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ERAMMP Report-137:
Farm Carbon Baseline Assessment

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Abbreviations Used in this Report

AGB	Aboveground biomass
BGB	Belowground biomass
CS	Carbon sequestration
DEFRA	Department for Environment Food and Rural Affairs
FCB	Farm Carbon Baseline
FR	Forest Research
GHG	Greenhouse Gas
GHGI	Greenhouse Gas Inventory
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry
NATMAP	The National Soil Map for England and Wales
NFI	National Forest Inventory
NLSW	National LiDAR Survey of Wales
SFS	Sustainable Farming Scheme
TOW	Trees Outside of Woodland
UK	United Kingdom
UKCEH	UK Centre for Ecology and Hydrology
UKWIR	UK Water Industry Research
WLF	Woody linear features

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1 EXECUTIVE SUMMARY

This report outlines a method for the spatially explicit estimate of carbon sequestration from tree canopy cover and vegetation, to be used to calculate on-farm carbon sequestration from woody features for each farm participating in the Sustainable Farm Scheme.

The methodology is designed to make use of recently acquired LiDAR data for Wales, and account for varying sequestration rates at different heights of woody features. T Carbon sequestration lookup tables were developed for three broad categories of woody features, defined according to their height and canopy area (Table 1-1): (i) woodlands, small woods, and groups of trees; (ii) lone trees; and (iii) hedgerows. Guidance is provided for the implementation of a methodology to calculate on-farm carbon sequestration using these lookup tables with national-scale tree and hedgerow metrics created from the National LiDAR Survey of Wales, other national scale datasets such as the National Forest Inventory, Trees Outside of Woodlands Map (Welsh Government, 2024), and information collected by Rural Payments Wales (RPW) as part of farmers' applications for scheme payments.

Table 1-1: Summary of lookup tables provided for types of woody feature in this report.

Woody feature	Carbon sequestration in scope	Lookup table weighting	Lookup keys
Woodland, small woods, groups of trees	Aboveground Biomass and Belowground Biomass	per metre^2 of woodland	stand height, 0.1m increments
Lone tree	Aboveground Biomass and Belowground Biomass	per lone tree	maximum height, 0.1m increments
Hedgerow	Aboveground Biomass, Belowground Biomass, and Soil Organic Carbon	per metre of hedgerow length	0.1m height increment, 0.25m width increment

Data for the carbon sequestration lookup tables for woodland, and the trees outside woodland categories of small woods and groups of trees come from Forest Research's CARBINE model. Lone tree sequestration rates by tree height are derived from biomass equations for broadleaf trees (Gruffudd *et al., unpublished*), with data on tree height and age and root:shoot ratio from the literature (Cairns *et al.,* 1996, Vaz Monteiro *et al.,* 2017). Data in the hedgerow carbon sequestration rates table are derived from hedgerow growth models informed by data from the ERAMMP National Field Survey of Wales, and hedge carbon density values, root:shoot values, and soil sequestration rates from the literature (Mokany *et al.,* 2006 , Axe *et al.,* 2017, Biffi *et al.,* 2023, Black *et al.,* 2023, Drexler *et al.,* 2023, Drexler *et al.,* 2024, Maskell *et al,* 2025, Beauchamp *et al., in preparation*).

The methodology is designed to be implemented across farms where detailed information on tree species, woodland yield class, and management of woodland and hedgerows is not known. Woodland lookup tables were created for two categories, unmanaged broadleaf and unmanaged conifer, by calculating a weighted average growth curve derived from the area of each species, yield class, and age group from the 2011 National Forest Inventory (NFI) for private woodland in Wales. The growth curves assumed management without thinning or felling (no thin, no fell), due to limited information on felling or thinning practices taking place on farms and on the assumption that this would be most representative of the management of on-farm trees. This assumption is consistent with assumptions in the UK Greenhouse Gas

Inventory that 93% of private broadleaf woodland is unmanaged, based on low timber production statistics from private forests in Wales (Forest Research, 2026). Hedgerow lookup tables were created using an average of the sequestration rates for managed and unmanaged hedgerows weighted by the national proportion of each management type (Maskell *et al.,* 2025). Biomass equations and published data for broadleaf trees were used to create lone tree lookup tables, consistent with the evidence that majority of TOW trees are broadleaf (Forestry Commission 1983, 2001).

Carbon sequestration values calculated using this method for three ‘model farms’ were compared to GHG sequestration values obtained from commercially available tools and found to be broadly similar. Differences between values calculated using this reports’ method and those calculated using commercial tools were on the same scale as differences between commercial tools. For the majority of ‘model farms’, carbon sequestration values calculated using commercial tools which include woodland in scope lie within the range of upper and lower carbon sequestration estimates from the method presented in this report.

Recommendations for future calculations of on-farm carbon sequestration include the inclusion of deadwood, litter and soil carbon pools for woodland, and the incorporation of more site-specific input data on tree species, stand age, and woodland or hedgerow management practices. Repeat LiDAR surveys provide the opportunity to calculate of on-farm carbon sequestration by estimating biomass change between two points in time. Repeat surveys, from LiDAR or other earth observation techniques, could capture an increase in tree size from growth or the removal of vegetation due to thinning, felling, or other disturbances. This could provide a more accurate on-farm estimate for the vegetation types included in this study, and enable other vegetation types, such as woody perennial cops to be included as well.

2 INTRODUCTION

2.1 Background

The Sustainable Farming Scheme (SFS) launched in 2026 and will assist the farming industry to meet the Sustainable Land Management Objectives under the Agriculture (Wales) Act 2023. Providing a Carbon Baseline to farms participating in the SFS was recommended by the Carbon Evidence Panel (Welsh Government, 2024), recognising the importance of farmers understanding their own farm carbon balance when taking on-farm actions towards increasing opportunities for carbon sequestration (CS) and reducing greenhouse gas (GHG) emissions. The project was mandated by the Agriculture Change Board, 26 March 2025, with the objective to produce a Carbon Baseline for every farm in Wales participating in the Sustainable Farming Scheme.

One aspect of a farm's Carbon Baseline is on-farm carbon sequestration. A methodology for calculation of farm-scale carbon sequestration from on-farm trees (including woodland) and hedgerows, suitable for application to each farm participating in the SFS, is presented in this report. The Carbon Evidence Panel highlighted the complexity and lack of standardisation of carbon audit tools available on the market, and the need for an approach to calculate Carbon Baseline that was simple for farmers to undertake. To meet these requirements, we detail a standard methodology which can be applied by the Welsh Government to each farm in the SFS which uses Earth Observation data (including the National LiDAR Survey of Wales, and the National Forest Inventory and Trees Outside of Woodlands maps) and does not require additional data collection by farmers beyond information already collected by Rural Payments Wales (RPW) as part of farmers' applications for scheme payments.

