics of a UK saltmarsh Carbon Code. Based on their literature search they have calculated average carbon storage and sequestration values for both natural and restored saltmarsh, the figures have been included in Table 7.

Coastal and marine

Table 8. New carbon figures for Coastal and Marine based on research for evidence gaps identified in NERR094. Note some cells have been left blank.

Habitat	Study region	NERR094 Figures		Evidence gaps research		Confidence	Comments/ sources
		Storage (t C ha-1)	Sequestration (t C ha-1 yr-1)	Storage (t C ha-1)	Sequestration (t C ha-1 yr-1)		
Wetland	European Union			50 - 150		Medium	Malak et al, 2021
Seagrass	European Union				0.43 – 0.52 (43 - 52 g C m-2 yr-1)	Medium	Malak et al, 2021
Sand dunes (sediments)	UK	9.5 [4 to 15]					Corrected figures from Beaumont et al (2014)
Sand dunes (vegetation)	UK	5 [1.6 to 8]					Corrected figures from Beaumont et al (2014)

Research Trends and Evidence Gaps

- There remains a need for increased evidence on carbon stocks and sequestration rates in coastal and marine habitats.

New Evidence

The paper released by Beaumont et al 2014 has since released corrections for carbon storage figures in sand dunes. See Table 8 for the updated figures.

New evidence was found for only some of the coastal habitats Included in the NERR094 report, see Table 8. Please see the NERR094 for more Information on the coastal habitats that have not been Included In this report.

Coastal and saltmarsh habitats, when healthy, hold high and varied ranges of carbon namely that alter between 50 - 150 t C ha^{-1} of carbon stock (Malak et al, 2021). Coastal wetlands incorporate many habitats, including saltmarsh, intertidal flats and estuaries.

All coastal and marine habitats discussed In the NERR094 report were research, however only

The figures published by Malak et al (2021) are based on a meta-analysis of 34 peer reviewed studies and they have assigned low confidence

Mapping Method

An updated methodology for the Spatial Prioritisation of Land Management for Carbon was created. This included identifying above and below ground soil carbon storage, carbon sequestration values and areas for potential carbon abatement. The final expectation was England-wide vector datasets for above and below ground carbon storage, carbon sequestration, and abatement.

The first stage was to produce a representative carbon value for each of the habitats considered in the datasets sourced. This was calculated from values gathered in the review and update of existing evidence stage of the project. Secondly, FME workbenches were developed to model the data spatially (Figure 2). Finally, maps were produced and priorities investigated.

Relating carbon values to spatial data

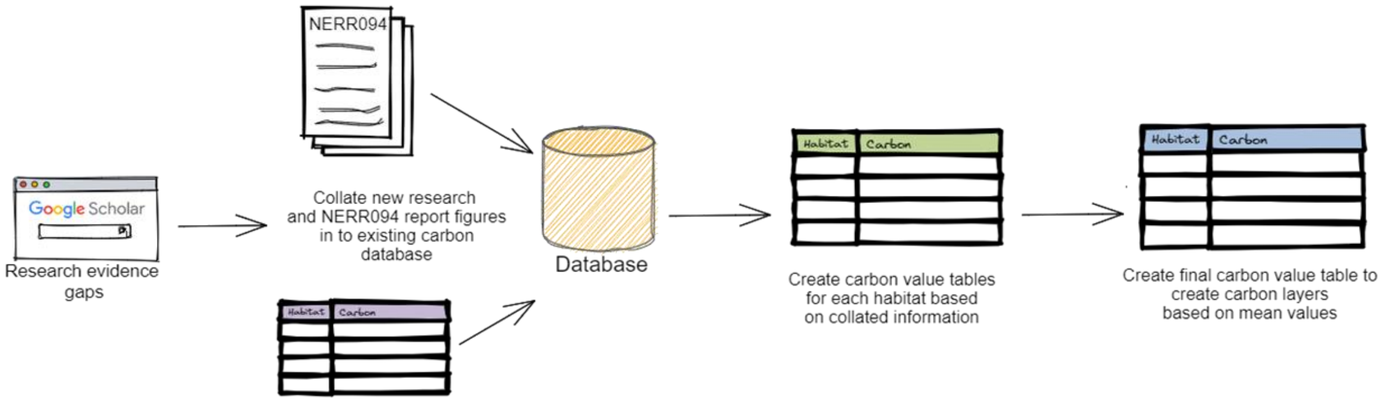


Figure 2. Relating spatial data to soil carbon values

Having conducted research for the evidence gaps Identified in the NERR094 report, the figures were collated. Carbon tables were completed for each type of habitat individually, with values being assigned to carbon storage in soil and vegetation, and carbon sequestration in soil and vegetation. Ranges for each habitat carbon value were created based upon the minimum and maximum reasonable values found from the research, which were then used to calculate a mean value, with the idea that these mean values can be applied to carbon tables to create map layers.

In areas where no new research was found for the evidence gaps identified In NERR094, there remains a knowledge gap for some habitats. In these instances, educated estimates were made according to comparison with other habitats. For example, Neutral grassland figures were used to educate an estimate for lowland meadows. Where there remains a lack of scrub carbon values in literature, bracken figures were used for the low range of scrub carbon values and hedgerows were used for the higher range values.

The final step was to create the carbon table that would be used to create the map layers. The figures from the Natural England scoring table used for the previous map layer were updated to reflect new and up to date research.

Beaumont et al (2014) updated their carbon figures for sand dunes and saltmarsh therefore It was ensured that these changes were included in the new scoring table for the map layer.

Table 9 contains a summary of the reasoning behind the decisions for some of the habitat scoring values.

Table 9. Reasoning behind carbon values applied to PHI habitats.

Habitat	Reasoning behind scoring
Deciduous woodland	Used broadleaved woodland figures for soil and vegetation storage.
Lowland meadows	Neutral grassland used for soil and vegetation carbon storage
No main habitat but additional habitats present	Neutral grassland used for soil and vegetation carbon storage
Upland hay meadow	Neutral grassland used for soil and vegetation carbon storage
Good quality semi-improved grassland	Neutral grassland used for soil and vegetation carbon storage
Upland heathland	Figures used from Heathland. Same figures used for lowland and upland. Sequestration values range from minus to plus.
Lowland heathland	Figures used from Heathland. Same figures used for lowland and upland. Sequestration values range from minus to plus.
Lowland fens	Sequestration value from fen, marsh and swamp
Coastal saltmarsh	Update from new figures updated in Beaumont et all
Upland flushes, fens and swamps	Sequestration value from fen, marsh and swamp
Lowland calcareous grassland	Figures used from Semi-natural calcareous grassland. Same figures used for lowland and upland
Upland calcareous grassland	Figures used from Semi-natural calcareous grassland. Same figures used for lowland and upland
Coastal sand dunes	Update from new figures updated in Beaumont et all
Lowland dry acid grassland	Figures used from Semi-natural acid grassland.
Mudflats	Mudflat figures used. Sequestration calculated from mean of intertidal/mudflat values.
Saline lagoons	Mudflat figures used
Calaminarian grassland	No figure but new soil on mine waste (so will be very small) and very open habitat structure - small area
Fragmented heath	Same figure for storage as purple moor grass and rush pastures. Slightly lower sequestration as an estimate.

Considerations and drawbacks

There are still significant evidence gaps for a number of different habitats which can cause difficulty when attempting to score the habitats with carbon values confidently. Soil depth must also be considered when allocating a carbon score. Not all papers specify the soil depth used either in their own research or when referring to other research.

In many cases the sequestration figures given in the literature do not specify whether this refers to the vegetation (which is how we are describing carbon stored longer term by net primary productivity) or the soil and often just refer to a habitat generally. As it is difficult to know which is being referred to, these values were assumed to apply to the habitat as a whole (soil and vegetation). Therefore, sequestration values for the layers were considered as total habitat sequestration, as opposed to having separate values for soil and vegetation.

Spatial Data

Habitat data conflation

- Data conflation – data are amalgamated together in a priority order with the layers lying on top superseding those below as they either are enhanced temporal or spatial detail. (Figure 3)
    - The base data are Natural England's newly released and up-to-date evaluation of the land cover of England based on satellite imagery. The mapping deploys an automated analysis largely built on a technique called Random Forest classification. Training data from fieldwork feed into an algorithm which allows the comparison of all included datasets to devise attributes which split them into predefined classes.
    - The PHI form the next layer of the conflation. These are spatially more precise and most of these sites have some form of field survey. For this project we have not considered the confidence in the habitat designation so as to catch the maximum likely extent of suitable habitat.
    - Finally, we use certain attributes from the National Forest Inventory which best describe the extent of woodland blocks (Appendix 2). Woodland is a significant resource for both above and below ground carbon and this data set gives the most accurate rendition of woodland resource. It is now about five years old and new woodland planting schemes will not be captured by it, but these are not yet likely to be contributing strongly to carbon resources, they normally need to be about ten years old and closed canopy to begin to have a marked effect on carbon sequestration and storage.