2.2 Scope of the Methodology

This report outlines a methodology to measure on-farm carbon sequestration from trees (including woodland, small woods and lone trees) and hedges. For woodland, small woods and lone trees, carbon sequestration values are for total living tree biomass, with carbon in deadwood, litter and soil not reported at this stage due to uncertainty (discussed further in Section 6). For hedgerows, carbon sequestration values for both biomass and soil are included, though presented separately. Sequestration by soils under hedgerows is included in the methodology as there is consistent evidence of high rates of carbon sequestration in hedgerow soils. There is less evidence for sequestration rates by soils under lone trees or TOW. Soil sequestration rates under woodland and small woodland have a strong relationship with the time since establishment, which was unknown for this study and would thus introduce a high degree of uncertainty. This method is based on the best information currently available.

The methodology is designed to make use of recently acquired LiDAR data for Wales, and account for different sequestration rates at different heights. Sequestration rates are presented as lookup tables that estimate sequestration at different height intervals for woodland and trees outside of woodland (TOW) and at different height and width values for hedgerows. These are to be combined with spatial datasets, such as the National Forest Inventory, land use information collected by RPW as part of farmers' application for scheme payments and the recently developed TOW map (Welsh Government, 2024), to provide a spatially explicit estimate of sequestration from woody vegetation for farm parcels. The methodology is consistent with a Tier 2 approach under the IPCC guidelines for GHG

inventory reporting, with sequestration rates derived from UK specific data for each vegetation type.

The methodology does not account for field- or farm-level variation in management practices for woodland, TOW, or hedgerows, instead making national-scale assumptions about management. Future incorporation of local-scale information on management into carbon sequestration calculations is discussed in Section 8 (Further Recommendations). The impact of land use change, removal of vegetation, and soil management practices are also not included. While this would provide a more complete picture of a farm's net position (overall GHG balance), this was considered out of scope with the limited information available (see discussion in Section 8 for potential future improvements).

Methodology overview

On-farm woody features are divided into three categories: woodland (both National Forest Inventory woodland (at least 0.5 hectares, minimum 20 m width and at least 20% canopy cover) and small woods (0.1 to 0.5 hectares) and groups of trees from the Trees Outside of Woodland map), lone trees, and hedgerows. For each category of woody feature, relevant growth models are used to provide the data for carbon sequestration tables, which allow carbon sequestration in woody features to be calculated based on their dimensions i.e. tree height and hedgerow height and width.

Woodland

For woodlands, small woodlands, and small groups of trees, a weighted mean lookup table, weighted by the composition of private woodlands in Wales, was created to provide mean sequestration values for each 0.1m increment in top height, for conifer and broadleaf woodland.

Data for woodland carbon sequestration tables comes from CARBINE, the Forest Research carbon accounting model. CARBINE is used for the forestry component of the UK National Greenhouse Gas Inventory (Brown *et al*., 2025) and uses a consistent underlying model theory to the Woodland Carbon Code, a carbon accounting calculator designed to create carbon credits that is the basis of woodland carbon sequestration calculations in many commercial carbon accounting tools (ADAS, 2023). Using the carbon stock data from CARBINE, tables of carbon sequestration by height increment were created for each species and yield class for no thin, no fell woodland. A weighted growth curve was created for overall categories of unmanaged broadleaf or conifer woodland using a weighting for each species and yield class derived from the area of each species, yield class, and age group from the 2011 National Forest Inventory (NFI) for private woodland in Wales.

The use of a national weighted average growth curve is an assumption that must be made to compensate for the lack of knowledge of the particular conditions of species and yield class in a given land parcel. Similarly, in the absence of land parcel- or farm-level information on woodland management, the assumption that on-farm woodland (broadleaf and conifer) is unmanaged was considered on the basis of expert advice from Forest Research to be most likely to be consistent with the management of on-farm trees. This assumption is consistent with assumptions in the UK Greenhouse Gas Inventory that 93% of private broadleaf woodland is unmanaged, based on low timber production statistics from private forests in Wales (Forest Research, 2026). The assumption of unmanaged woodland is likely to bias tree biomass sequestration estimates upwards, as management practices such as thinning removes standing biomass and transfers the carbon to the harvested wood products pool.

The CARBINE lookup tables for woodland were also applied to the TOW categories of small woodland and small groups of trees, as there was no other suitable data to develop a method specific for these vegetation types.

Hedgerows

For hedgerows, lookup tables are weighted by length (m), with carbon sequestration values for combinations of width (to nearest 0.25 m) and height (to nearest 0.1 m). Data for hedgerow carbon sequestration tables come from hedgerow growth models, with assumptions made to represent average hedgerow management and hedgerow attributes such as age, species and site conditions.

Annual aboveground biomass carbon stock change for different size categories of managed and unmanaged hedges is calculated as a product of the volume increase of a hedge, based on its measured dimensions and annual width and height increments derived from the ERAMMP National Field Survey of Wales (Maskell *et al.*, 2025), and published carbon density values for managed and unmanaged hedges (Biffi *et al*., 2023, Beauchamp *et al*., *in preparation*). National hedgerow sequestration rates are created using an average of the sequestration rates for managed and unmanaged hedgerows weighted by the national proportion of each management type. Belowground biomass carbon sequestration rates were calculated from aboveground biomass rates using root:shoot values from the literature (Mokany *et al*., 2006, Axe *et al.,* 2017, Black *et al*. 2023, Drexler *et al.,* 2023, Drexler *et al.,* 2024), and carbon sequestration in soil was also calculated using published sequestration rates (Biffi *et al.,* 2023).

Lone trees

For lone trees, carbon sequestration is calculated for the maximum height of a single tree. A lookup table is provided for the carbon sequestration at each 0.1 m interval in tree height. The sequestration rates by tree height are derived from TOW specific biomass equations that predict aboveground biomass from tree height (Gruffudd, *unpublished*), and data on height by age for urban TOW trees (Vaz Monteiro *et al.,* 2017). Belowground biomass was included by applying a root:shoot ratio, available from the literature (Cairns *et al.,* 1996). Data was only available for broadleaf tree species. However, this is consistent with the evidence that majority of TOW trees are broadleaf (Forestry Commission, 1983, 2001). The method does not account for the canopy area of the trees.

2.3 Use of the Methodology by Welsh Government

Detailed guidance for use of the carbon sequestration lookup tables to generate on-farm carbon sequestration values is provided in Section 5. The lookup tables are designed to be easy to use with national-scale tree and hedgerow metrics created by Welsh Government from the point cloud data of the National LiDAR Survey of Wales. The National Forest Inventory (NFI) and Trees Outside Woodland (TOW) maps of Wales are used to categorise the LiDAR raster into the three categories of woody feature, with the NFI providing the source of land parcel-scale classification of woodland into broadleaf and conifer, supplemented by the farmer-reported information on land parcels collected by RPW during the application process for scheme payments.

It is anticipated that this methodology will be applied by Welsh Government to create carbon sequestration values for the 2026 Farm Level Carbon Baseline.