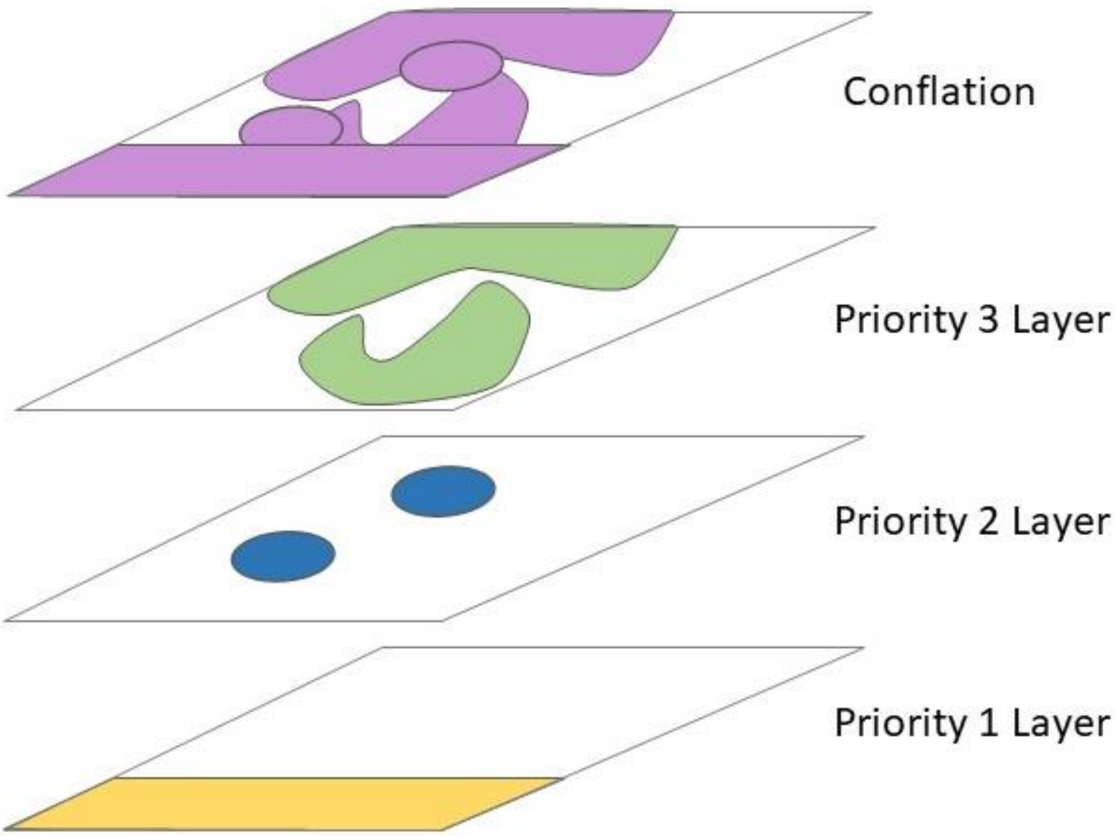


Figure 3. Conceptional diagram of vector data conflation.

Soil data conflation

- The soil data used were Cranfield's SoilScape dataset which are less detail than their NatMap vector data from which they derive their soil carbon layer and values, but are open data, and as the map is strategic it is considered to be at a suitable scale.
- Supplemented by the Natural England peatland data set which lies on top and will supersede the SoilScapes.
- The soil data layers were also supplemented by the below ground fraction of the vegetation storage values from the overlying habitat. This helps provide a better spatial resolution for the below ground storage figures
- Soil depth is an important consideration when evaluating how much carbon is likely to be stored within the soil. Most carbon is held in the topsoil, although a lesser amount of carbon can be held deep into the soil profiles. In order to build this consideration into the model each soil type was allocated to one of four depth classes:
  - Shallow soils with a profile likely to be 15-50 cm or less. The models assumed a 30 cm depth for carbon calculations.
  - Normal depth mineral soils with a profile between 1 m and 1.25 m. The models assumed a 1 m depth for carbon calculations.
  - Blanket peat soils. The models assumed a 2 m depth for carbon calculations.
  - Raised bog and fen peat soils. The models assumed a 4 m depth for carbon calculations.

Influencing factors

For any given habitat, a range of factors could influence the potential for carbon storage or sequestration.

Slope

- Slope is a key influencing feature in the below ground soil storage. Soils on steep slopes tend to be shallower, therefore store less carbon (Figure 4).
- Above ground on very steep slopes (over 18°) tree species in particular grow more slowly and are not as high as trees which grow on deeper soil. For woodland therefore very steep slopes have also been introduced as a factor for a slight decrease in carbon storage and sequestration in these areas.

Condition / Age

- Management and condition will influence the amount of carbon stored, its uptake and release.
- Differently aged vegetation sequester carbon at differing rates, depending on their growth stage.

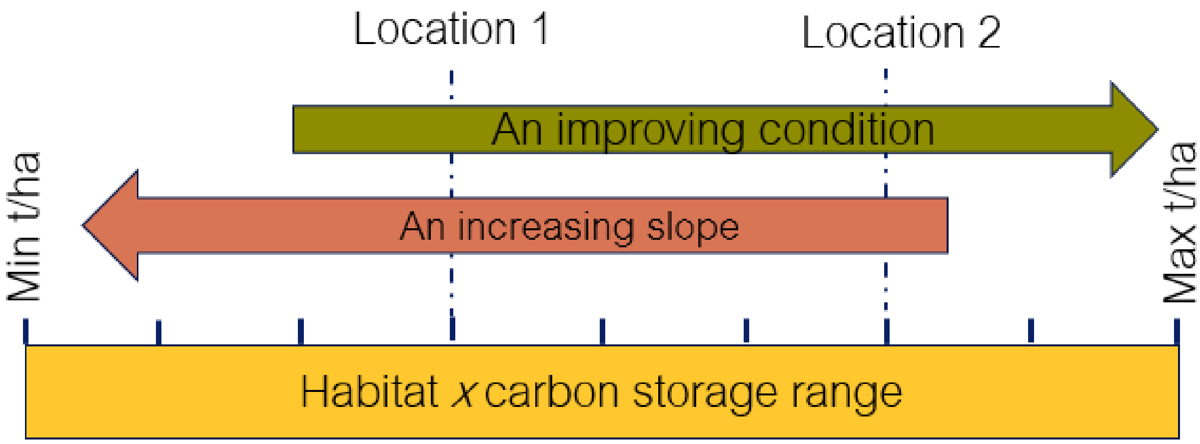


Figure 4. Example of factors impacting the range of possible tonnes carbon per hectare storage and sequestration in habitats. (FIG)

Mapping Carbon Abatement Opportunities

Certain soil types and vegetation types are inextricably linked. For example, peat soils have developed under bog, fen and heathland habitats. Where existing habitats occur on appropriate soils then there is often a chance to improve the ecological condition of these areas. This project has not looked at site condition, so all these areas have been flagged as maintain and enhance existing habitat. As this will prevent carbon loss form the soils and vegetation, and it is the most important action that should be undertaken in these areas.

Where the soil type is no longer covered by its natural habitat, for example where peat is now under grass or arable crops then restoring the natural habitat will return the system to the best ability to sequester and store carbon. For example, where peatland soil has been under drained for arable farmland, restoring it to wetland will stop the carbon loss.

Over much of England, woodland would have been the original habitat type before human clearance of land for grazing and arable crops. Although there are large targets for woodland planting for carbon it does not make sense to plant trees everywhere, this would disbenefit food production and rural sociality needs.

In this project we have not concentrated on commercial plantation woodland, which has a very wide biogeographic land type spread, but instead on planting broadleaved woodland of native species to aid both carbon and biodiversity. This type of woodland establishes fastest on land that has not been heavily fertilized prior to planting. If levels of nitrogen and phosphorus in the soil are too high, establishment is problematic due to competition from nettles and course grasses. The understory on such land is impoverished for tens of years, comprising mostly fast growing competitive ruderal species such as nettles with few of the shrubs, climbers and ground flora of a diverse carbon rich environment.

For this reason, we have therefore concentrated on the Living England Class calcareous, acid and neutral grassland which seems to identify land which has been improved and reseeded many years ago but has not has a high an important of fertilizer as short- and longer-term perennial rye grass lays.

It is important though to acknowledge that some of these grasslands might well be of good quality and better restored to native grassland types, therefore a field visit is essential before starting a restoration scheme to ascertain areas for plating woodlands and areas for restoring grassland and species rich hay meadows, both will have carbon enhancement benefits.

The amount of carbon abatement improvement possible on any land has been calculated into classes from a 'high' score, e.g. rewetting of peat under arable, through to enhancing carbon by active carbon management of improved perennial rye grassland lays medium. Arable land is likely to be needed for food security, there is always the opportunity to enhance carbon on arable land, but this is a lower level and so has been scored ‘low’. The logic rules are listed in Appendix 3.

FME workbenches

FME is a priority Data Integration Platform produced by Safe Software. FME Workbenches allows building scripts for data transformation using a drag-and-drop GUI, therefore making it ideal for repeatable multistep processes. Three FME workbenches were created; 1) above ground carbon, 2) below ground carbon, 3) carbon sequestration. Note, the Carbon Abatement layer was produce using python, due to the complex nature of the rules (Appendix 3). Flow diagrams outlining the FME processing steps are shown in Figures 5 - 8.

Figure 5. Flow diagrams outlining the FME processing steps for the above ground carbon analysis.

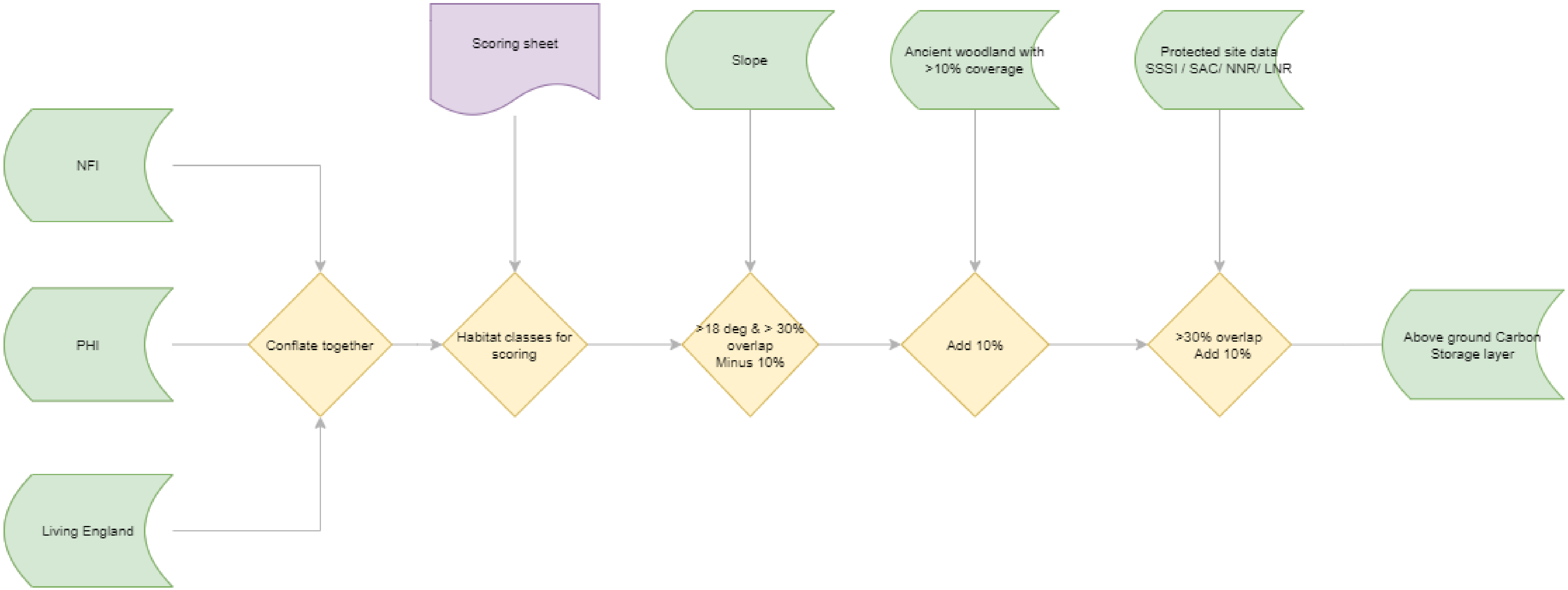


Figure 6. Flow diagrams outlining the FME processing steps for the below ground carbon analysis.

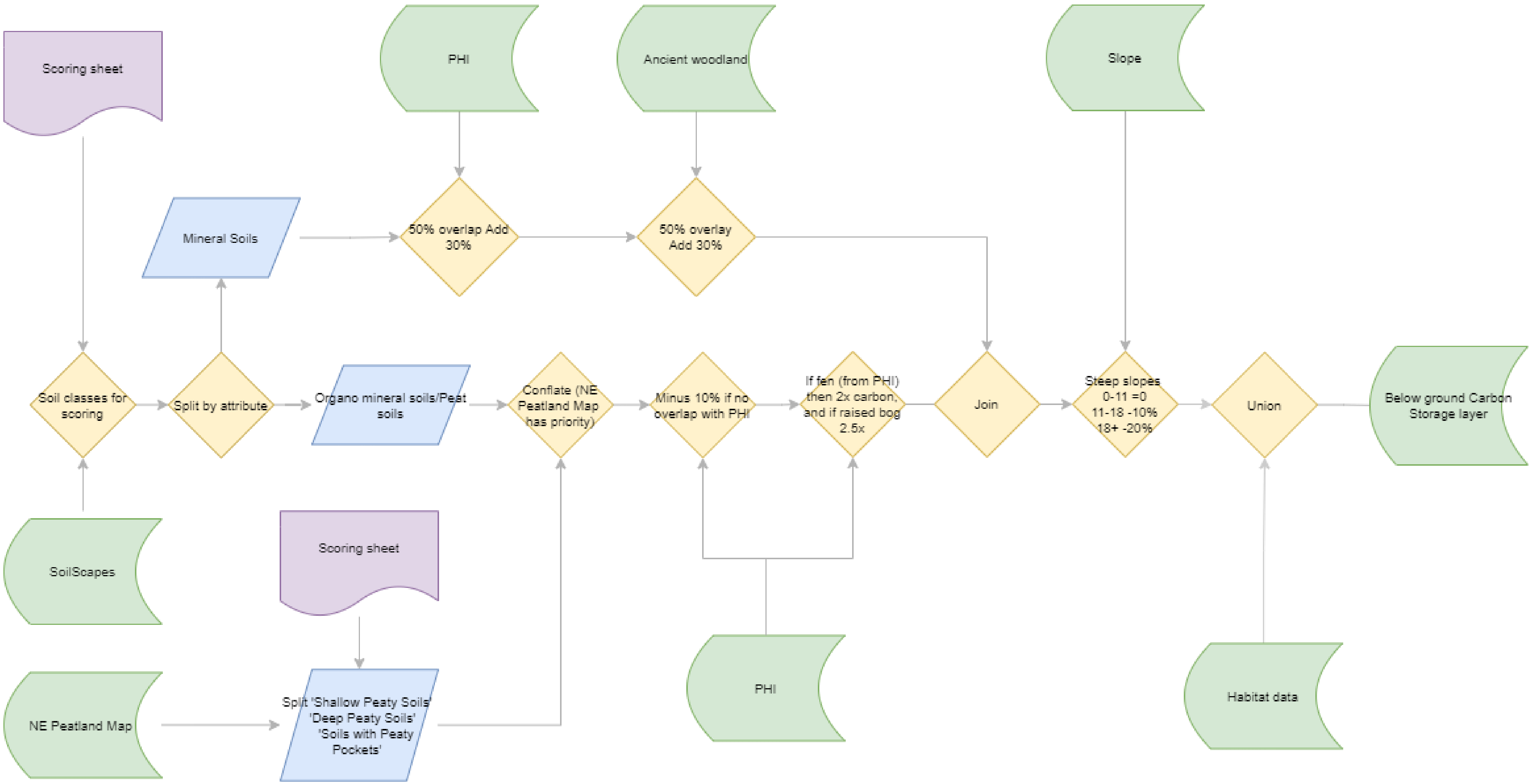


Figure 7. Flow diagrams outlining the FME processing steps for the sequestration analysis.