3 Background to Current Carbon Sequestration Approaches Available for Woody Features

A number of approaches were considered for calculation of carbon sequestration values on farms prior to selection of the approach taken. Considered methods can be broadly divided into approaches using either a) process-based models or b) lookup tables of emissions factors.

A coupled ecosystem carbon model under development at UKCEH has the potential to provide estimates of carbon sequestration on a farm scale. This modular ecosystem-scale carbon model is a process-based framework built from distinct modules that each simulate specific processes, such as plant growth, carbon allocation and soil carbon dynamics. Critically, it is driven by Earth Observation data (dating from 2016 onwards) and detects vegetation changes such as grazing, harvests, or tree cutting, tracking resulting carbon flows to livestock, manure, and removed biomass. Using these dynamics, it provides weekly estimates of net ecosystem carbon balance and soil carbon change. It operates on a sub-field scale and is therefore suitable for calculating farm-scale carbon sequestration. The model integrates optional ground data, i.e. information on manure use, crop type, and livestock density, to reduce output uncertainty. Leaf area index observations are currently used to constrain the leaf biomass carbon component of the simulated aboveground biomass. Estimates of aboveground biomass from LiDAR (or LiDAR-derived biomass height) could be incorporated as an additional observational constraint on simulated “plant carbon”, the sum of carbon in roots, stems and branches, and leaves. This process-based model has the capabilities to provide estimates of carbon sequestration, incorporating Welsh Government proprietary data sources from the National LiDAR Survey of Wales and farmer-reported information gathered through Rural Payments Wales. However, work on model development and testing has not yet been published, with further model validation also needed, and this methodology was therefore decided as being currently in too early a stage to use in this project.

An alternative approach considered utilises a technique under development in UKCEH to determine carbon stock. This technique determines aboveground carbon stock by using LiDAR and RGB Earth Observation imagery to map trees and woody structures, and allometric expressions to get biomass from height and crown diameter. When applied in England, the UKCEH 3m Land Cover Map is used to determine tree type (broadleaf vs. conifer); at this resolution, the tree type of large individual trees can be resolved. The 3m Land Cover Map is not available in Wales, though the Living Wales map (10m resolution) might prove an alternative. This model is being validated, and has not yet undergone peer-review, though initial results are promising and carbon stocks have been generated for demonstration farms in England. In conjunction with this model for aboveground carbon, belowground carbon stock may be determined with a statistical model also developed by UKCEH. This is a predictive soil carbon model is parameterised by approximately 20,000 soil analyses, which uses soil type and texture, topography and climate, and assimilates satellite-derived land use and land use history, cropping history and cropping cover to predict soil carbon stocks. Model outputs include associated model validation and uncertainty estimates. Though this approach provides spatially explicit estimates of carbon stock, further conversion to carbon sequestration would be necessary to meet the needs of this project. The technique to determine aboveground carbon stock from LiDAR is being developed by UKCEH for commercial application; IP and licensing costs may also make this method unattractive for Welsh Government use.

Emissions factors from the Land Use, Land Use Change and Forestry (LULUCF) sector of the Greenhouse Gas Inventory (GHGI) (Brown *et al*., 2026) could be adapted to calculate carbon sequestrations on farms using a lookup table approach. Emissions factors from the LULUCF GHGI could be used to provide sequestration rates per area of woodland, coarsely divided by tree type and recency of land use change, and per kilometre of hedgerow, managed or unmanaged. These emissions factors were developed in accordance with the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006, 2019). However, no emissions factors exist in the LULUCF GHGI for Trees Outside Woodland (TOW). A further drawback of using a top-down approach designed for calculating a national inventory is also not best-suited to a per-farm calculation, which would benefit from consideration of detail and the specifics of on-the-ground conditions. In addition, using lookup tables based on area of woodland or length of hedgerow would not fully utilise the detail afforded by the National LiDAR Survey of Wales (NLSW), which provides additional information on features' dimensions such as hedgerow width or canopy height.

A spreadsheet-based tool to calculate carbon sequestration on landholdings aligned to the approach used in the UK GHGI LULUCF sector, and including 'default' country-specific assumptions for woodland such as "average broadleaf" and "average conifer" species codes, yield class, age class and percentage tree cover, was developed for UK Water Industry Research (UKWIR, 2022). This tool provides a carbon calculator for woodland and agroforestry "forest areas", including sequestration in aboveground biomass (AGB), belowground biomass (BGB) and soil, in hedgerows, and in "other land use areas" including cropland, orchards, vineyards, coppice, and grassland. The impact of soil type on emissions (i.e. organic soil) is also calculated in the tool. As with the previously mentioned lookup table approach, a methodology based on this tool would make limited use of the information provided by the National LiDAR survey; for example, using only area of woodland with a default age-class assumption and making no use of canopy height.

The Woodland Carbon Calculator (Woodland Carbon Code, 2025) is another spreadsheet-based tool which provides carbon sequestration rates for areas of woodland and is designed to be robust enough to create carbon credits. This tool contains lookup tables for carbon sequestration in woodland per hectare based on species, age of tree, planting spacing, yield class and management activity. Though farmer-reported information gathered through Rural Payments Wales distinguishes between areas of broadleaf and conifer woodland, neither this nor the National LiDAR survey provides direct information on age, spacing, yield class or management; default assumptions tailored to the type of planting typically found on farmland would have to be made. For this reason, the tool as-is is not a good fit to the data inputs with which the methodology for calculating farm carbon sequestration would need to work. The Woodland Carbon Calculator could also not be used alone to calculate carbon sequestration in woody features on farms, as sequestration in hedges and TOW are out of its scope. A hedgerow carbon code is in development but has not yet been launched (Allerton Project, no date).

CARBINE, Forest Research's carbon accounting model is used to calculate carbon sequestration rates for forest land in the LULUCF sector of Greenhouse Gas Inventory. The methodology ultimately adopted for this project, described in more detail in subsequent sections, adapts this model to provide lookup tables of carbon sequestration by species and height for areas of woodland by boiling down the relationship height-increment/height/age to height-increment/height. Though this methodology still requires estimates of representative broadleaved and conifer species, yield class, and management activity, judgement of maturity can be made from the combination of height (from LiDAR) and species. Lookup tables of carbon sequestration in lone trees and hedgerows were created using growth models developed by Forest Research.

This final method allows the spatially explicit estimate of carbon sequestration by tree canopy cover and vegetation alone, exploiting the investment by Welsh Government in detailed LiDAR surveys. The methodology to calculate biomass carbon sequestration is consistent with a Tier 2 approach under the IPCC guidelines for GHG inventory reporting. The calculation of carbon sequestration in woodland is aligned with the UK LULUCF GHG Inventory methodology, as it is derived from the CARBINE model and applies the same assumptions for the composition of species, yield class and age for private sector woodland in Wales.

4 Method for Calculating Carbon Sequestration by On-Farm Woody Features

There is currently no readily available method to directly calculate biomass sequestration rates from LiDAR derived tree biometrics alone (tree height and canopy area). This is limited either by the requirement for additional input data, such as species, age, and growth rate required for woodland trees, or, for trees outside of woodland and hedgerows, because methods have not yet been developed.