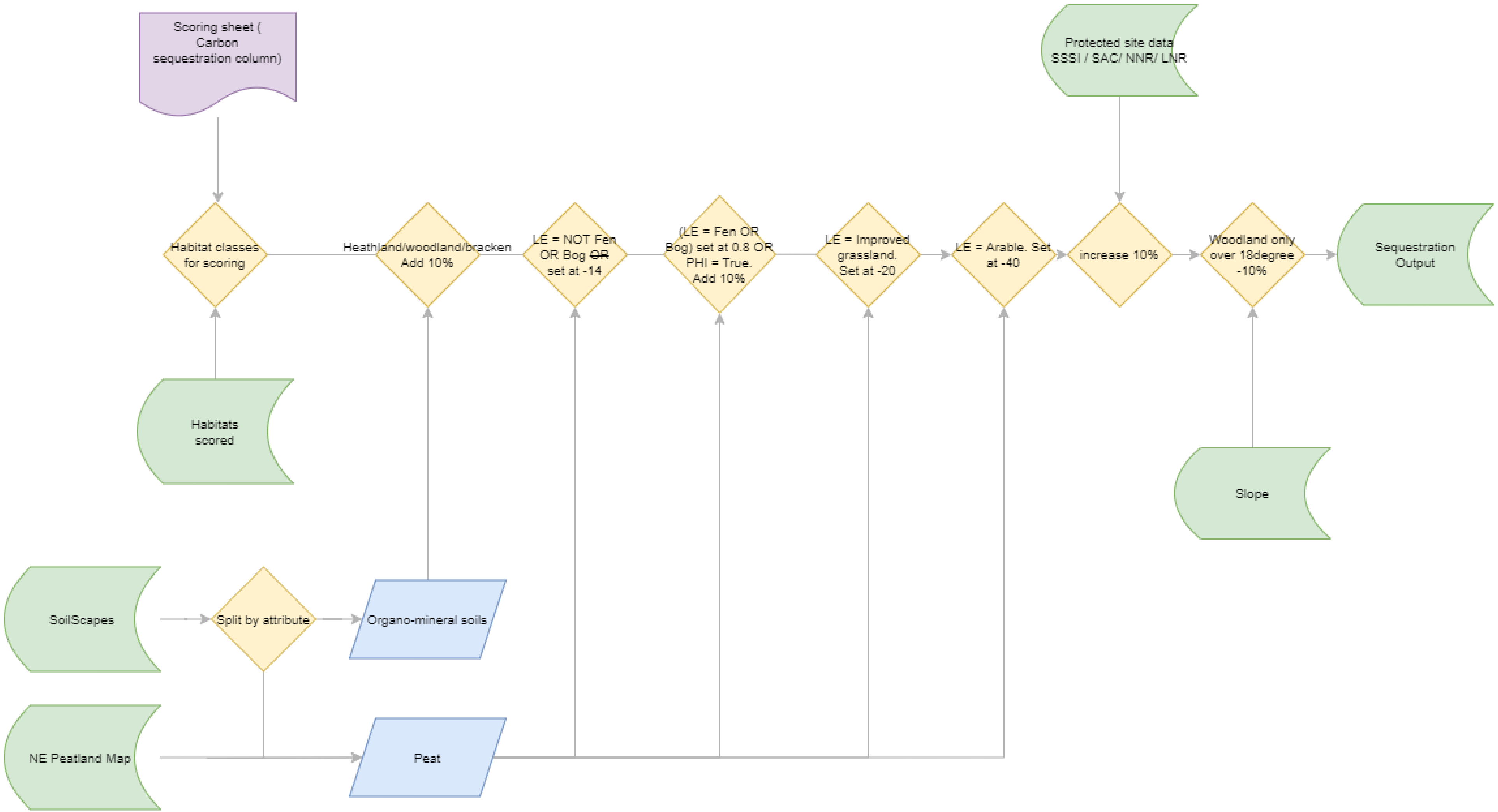
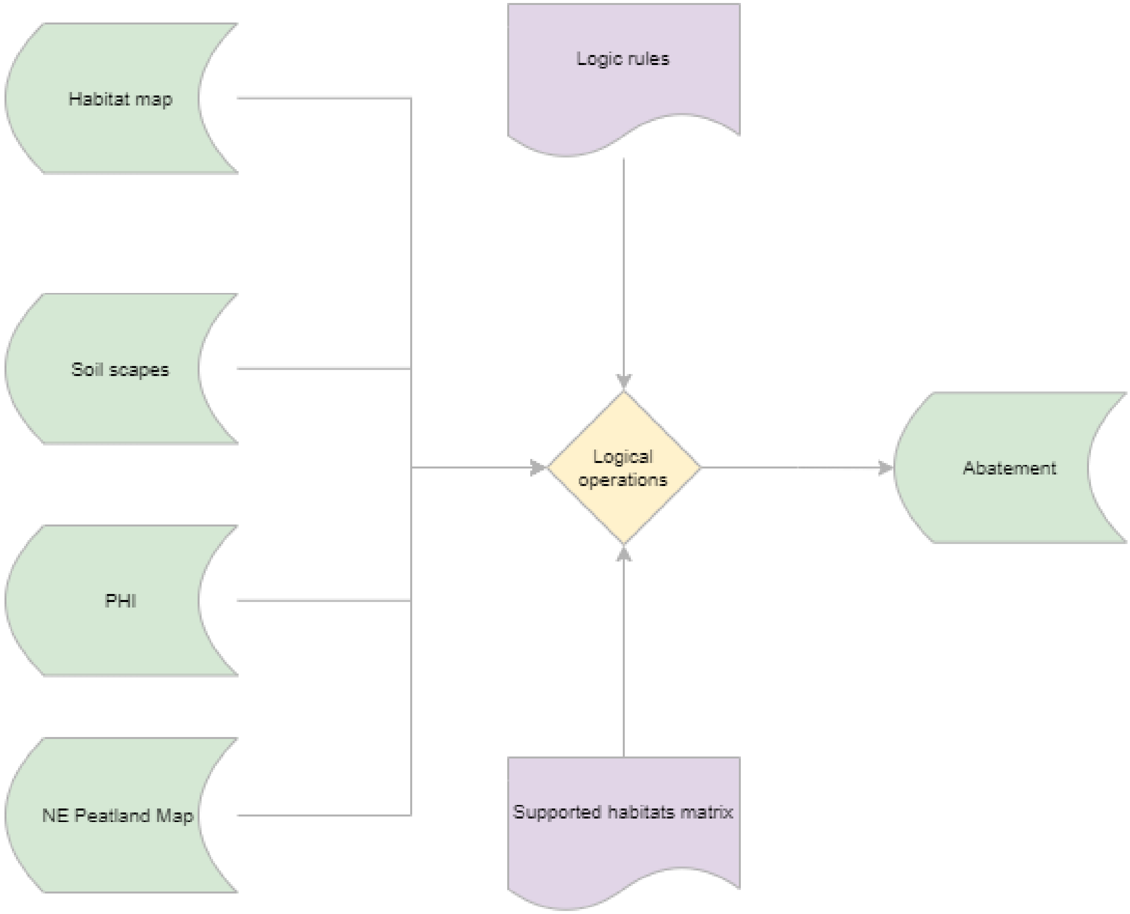
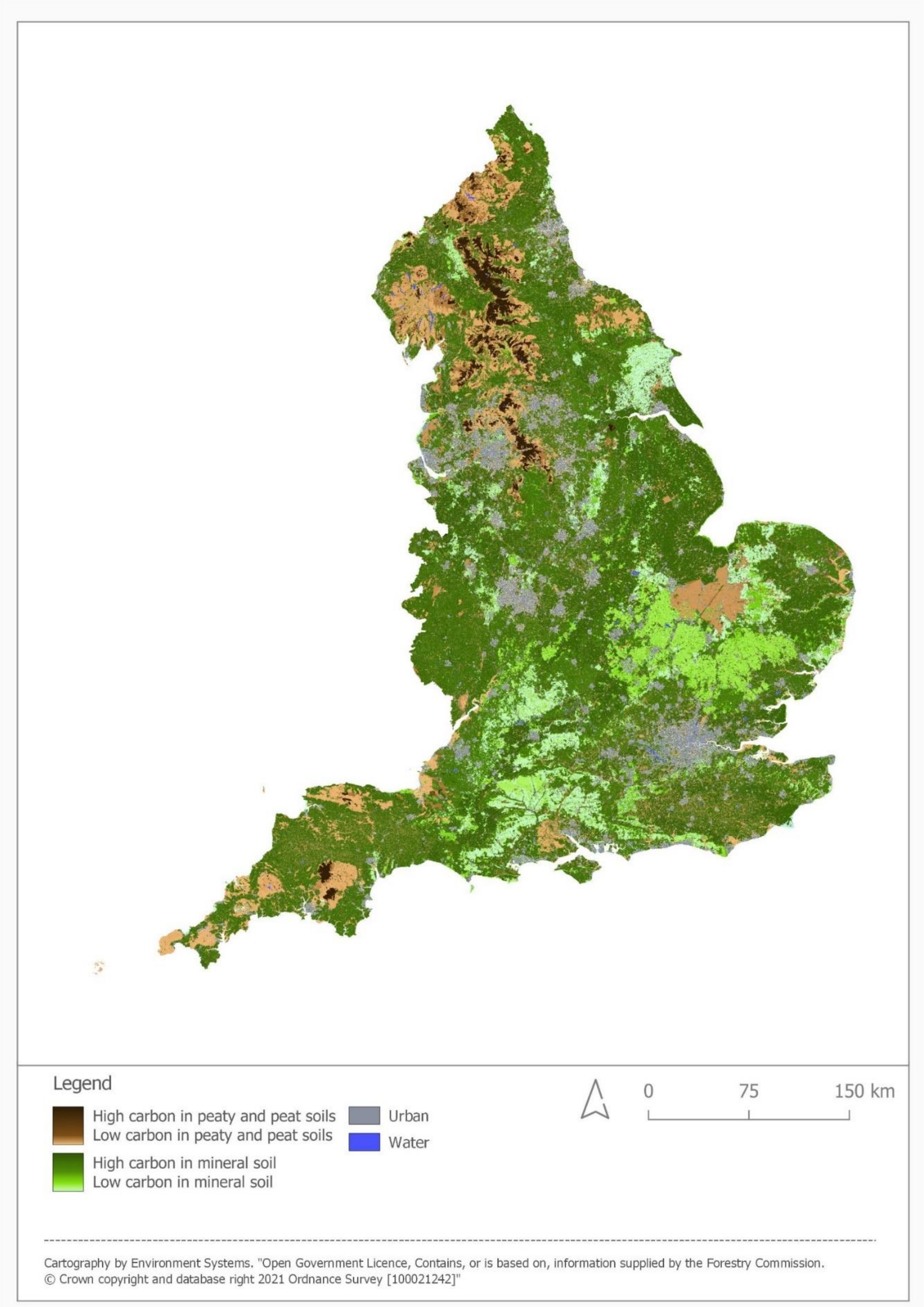


Figure 8. Flow diagrams outlining the FME processing steps for the abatement analysis (for logical operations see Appendix 3).



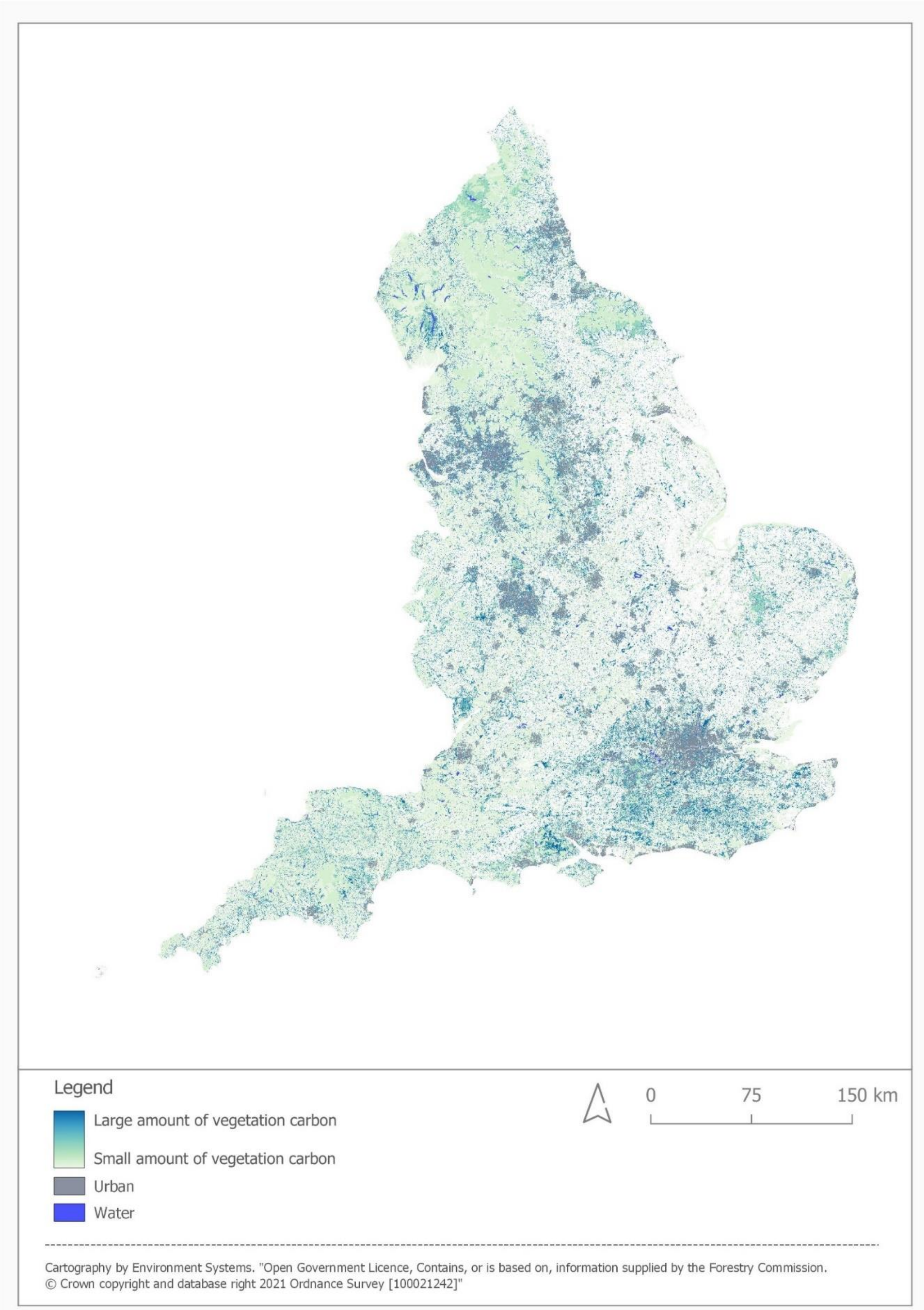
Below Ground soil Carbon Layer

Figure 9 shows below ground storage across England. It Highlights areas of peat, deep brown soils under woodlands. Shallower soil particularly on chalk and limestone are lighter.



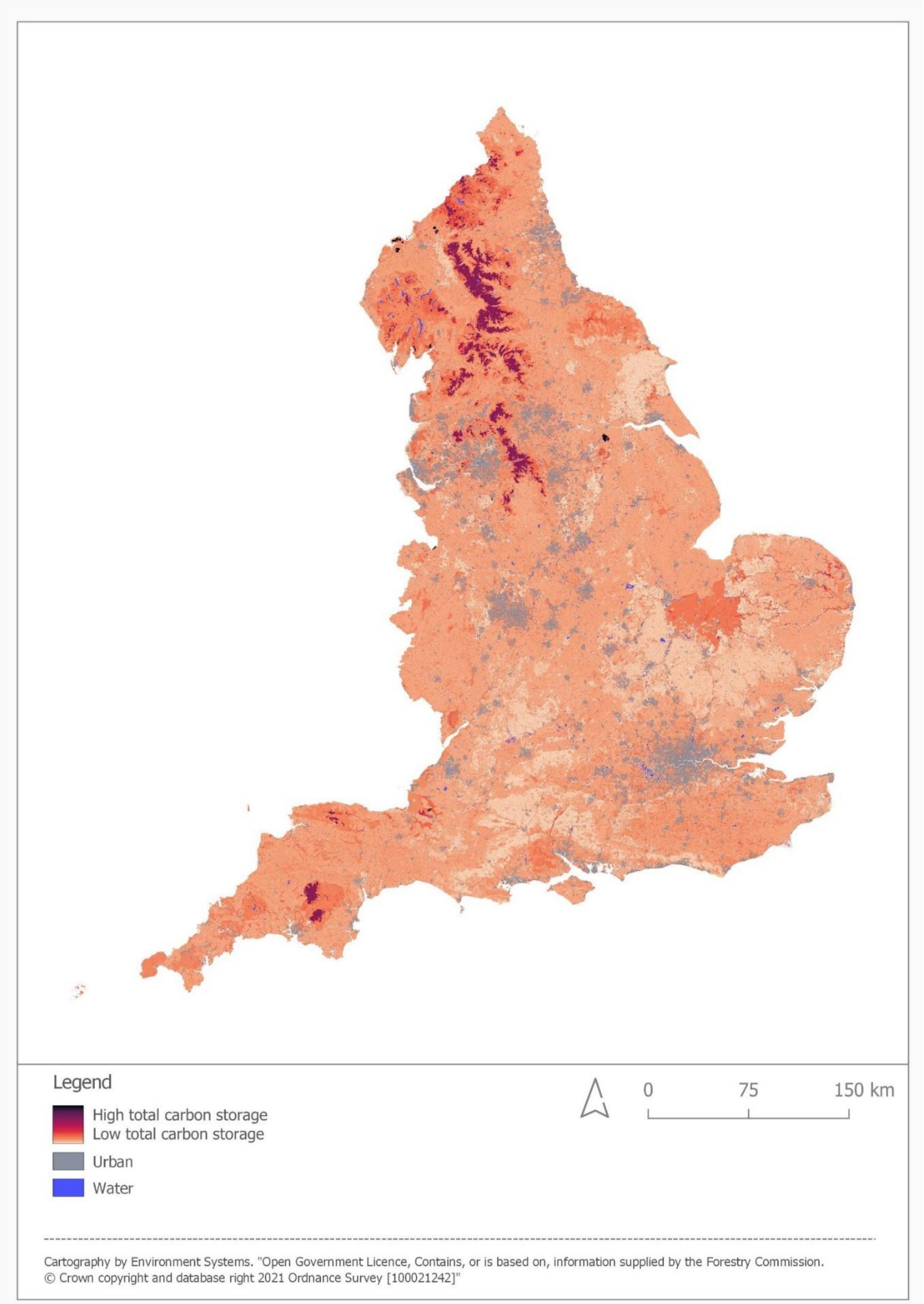
Carbon Storage Above Ground Layer

Figure 10 shows longer term above ground carbon storage across England. It highlights areas of woodlands, scrub and marsh. Arable crops have little-no longer term above ground biomass.



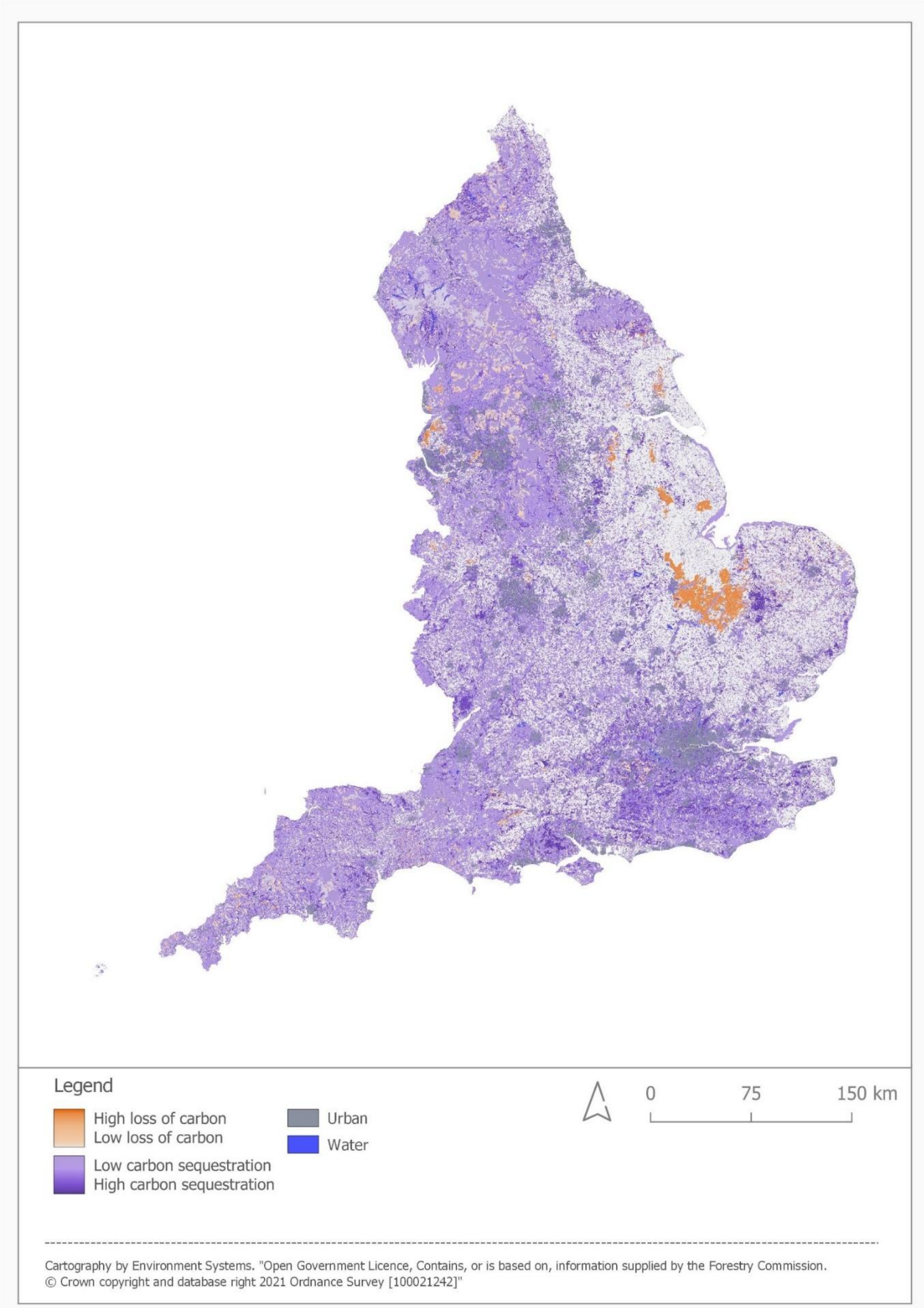
Total Carbon Storage Layer

Figure 11. This map considers both the below ground and longer term above ground carbon storage. Highlights areas of woodlands, scrub and marsh. Least on arable on thinner soils.