The Welsh TOW map and its underlying canopy height model provide spatially explicit heights of all trees and woodlands in Wales. The availability of this height data allows more nuanced estimation of carbon stock and sequestration rates associated with trees, in contrast to applying a flat sequestration rate applied to all trees regardless of their size. Standard tree carbon accounting methods are based on ground-based measurements, primarily using species and trunk diameter, while the LiDAR-derived canopy height data provide only tree height. Therefore, some reframing and reworking of Forest Research's existing datasets and methods was required to enable prediction of carbon sequestration based solely on tree height.

Development of the methodology considered: data available to develop lookup tables, how sequestration rates may differ between vegetation types, and how different on farm vegetation types are recorded in geospatial datasets. Consequently, separate methodology was developed for:

Woodland, small woods, and small groups of trees (per area of canopy cover, by height)
Lone trees (per tree, by height)
Hedgerows (per length of hedgerow for a given width and height)

4.1 Woodland, Small Woods and Small Groups of Trees

An area weighted carbon sequestration table at each 0.1 m height increment was created for broadleaf and conifer woodlands. Sequestration data was taken from CARBINE, the Forest Research carbon accounting model, for unmanaged woodland (no thinning and no felling). Unmanaged woodland was selected for both conifer and broadleaf, as it what considered to be most likely to be consistent with the management of on farm trees. CARBINE can model sequestration rates based on tree species and yield class, which is an index of stand productivity. Stand level annual sequestration rates and stand top height (a metric describing the mean height of the 100 trees of largest diameter at breast height (DBH) per hectare), were extracted from CARBINE.

Carbon sequestration for total living tree biomass was reported. Carbon in deadwood, litter and soil was not reported at this stage, due to uncertainty and to maintain consistency with the other vegetation types to be modelled as part of this project

Following steps were applied to calculate the top height-based lookup table.

1. **Create a carbon sequestration curve at each top height increment, for each species and yield class**

The carbon data reported in CARBINE, usually reported as carbon stock by age, was reverse engineered to create a table of carbon stock change by top height value, for unmanaged woodland. The values were then interpolated to create a table of carbon

sequestration at every 10 cm height increment, for each species and yield class. The sequestration curves for broadleaf species are shown in Figure 4-1.

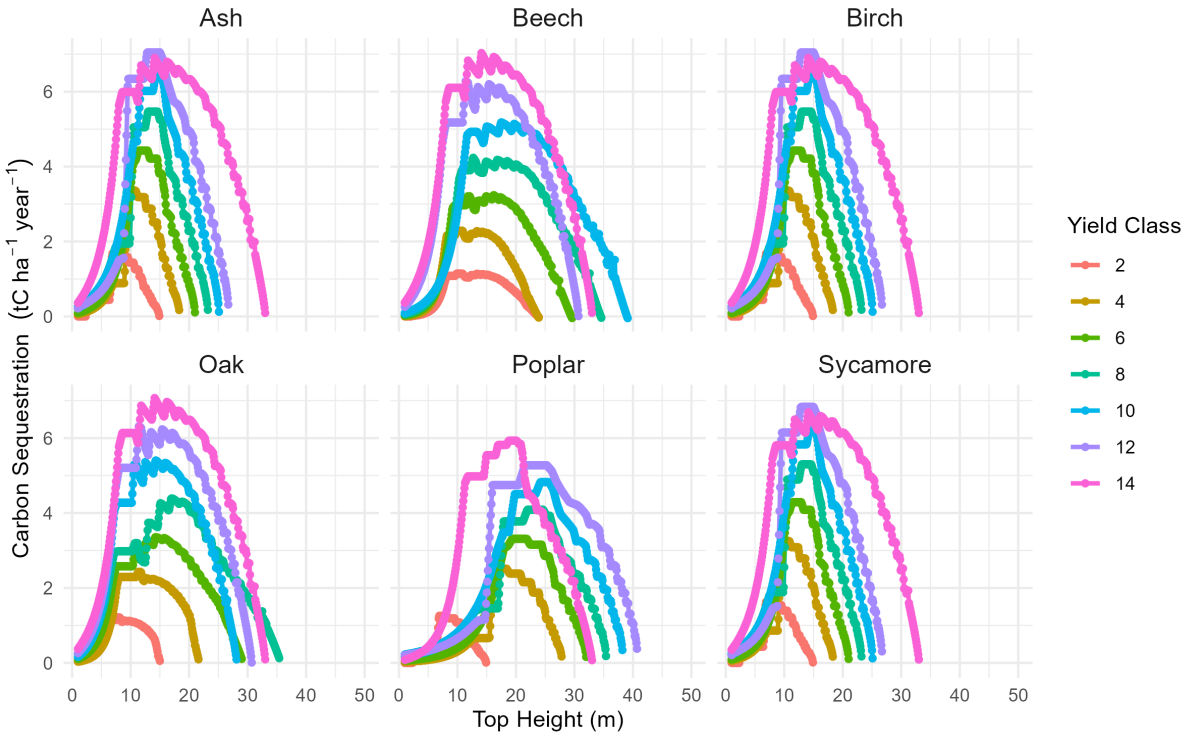


Figure 4-1: Carbon sequestration by interpolated height value, for each broadleaf species and yield class

2. Calculate area weighted growth curve

The area of each species, yield class, and age group (by decadal band) was taken from the 2011 NFI for private woodlands in Wales. This data was used as it is readily available as an input into the UK GHG inventory.

This was used to calculate the area weighting for each species and yield class at a given height range, as a proportion of the total private woodland in Wales. An area weighted growth curve was calculated by multiplying the sequestration at each height interval by the weight, for each species and yield class, and then summing to get a total for that height value.

Sitka spruce was excluded from the calculation for conifer woodland, to avoid the potential bias from including fast growing productive stands managed for timber production.

3. Adjust curve to reduce noise

The area weighted growth curve increases steadily and then fluctuates as certain species and yield class combinations are not included from the calculation because either i) they cannot reach that height, or ii) they have a weighting of zero. Figure 4-2 demonstrates this for broadleaf woodland.

To minimise this a rolling average of ±1m either side of the top height value was applied to smooth the relationship (shown in Figure 4-3 for broadleaf and Figure 4-5 for conifer). While this improved the relationship, there remained an issue of increased uncertainty and volatility

at higher height values, due to reduced number of yield class and species combinations present.

A further adjustment was then made to interpolate a linear relationship between the first peak in sequestration to a trough at 18 m for broadleaf and at 30 m for conifer. These values were selected visually based on the overall trajectory of the relationship, and are intended to be conservative.

This provides a slightly negative linear relationship between tree height and sequestration, after the first peak has been reached, which is consistent with our understanding of a decrease in growth rate in older stands. The linear relationship was then extrapolated to 40 m. The final lookup tables are shown in Figure 4-4 for broadleaf and Figure 4-6 for conifer.