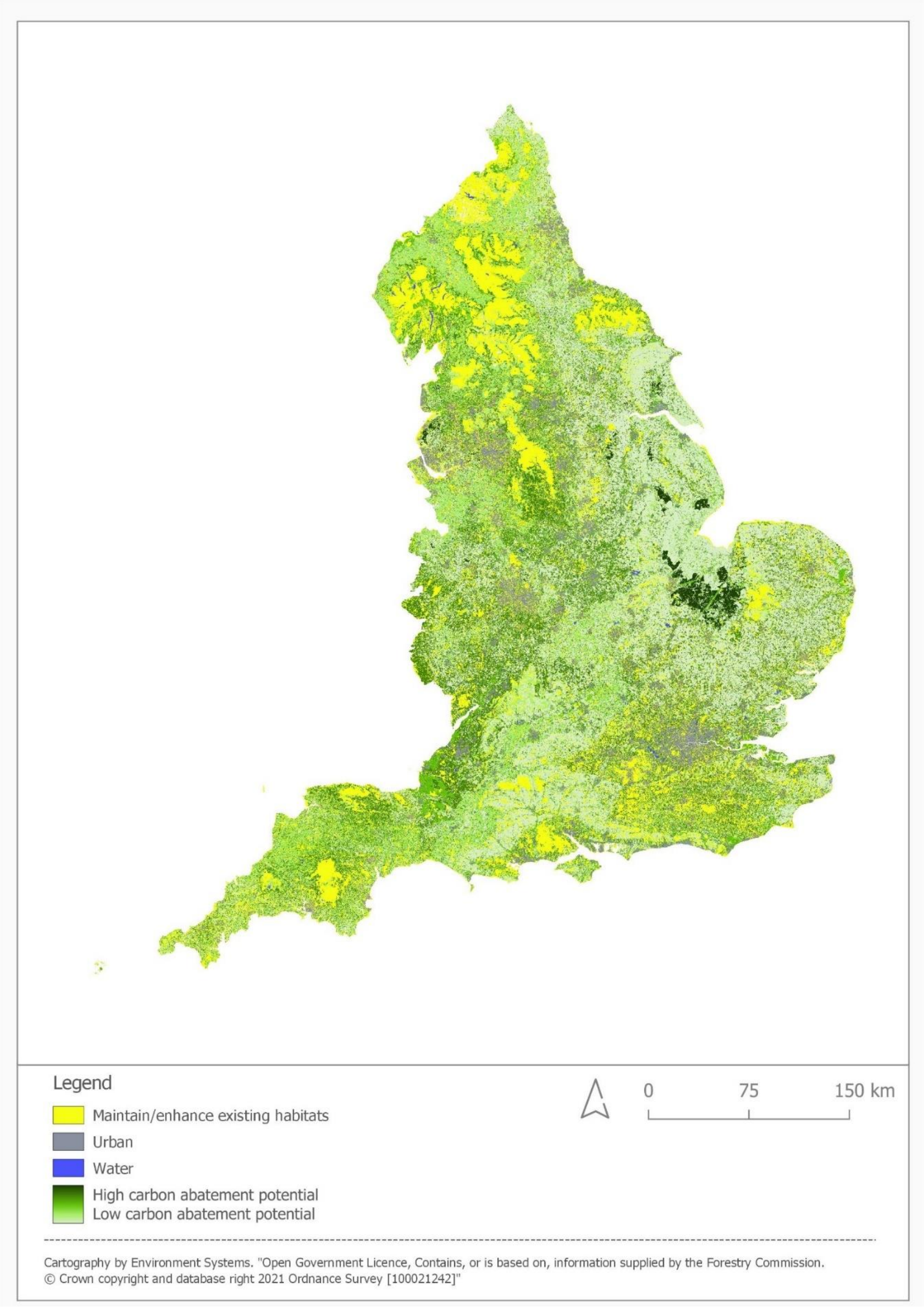
Carbon Sequestration Layer

Figure 12. This map shows the likely rate of carbon sequestration above ground. Values are higher on areas with woodlands, scrub and marsh and least on arable on thinner soils.



Carbon Abatement Layer

Figure 13. This map shows the possible abatement for carbon across England. It gives a five-post scale, from 'High' possible abatement from restoring bog habitats on arable land with deep peat, through to 'Low', farming arable land in a way that enhances carbon.



All Five layers (Figures 9-13) are available as raster GIS layers, with the corresponding GIS style file for Arcmap and ArcGIS pro. This allows the viewer to navigate around the maps, and compare above, below and total carbon, sequestration and abatement, for a given area. within a GIS application.

Sensitivity Analysis

For the sensitivity analysis two focus areas were chosen (Figure 14: Map showing location of two study areas used in the sensitivity analysis.:

- The areas have contrasting habitats, soils and geology as well as occur in different biogeographical zones, so they represent conditions found across England from the lowland to the upland
- The two areas represent resent work, where both clients have quality assured the results and are happy with the results on the ground.
- For both areas a detailed habitat asset register map was created at sub-field level including the presence of hedgerows and small in field habitat patches.
- These datasets therefore give a good comparison for the accuracy of the layers produced.

Figure 14: Map showing location of two study areas used in the sensitivity analysis.

Methodology

A qualitative assessment was done to compare the spatial trends within the Total Carbon layer and the Cotswolds Carbon layer. When doing an initial qualitative comparison of the Living England data it was noticeable particularly in the NYM that bracken seemed to be classified as marsh fen and swamp in Living England. Marshy grassland can have a similar spectral signature to bracken in remote sensing, so the miss-classification is possible. For the carbon values in this project the carbon storage of bracken and marshy grassland lie within the same range as each other and so this was deemed to be acceptable. The accuracy for Living England is suggested at 80%. The boundaries or 'segmentation' of the data matches very closely to features on the ground, however not all are correctly assigned to a category. It is therefore, recommended when using Living England for local studies to use a GIS and those areas which are in an inappropriate classification are changed to reflect the situation on the ground. This will enable an extremely useful data set to be available for use.

An additional quantitative was done using 1000 randomly data points generated for each of the test areas. Where habitats do not agree, we did not consider it a fair comparisons as more detailed data which shows habitats such as hedgerows which cannot be incorporated in a strategic, all England dataset, is not a reasonable comparison. Therefore, for comparison purposes, these points were filtered based upon where the habitat classes within each dataset are similar. Both of the comparison datasets had a quality assurance of the underlying data layers, which was not possible for the strategic all England data set.

Results

For the qualitative analysis, although the parameterisation of the two layers is different, the spatial similarities are apparent across the comparison area. The greater level for detail in the underlying data is however clear, for the two study areas in the habitat and this is reflected in the individual carbon storage maps

For the qualitative analysis, the filtering of the randomly generated points resulted in is 433 for North York Moors National Park and 419 for the Cotswolds were used for analysis. The main reason for the difference in sample point quantity is the differences in the detail of the mapping. For example, hedgerows picked up 57 times with the random points from the Cotswold data, with no equivalent class within Living England.

The carbon the range of values for the Cotswolds is 102 to 561 tC ha^{-1}. Cotswolds had 419 equivalent habitat points, with 81% of the points falling with 1 standard deviation of the mean total carbon value for that habitat combination

The carbon the range of values for the North York Moors National Park is 102 to 1943 tC ha^{-1}. North York Moors National Park had 433 equivalent habitat points, with 78% of the points falling with 1 standard deviation of the mean total carbon value for that habitat combination.

Conclusion of sensitivity analysis

The results show a good level of consistency of carbon values within the habitat classes tested for total carbon layer. Improvements in the accuracy of the total carbon layer will be primarily as a result of new relevant scientific literature reducing the uncertainties in understanding, and from improved accuracy the underlying spatial data (e.g. updates to Living England).

Note, the sequestration and abatement layers were not able be quantitatively assessed, due to a lack of comparable independently generated datasets.

Integration with the Carbon Uplift Tool

Enhancement of carbon and biodiverse can go hand in hand. When planning activities such as tree planting to enhance both carbon and biodiversity the spatial position of the woodland on suitable ground is essential. Nature England have created Nature Recovery Networks showing where habitats planted within the network's areas will have access to natural genetic material which will enable them to develop biodiverse and resilient ecosystems as well as the carbon resource. Natural England have developed the carbon uplift tool to assist with this.

The Carbon Uplift Tool aims to highlight favourable areas for habitat restoration or creation for carbon, where biodiversity enhancement is also likely, within the "Action Zones of a particular National Habitat Network Map (Edwards et al., 2020). These zones, called Fragmentation Action Zone, Network Enhancement Zone 1and Network Expansion Zone, lie outside of a particular priority habitat but would be suitable for creating or restoring that priority habitat (Adolf, et. al. 2021).

The Carbon Uplift Tool calculates the long-term "Carbon Uplift" (in tC/ha) that could potentially be achieved by changing current land cover (as determined by the CEH Land Cover Map 2019) to a specific priority habitat, if this habitat were created or restored within the action zones of its network map (Adolf, et. al. 2021).

The tool has to be run for each available individual National Habitat Network Map, therefore, the five layers (above ground carbon, below ground carbon, total carbon, sequestration, and abatement) have been clipped to the extent of the Natural England Habitat Networks.

The classes Fragmentation Action Zone, Habitat Restoration-Creation, Network Enhancement Zone 1, Network Enhancement Zone 2, Network Expansion Zone, Restorable Habitat, and 'Core habitats' (all remaining habitat classes combined, with the exception of PHI. Other, Rivers, SSSI & Lakes, which are all discounted from the analysis), were incorporated in this clip. This will allow outputs from the Carbon Uplift Tool to be viewed alongside the carbon layers of the same spatial extent.

Indications of Priorities

Top sites for Carbon Delivery

The five carbon layers are a great resource for the decision-making process. However, it can be hard for discission makers to know where to prioritise effort for the increasing sequestration, storage, or reducing loss. To assist in this prioritisation of interventions for designated sites, a tool (in the form of a spreadsheet) was generated (Figure 15) to rank high to low (in tC/ha, and total tC per area boundary) for all designations (Country, ANOB, LNR, SSSI, NCA, NNR, NR) by either Above ground carbon, Below ground carbon, Total carbon, Sequestration, or Abatement. How the rankings are compared between designation scale, then communicated will be up to the tool's end user.

The filtering option are as follows:

- TEAM NAME - Lists of Natural England team name, attributed to a giving area boundary.
- DESIGNATION - The designation of area boundary.
- NAME - The name of the designated site.
- Area, hectares (ha) - The area of the boundary. Note an individual designation may consist of more than one boundary.
- Above ground carbon, tonnes (t) - Total tC for that boundary.
- Below ground carbon, tonnes (t) - Total tC for that boundary.
- Total carbon, tonnes (t) - Total tC for that boundary.
- Sequestration (carbon flux), tonnes CO2 equivalent per year (t co2 e Yr-1) – the total carbon flux for the boundary each year. [-ve figures is carbon sequestration & +ve figures is carbon loss]
- Above ground carbon, tonnes per hectare (t/ha) - The tC ha for that individual boundary.
- Below ground carbon, tonnes per hectare (t/ha) - The tC ha for that individual boundary.
- Total carbon, tonnes per hectare (t/ha) - The tC ha for that individual boundary.
- Sequestration (carbon flux), tonnes CO2 equivalent per hectare per year (t co2 e Ha-1 Yr-1) – the total carbon flux for the boundary each year. [-ve figures is carbon sequestration & +ve figures is carbon loss]
- The carbon flux figures expressed on a per ha basis to the boundary of area or site.
- Abatement, hectares (ha) - The total potential abatement area for that individual boundary.

Note, a designated site may contain more than one entry (i.e. row), due to the nature of designation boundaries not being mutually exclusive. Therefore, any statistic calculated from the spreadsheet needs to encompass all instances of a given designated site using the filtering options at the head of the spreadsheet.

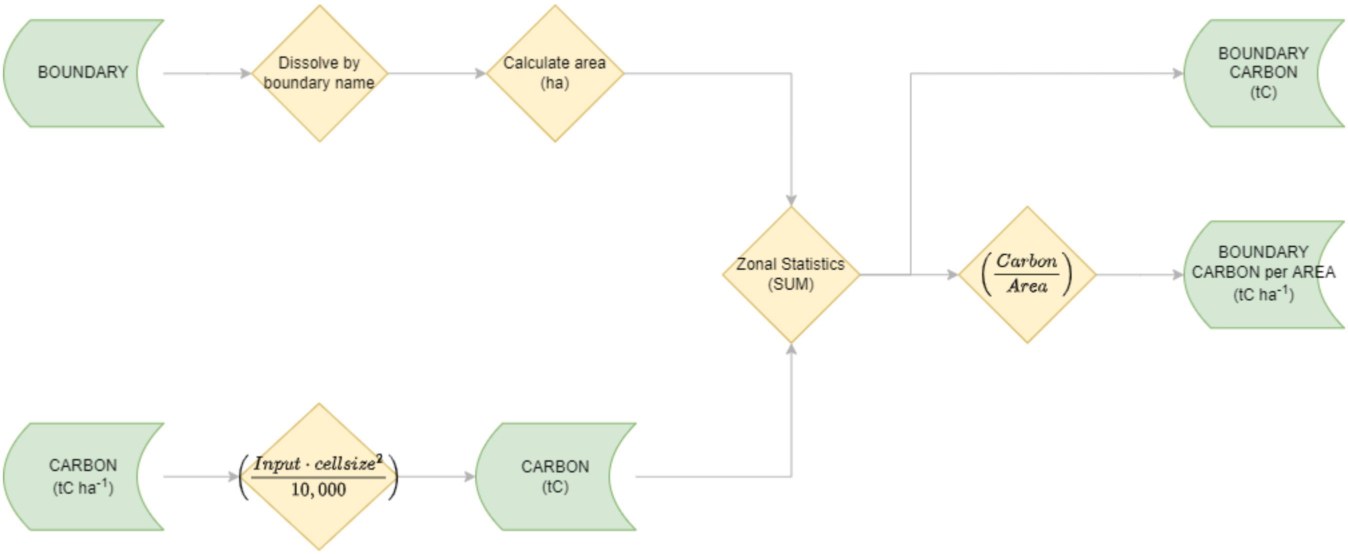


Fig 15. Process to generate the Top Sites tool.

Conclusion

The storage of carbon in very import in the fight against climate change. This work estimates that England has over four trillion tonnes of carbon stored, the distribution of which can be viewed in the Above Ground Carbon, and Below Ground Carbon data layers. These data layers, along with the Sequestration and Abatement layers, represent a strategic resource for England, that indicate the range of carbon storage and sequestration values in tonnes per hectare (t C ha^{-1} yr), at a local scale (e.g., 1:50,000). They are presented as a series of raster layers for use in GIS systems at a resolution of 25 m^2.

The layers have been created with the aim of qualifying for an Open Government Licence data licence, to enable maximum unhindered use, therefore increasing impact and environmental benefit. The method allows for periodic updates to take place at a low cost using FME.

These data layers will assist viewers to find out where the most important carbon stores in soil and vegetation are in their areas, and where sequestration of carbon is currently high. The abatement map can be used to find potential opportunity areas to enhance carbon sequestration and storage, guidance for which can be found in the *'Spatial Prioritisation of Land Management for Carbon User Guide*' published as part of this project.

For Natural England, these data layers will assist with strategic analysis for the three schemes that will underpin the 25 Year Environment Plan and the Environment Bill:

- Sustainable Farming Incentive (SFI).
- Local Nature Recovery (LNR).
- Landscape Recovery (LR).

In addition to the data layers, an interactive spreadsheet has been created to prioritise sites for action when considering:

- Nature based management solution delivery.
- Meeting the Government targets for tree planting to assist carbon storage and sequestration.
- Peat restoration work.
- Management of other protected sites.

These new data will contribute to Natural England's vision of 'thriving nature for people and planet', by allowing policy makers and land managers to understand the terrestrial carbon resource. It will help protect and enhance existing carbon stores whilst also demonstrating opportunities to enhance carbon sequestration through changes in land use and management.

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Appendices

Appendix 1: Evidence Gaps

Appendix 2: The coincidence between the Soilscapes and habitat data.

Appendix 3: NFI Woodland Categories used in the data conflation.

Appendix 4 Abatement logic rules

Annex 1: Spatial Prioritisation of Land Management for Carbon 2014

Appendix 1: Evidence Gaps

Evidence gap ID	Code	Habitat	Evidence Gap
1	OW_1	Trees outside woodland	Carbon sequestration and storage and supporting important aspects of biodiversity in trees outside woodland.
2	W_1	Woodland	Understanding the carbon balance of naturally colonised or regenerated woodlands in comparison to planted ones.
3	W_2	Woodland	Changes in soil depth or changing patterns of carbon storage at different depths.
4	W_3	Woodland	Soil carbon emissions under different management techniques, soil types, climates and weather conditions and the extent of inter-annual variation in soil carbon fluxes.
5	W_4	Woodland	Whole stand net carbon flux measurements covering the full range of forest types and ages.
6	W_5	Woodland	Understanding of the synergies and trade-offs between carbon storage and sequestration, biodiversity and the wide range of other services that woodlands provide.
7	W_6	Woodland	Carbon stock and flux of wood pasture and parkland and the impacts of different regeneration techniques in wood pasture.
8	HR_1	Hedgerows	The impact plant species biodiversity has on hedgerow carbon stock.
9	HR_2	Hedgerows	Availability of data regarding carbon storage and sequestration in hedgerows representing the diversity of hedgerows found in the English landscape and the Influence that vegetation management, different tree and shrub species, soil type and depth have on their ability to accumulate and store carbon above and belowground.

Evidence gap ID	Code	Habitat	Evidence Gap
10	HR_3	Hedgerows	Informing the need to boost biodiversity and climate change mitigation potential of hedgerows, including quantifying the carbon benefits of allowing hedgerow trees to become established.
11	HR_4	Hedgerows	Investigating how carbon storage in soils and biomass is offset by greenhouse gas emissions from trimming, flailing, disposal, laying, coppicing and cultivation methods and the role hedgerows can play in producing biomass for wood fuel, replacing fossil fuel emissions.
12	O_1	Orchards	The carbon storage and sequestration potential of orchards.
13	O_2	Orchards	The impact of orchard management on carbon stored in the biomass and soils.
14	S_1	Scrub	Significant gaps in the evidence on the carbon implications of scrub development in the UK.
15	S_2	Scrub	The changes on vegetation and soil carbon stocks in scrub in the UK.
16	HL_1	Heathlands	The carbon stocks in wet and dry heathland soils respond differently to management interventions. More experimental research on the impacts on different types of heathlands would help when providing tailored advice and management.
17	HL_2	Heathlands	The impacts of higher scrub and tree cover on carbon fluxes and particularly trade-offs with specialist species which require open niches are not clear
18	GR_1	Grassland	Carbon stocks and sequestration in semi-natural grasslands, especially calcareous grasslands.

Evidence gap ID	Code	Habitat	Evidence Gap
19	GR_2	Grassland	There are few carbon flux datasets from grasslands and very few which assess changes with different management practice or grassland restoration from arable sites.
20	GR_3	Grassland	Increasing understanding between the trade-offs and synergies between the specific management interventions in grasslands and their potential to store and sequester carbon.
21	GR_4	Grassland	Quantifying carbon stores at depth and their interaction and sensitivity to grassland interventions and understanding how the legacy of past management can continue to influence a grassland's carbon storage potential.
22	AP_1	Peatland under agriculture	Carbon at scale and under field conditions.
23	AP_2	Peatland under agriculture	The impact of management on subsoil C.
24	BB_1	Blanket bogs and raised bogs	Improving accuracy in peat depth mapping to increase accuracy in peat carbon stock estimates.
25	BB_2	Blanket bogs and raised bogs	Differentiating between blanket bog and raised bog. Evidence need regarding the impact of dominant vegetation type and burning management on carbon and greenhouse gas emissions to generate specific emission factors and quantification of the potential benefit for carbon and greenhouse gas emissions that restoration interventions may have on peatland habitats.

Evidence gap ID	Code	Habitat	Evidence Gap
26	BB_3	Blanket bogs and raised bogs	Quantifying the co-benefits of raised bog restoration for biodiversity and climate change mitigation.
27	F_1	Fens	Representation of the diversity of fen habitats across England and the rest of the UK.
28	F_2	Fens	The extent of fen habitats, especially in the uplands.
29	RLW_1	Rivers, lakes and wetland	Increasing understanding of the role of freshwaters in the carbon cycle. Recommendations for priority areas to increase confidence in the evidence base: 1) Better representation of key freshwater habitats. 2) Consideration of the linkages between terrestrial nature-based solutions and freshwaters. 3) Assessment of the carbon benefit of restoring human-modified habitats back to their natural state.
30	SM_1	Saltmarsh	Impact of grazing on carbon sequestration rates.
31	CM_1	Coastal and marine	Carbon stocks and sequestration rates of coastal and marine habitats.

Appendix 2: The coincidence between the Soilscapes and habitat data.

Note some cells have been left blank.