4. Calculate uncertainty

An uncertainty value was estimated by calculating a weighted mean of values above and below the overall mean, providing a measure of spread analogous to a weighted quartile approach. These values indicate that we would expect the value to fall within this range 50% of the time.

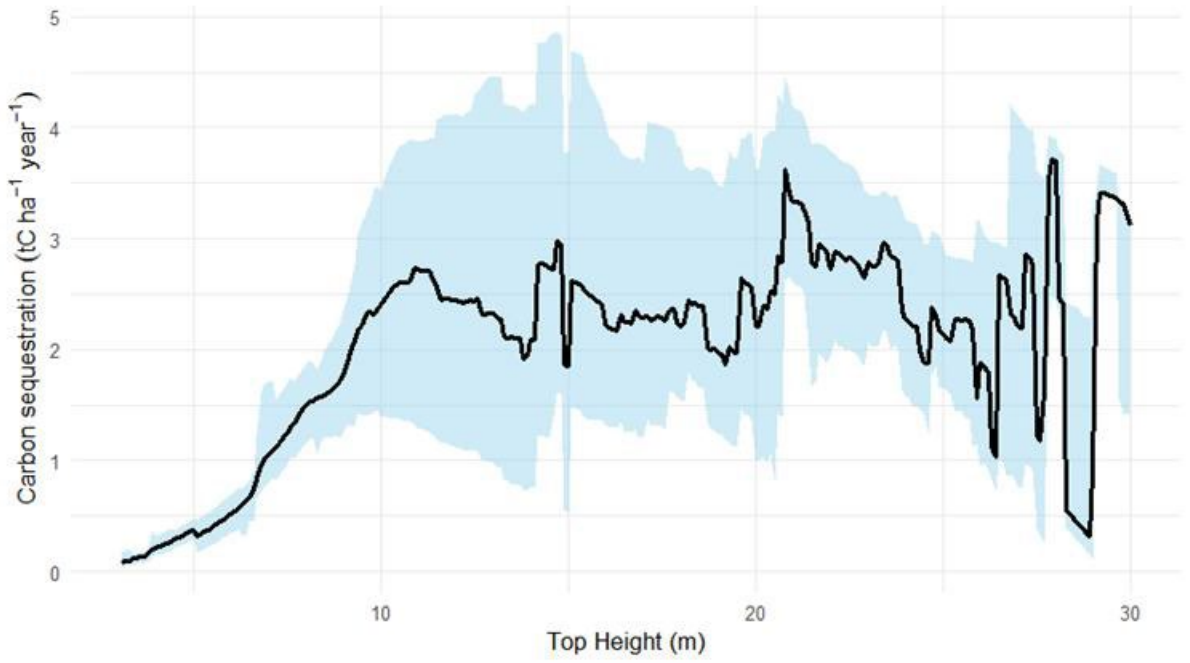


Figure 4-2. The area weight mean sequestration by top height table for broadleaf woodland. Blue represents the weighted mean for all values above and below the mean

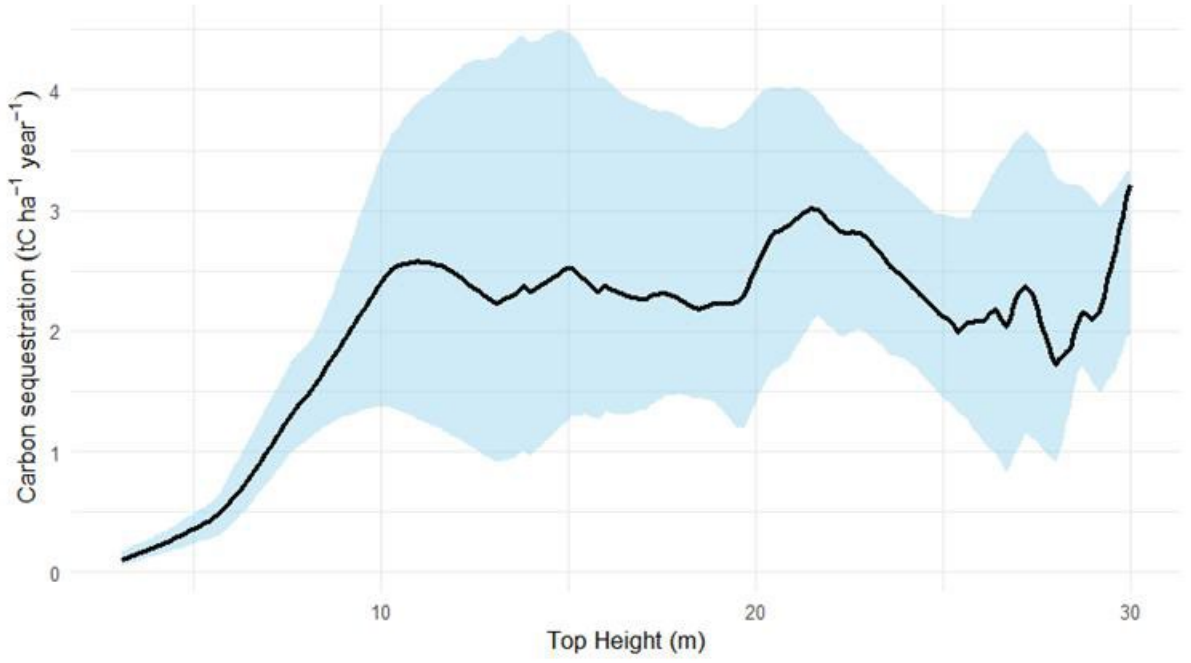


Figure 4-3. The area weight mean sequestration per hectare by top height for broadleaf woodland, with a ±1 m rolling average applied. Blue represents the weighted mean for all values above and below the mean