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Acid, Calcareous, Neutral Grassland	Living England			T		T	T	T	T	T	T	T	T	T	T	T	T	T	T		T		T	T								
Arable and Horticultural	Living England																															
Bare Ground	Living England																															

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Bare Sand	Living England				T																											
Blanket bog	PHI																									T						
Bog	Living England																			T						T	T	T		T	T	T
Bracken	Living England						T	T	T		T		T	T	T		T															
Broadleaved	NFI					T	T	T	T	T	T		T	T	T	T	T	T	T		T	T	T	T				T				T
Broadleaved, Mixed and Yew Woodland	Living England					T	T	T	T	T	T		T	T	T	T	T	T	T		T		T	T				T				T

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Built-up Areas and Gardens	Living England																															
Calaminarian grassland	PHI																								T							
Coastal and floodplain grazing marsh	PHI	T							T				T								T	T										
Coastal saltmarsh	PHI	T																														
Coastal Saltmarsh	Living England	T																														

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Coastal sand dunes	PHI				T																											
Coastal Sand Dunes	Living England				T																											
Coastal vegetated shingle	PHI																															
Conifer	NFI										T												T									
Coniferous Woodland	Living England										T												T									
Coppice	NFI					T	T	T	T	T	T		T	T	T	T		T	T		T	T	T	T								

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Coppice with standards	NFI					T	T	T	T	T	T		T	T	T	T		T	T		T	T	T	T								
Deciduous woodland	PHI					T	T	T	T	T	T		T	T	T	T	T	T	T	T	T	T	T	T				T			T	T
Dwarf Shrub Heath	Living England		T								T						T			T												
Fen, Marsh and Swamp	Living England									T						T	T	T	T	T	T		T	T				T			T	T
Fragmented heath	PHI		T					T	T				T	T			T			T										T	T	

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Good quality semi-improved grassland	PHI			T		T	T	T	T	T	T		T	T	T	T		T	T		T		T	T								
Grass moorland	PHI		T								T			T	T		T			T											T	T
Improved Grassland	Living England					T	T	T	T	T	T		T	T	T	T	T	T	T		T	T	T									
Limestone pavement	PHI			T																												
Lowland calcareous grassland	PHI			T		T		T	T																							

Vegetatio n Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Lowland dry acid grassland	PHI			T			T		T		T			T	T						T			T								
Lowland fens	PHI																							T			T	T			T	T
Lowland heathland	PHI		T								T	T			T	T											T					
Lowland meadows	PHI					T	T	T	T	T	T		T	T		T	T	T	T		T	T	T	T								
Lowland raised bog	PHI																									T	T	T		T	T	T
Maritime cliff and slope	PHI		T																													
Mixed mainly	NFI					T	T	T	T	T	T		T	T	T	T	T	T	T		T	T	T	T				T				T

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
broadleaved																																
Mixed mainly conifer	NFI								T		T												T									
Mountain heaths and willow scrub	PHI		T				T							T			T			T						T					T	
Mudflats	PHI																															
No main habitat but additional habitats present	PHI		T	T		T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T								

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Purple moor grass and rush pastures	PHI								T	T						T	T	T	T	T	T		T									
Reedbeds	PHI												T																			
Saline lagoons	PHI																															
Scrub	Living England						T	T																								
Shrub	NFI		T		T																											
Traditional orchard	PHI					T	T	T	T	T	T		T		T																	
Unclassified	Living England																															

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Upland calcareous grassland	PHI			T		T																										
Upland flushes, fens and swamps	PHI		T														T			T						T					T	
Upland hay meadow	PHI							T																								
Upland heathland	PHI		T											T			T													T	T	
Water	Living England																												T			

Vegetation Class	Source	Saltmarsh soils	Shallow very acid peaty soils over rock	Shallow lime-rich soils over chalk or limestone	Sand dune soils	Freely draining lime-rich loamy soils	Freely draining slightly acid loamy soils	Freely draining slightly acid but base-rich soils	Slightly acid loamy and clayey soils with impeded drainage	Lime-rich loamy and clayey soils with impeded drainage	Freely draining slightly acid sandy soils	Freely draining sandy Breckland soils	Freely draining floodplain soils	Freely draining acid loamy soils over rock	Freely draining very acid sandy and loamy soils	Naturally wet very acid sandy and loamy soils	Very acid loamy upland soils with a wet peaty surface	Slowly permeable seasonally wet acid loamy and clayey soils	Slowly permeable seasonally wet slightly acid but base-rich	Slowly permeable wet very acid upland soils with a peaty	Loamy and clayey floodplain soils with naturally high	Loamy and clayey soils of coastal flats with naturally high	Loamy soils with naturally high groundwater	Loamy and sandy soils with naturally high groundwater and a	Restored soils mostly from quarry and opencast spoil	Blanket bog peat soils	Raised bog peat soils	Fen peat soils	water	Deep Peaty Soils	Shallow Peaty Soils	Soils with Peaty Pockets
Young trees	NFI					T	T	T	T	T	T		T	T	T	T	T	T	T		T	T	T	T								

Appendix 3: NFI Woodland Categories used in the data conflation.

NFI Woodland Categories
Bare area
Urban
Agriculture land
Grassland
Quarry
Road
Other vegetation
River
Open water
Assumed woodland
Broadleaved
Conifer
Felled
Failed
Ground prep
Low density
Mixed mainly broadleaved
Mixed mainly conifer
Young trees
Coppice
Coppice with standards
Shrub
Windblow
Uncertain

Woodland categories highlighted in green were used in the habitat data conflation.

Appendix 4 Abatement logic rules

```
IS 'Blanket bog peat soils' OR
      'Raised bog peat soils' OR
      'Bog' OR
      'Fen peat soils' OR
      'Deep Peaty Soils' AND NOT 'TRUE'
      THEN
            'Arable and Horticultural' to 'H',
            'Improved Grassland' to 'H/M',
            'Dwarf Shrub Heath' to 'M/L',
            'Upland heathland' to 'M/L',
            'Lowland heathland' to 'M/L',
            'Dwarf Shrub Heath' to 'M/L',
      ELSE
            to 'Maintain/enhance existing habitat'

NOT 'Blanket bog peat soils' OR
      'Raised bog peat soils' OR
      'Fen peat soils' OR
      'Deep Peaty Soils' AND NOT 'TRUE'
      THEN
            'Arable and Horticultural' to 'L'



IS 'Calaminarian grassland' OR
      'Good quality semi-improved grassland' OR
      'Lowland calcareous grassland' OR
      'Lowland dry acid grassland' OR
      'Lowland meadows' OR
      'Upland calcareous grassland' OR
      'Upland hay meadow'
      THEN
            'Maintain/enhance existing habitat'
```

```
IS    'Broadleaved, Mixed and Yew Woodland' OR
      'Dwarf Shrub Heath' OR 'Broadleaved' OR
      'Young trees' OR 'Shrub' OR
      'Mixed mainly broadleaved' OR
      'Coppice' OR
      'Coppice with standards'
      THEN
            'Maintain/enhance existing habitat'

IS    'Freely draining lime-rich loamy soils' OR
      'Freely draining slightly acid loamy soils' OR
      'Freely draining slightly acid but base-rich soils' OR
      'Slightly acid loamy and clayey soils with impeded drainage' OR
      'Lime-rich loamy and clayey soils with impeded drainage' OR
      'Freely draining slightly acid sandy soils' OR
      'Freely draining floodplain soils' OR
      'Freely draining acid loamy soils over rock' OR
      'Freely draining very acid sandy and loamy soils' OR
      'Naturally wet very acid sandy and loamy soils' OR
      'Very acid loamy upland soils with a wet peaty surface' OR
      'Slowly permeable seasonally wet acid loamy and clayey soils' OR
      'Slowly permeable seasonally wet slightly acid but base-rich loamy and
clayey soils' OR
      'Loamy and clayey floodplain soils with naturally high groundwater' OR
      'Loamy and clayey soils of coastal flats with naturally high groundwater'
OR
      'Loamy soils with naturally high groundwater' OR
      'Loamy and sandy soils with naturally high groundwater and a peaty
surface'
      THEN
            = 'Tree soil types'

            IS 'Acid, Calcareous, Neutral Grassland' AND 'Tree soil types',
            THEN
                  'M/H'

            IS 'Acid, Calcareous, Neutral Grassland' AND 'NOT Tree soil types',
```

```
            THEN
                  'M/L'

            IS 'Improved Grassland' AND 'Tree soil types'
            THEN
                  'Improved Grassland' to 'M/L'

            IS 'Improved Grassland' AND NOT 'Tree soil types'
            THEN
                  'Improved Grassland' to 'L'

IS    'Blanket bog ' OR
      'Coastal and floodplain grazing marsh' OR
      'Coastal saltmarsh' OR
      'Coastal sand dunes' OR
      'Coastal vegetated shingle' OR
      'Deciduous woodland' OR
      'Fragmented heath' OR
      'Grass moorland' OR
      'Limestone pavement' OR
      'Lowland fens' OR 'Lowland heathland' OR
      'Lowland raised bog' OR
      'Maritime cliff and slope' OR
      'Mountain heaths and willow scrub' OR
      'Mudflats' OR
      'No main habitat but additional habitats present' OR
      'Purple moor grass and rush pastures' OR
      'Reedbeds' OR
      'Saline lagoons' OR
      'Traditional orchard' OR
      'Upland flushes, fens and swamps' OR
      'Upland heathland'
      THEN
            = 'PHI classes'

            IS 'PHI classes' AND IS NOT 'Coastal and floodplain grazing marsh'
THEN 'Maintain/enhance existing habitat'
```

```
IS    'Coastal and floodplain grazing marsh'
        THEN
            M

IS    'Bracken' OR
      'Fen, Marsh and Swamp' OR
      'Scrub'
        THEN
            'M'

IS    'Bare Sand'
        THEN
            'Maintain/enhance existing habitat'

IS    'Coastal Saltmarsh'
      THEN
            'Maintain/enhance existing habitat'

IS    'Coniferous Woodland' OR
      'Mixed mainly conifer' OR
      'Conifer'
        THEN
            'Maintain/enhance existing habitat'

IS    'Dwarf Shrub Heath'
        THEN
            'Maintain/enhance existing habitat'

IS    'Unclassified'
        THEN
            'L'

IS    'Coastal Sand Dunes'
        THEN
            'Maintain/enhance existing habitat'
```

```
IS    'Bare Ground'
        THEN
            M/H

IS    'Built-up Areas and Gardens'
        THEN
            'URBAN'

IS    'Water'
        THEN
            'WATER'
```

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