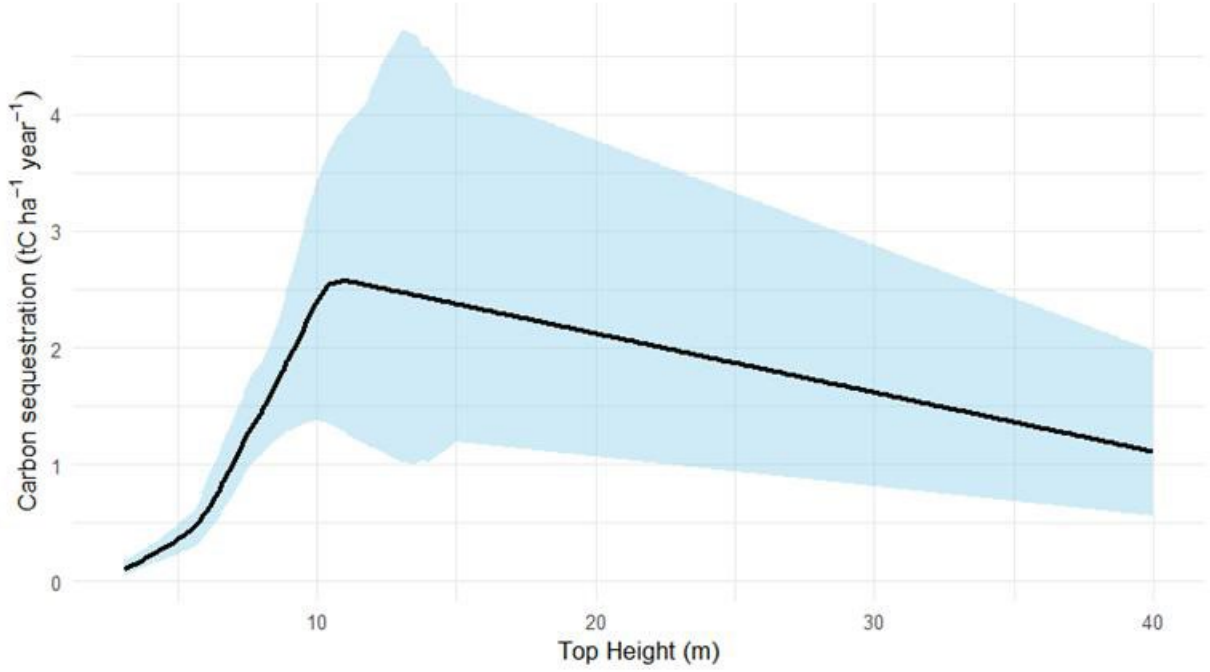


Figure 4-4. The final area weight mean sequestration per hectare by top height for broadleaf woodland, with a linear interpolation applied after the first peak. Blue represents the weighted mean for all values above and below the mean

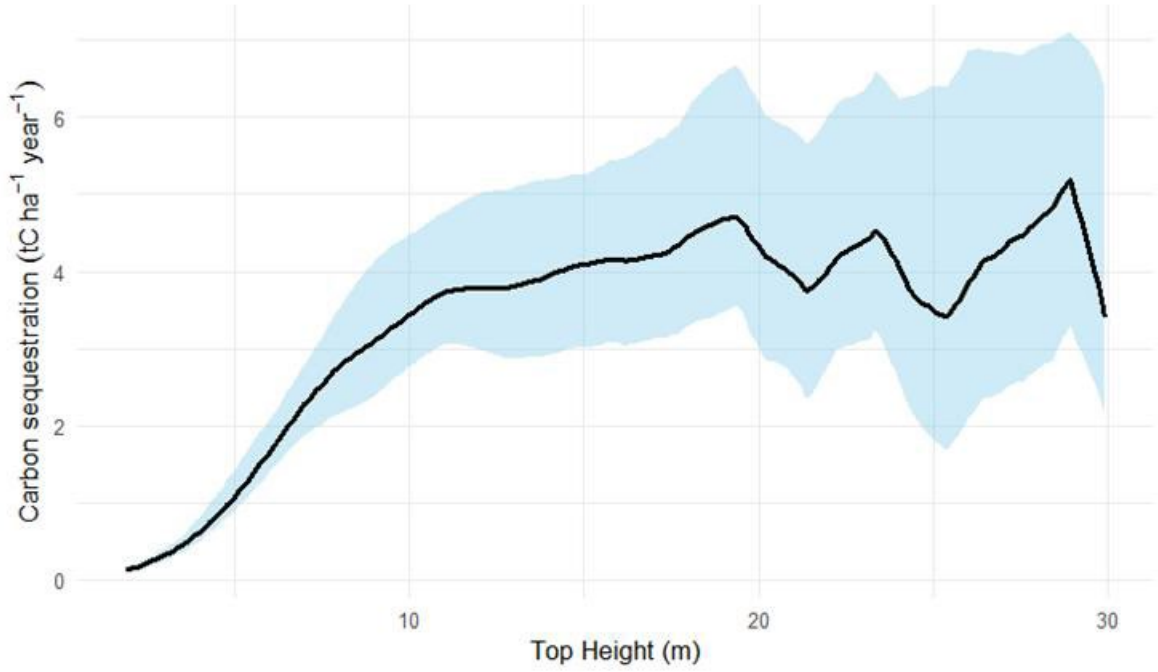


Figure 4-5. The area weight mean sequestration per hectare by top height for conifer woodland, with a ±1 m rolling average applied. Blue represents the weighted mean for all values above and below the mean

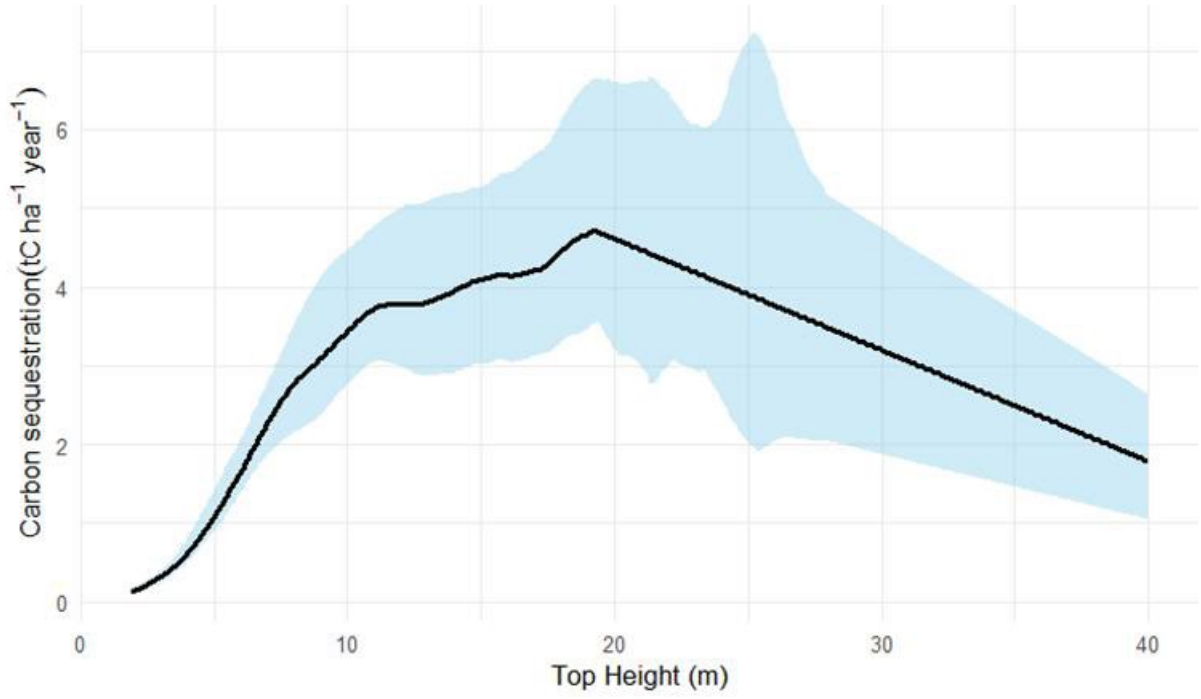


Figure 4-6. The final area weight mean sequestration per hectare by top height for broadleaf woodland, with a linear interpolation applied after the first peak. Blue represents the weighted mean for all values above and below the mean.

4.2 Lone Trees

Trees growing in isolation are found to have different growth and carbon storage relationships in comparison to forest-grown trees (Forrester *et al.,* 2017; Moeys *et al.,* 2025). Reduced competition for light can mean slower height growth, with greater allocation of annual biomass to stem diameter and branch growth instead, and higher per-tree carbon stocks than in forest-grown trees. This suggests that TOW specific datasets will provide more representative estimates of carbon sequestration rates for lone trees, rather than extrapolating woodland values.

The sequestration rate of lone trees was estimated by combining separate assessments of TOW-specific biomass and growth. The uncertainty was assessed using combined confidence intervals from both height and biomass models. Confidence intervals represent the range of values where the mean sequestration rate is expected to fall within, with 95% certainty.

4.2.1 Height Increment

The height growth rate for lone trees was modelled from a study calculating age and height for five broadleaf species located in parks in across four UK cities (Vaz Monteiro *et al.,* 2017). Height increment at each height bin was extracted along with confidence intervals. Increments for heights beyond the range of the initial dataset (4 to 25 m) was interpolated, assuming that there is zero increment at zero height (Figure 4-7).

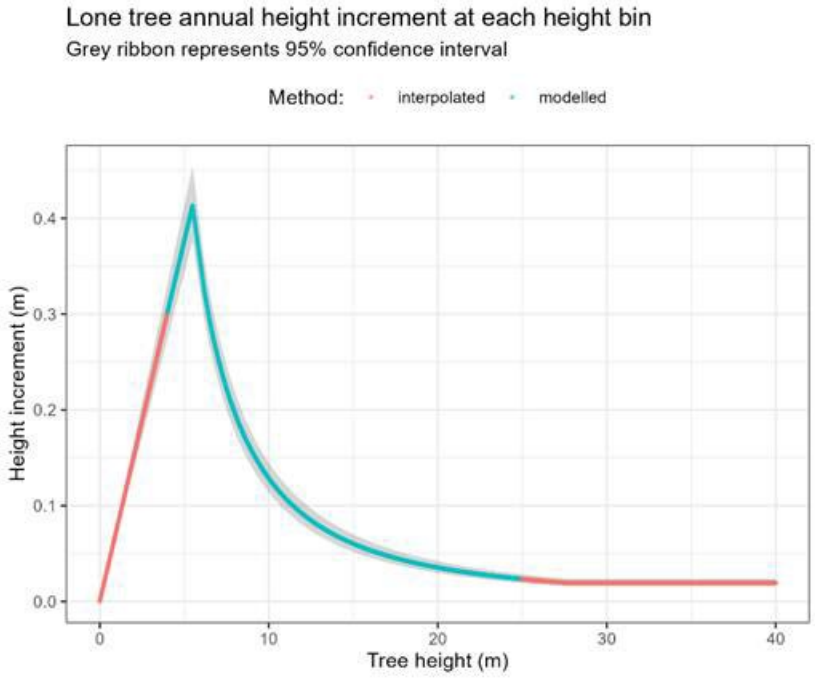


Figure 4-7. Predicted annual height increment at each tree height bin for lone trees. The line colour indicates the source of the data, with the blue line indicating data derived directly from the height growth model and the orange line indicating where height increments have been interpolated beyond the initial height range of the model. The grey ribbon shows 95% confidence intervals.

4.2.2 Lone Tree Carbon Stocks

Aboveground woody biomass in lone trees was estimated using a TOW biomass dataset gathered as part of another project estimating carbon stocks for the England TOW map. This dataset was re-modelled to provide a direct height to biomass equation with confidence intervals. This equation was applied to predict aboveground biomass at 0.1 m height bins. Aboveground woody biomass was converted to whole tree woody biomass using a root:shoot conversion factor of 0.26 (Cairns *et al*., 1996). Woody biomass represents all biomass in the tree apart from foliage biomass. Biomass was converted to carbon by multiplying the biomass value by a carbon content factor of 0.5, consistent with the value used in CARBINE.

4.2.3 Lone Tree Carbon Sequestration Rates

A predicted height increment after 1 year of growth was estimated for 0.1 m binned height values, the carbon stocks were then calculated for height at year 1 and year 2. The sequestration rate was calculated as the difference in estimated carbon stocks at heights years 1 and 2, where the year 2 height is the initial height plus the annual height increment.

To address the high variability in the data from around 17 m height onwards, a similar approach was used as to that applied for woodland trees. First a ±1 m rolling average was used to smooth the data (Figure 4-8). Then to smooth out the remaining variability and provide a conservative estimate for large trees, a constant sequestration rate was applied from height 17 m onwards (Figure 4-9). This approach is prudent due to limitations in the datasets available:

- There is a lack of data for large trees, making estimates for these trees less robust,
- the growth and biomass datasets are biased to larger tree species (e.g. beeches not apples),
- the data tend to be collected from trees in excellent condition, which may not be the case for all farmland trees.

The final sequestration rates even out at ~ 10 kg C tree $^{-1}$ p year $^{-1}$, with a lower estimate of ~ 5 kg C and an upper estimate of 18 kg C. There are relatively few per tree sequestration rates in the literature to compare these rates to. However, they were found to be within the same range as those reported in Simovic *et al*. (2024) and Hand & Doick (2021).

The output of this method is a lookup table of carbon sequestration rate (kg C tree $^{-1}$ year $^{-1}$ and t CO_2 tree $^{-1}$ year $^{-1}$) for tree heights at 0.1 m increments up to 40 m height. A lower and upper estimate of the mean value (derived from 95% confidence intervals) is also provided. Unlike the woodland data, the lone tree lookup does not differentiate between conifer and broadleaf trees, nor is it weighted based on the distribution of different species. This is due to two main reasons:

- There is limited biomass and growth data available for lone trees, with the vast majority of this only available for broadleaf tree species. Therefore, attempting to derive separate equations for different tree types or species was not possible
- The majority of TOW are expected to be broadleaf species (Forestry Commission, 1983; 2001), so not differentiating conifer sequestration rates is unlikely to have a large impact on overall predicted sequestration rates.

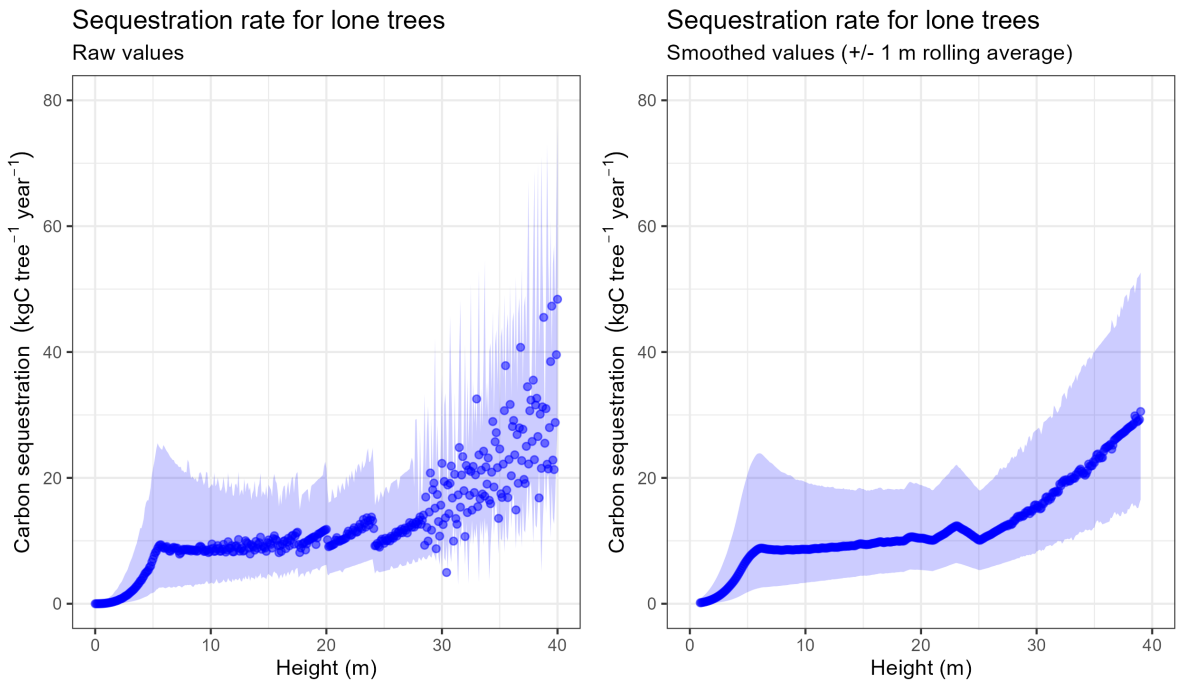


Figure 4-8. Per tree sequestration rates for lone trees for left: raw values and right: values with a ±1m rolling average applied. The ribbon area represents a 95% confidence interval

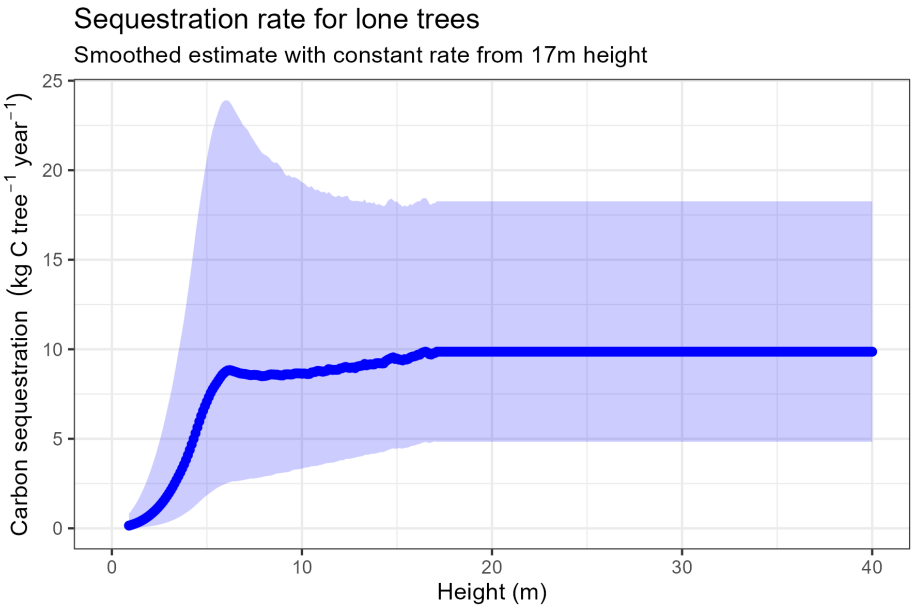


Figure 4-9. Estimated per tree carbon sequestration rate for lone trees with smoothed prediction and constant sequestration rate from 17 m height onwards. The ribbon area represents 95% confidence interval

4.2.4 Lone Tree Uncertainty

The upper and lower estimates provided in the lone tree lookup values represent the combined confidence intervals from the height growth model and the biomass model. The combined estimates were generated by pairing the corresponding lower estimate from the height model to that of biomass model, with this process repeated for the mean estimate and the upper estimate.

The uncertainty of this method should be considered high, largely due to limited data to build growth and biomass models from, but also it should be noted that the upper and lower limits reported for this method represent the error in the estimated mean value at any height. The variability in carbon sequestration values for any one tree will be more variable than the range given in the upper and lower uncertainty estimates. The limitations of this method are described in more detail in section 6.2.

4.3 Hedgerows

Rates of carbon sequestration by hedgerows differ to those of woodland and lone trees due to their frequent management by flailing, their shrubby species composition, higher stem planting density, and linear arrangement.

Sequestration rates are derived from modelled changes in hedgerow carbon stock over time using values from the published literature, including carbon in the aboveground biomass, belowground biomass and soil.

Hedgerow Definition

Hedgerows can be defined as any boundary line of trees or shrubs over 20 m long and less than 5 m wide, and where any gaps between the trees or shrub species are less than 20 m wide (Bickmore, 2002; JNCC, 2011).

For the derivation of sequestration rates for established hedgerows on farms in Wales using spatial hedgerow features of height, width and length, we calculated sequestration rates to be applied to 1.0 m of hedgerow length for 0.25 m width buckets and 0.1 m height buckets, for hedgerows between 0.5 m and 5 m in height and width. LiDAR derived height and width measurements are to the outer edge of the hedgerow biomass and gaps in hedgerows should be excluded.

4.3.1 Hedgerow Method Assumptions

The following assumptions have been made to address limitations in data availability:

- LiDAR data is assumed to be current, that is hedgerows are assumed to still be present, and to be the same size and condition as when scanned; no adjustment for change since scanning have been applied, nor consideration of the variation in the date of scan.
- Hedgerow species are assumed to be primarily hawthorn. 70% of UK hedgerows are hawthorn. Assessment of hedgerow carbon sequestration has primarily been for hawthorn hedgerows and limited data are available for variation by species.
- All hedgerows are assumed to follow average growth rates (from Maskell *et al.*, 2025) and to be of good health. There is insufficient evidence for variability in growth rates across sites or by site conditions, including the effects of climate, soil, elevation or wind exposure.
- Managed hedgerows are assumed to be incrementally trimmed every 3 years, with not all farm hedgerows trimmed at once which ensures habitat continuity for wildlife, therefore sequestration rates are mean annual averages across the triennial trimming period. Hedgerows are assumed not to have been trimmed just before LiDAR assessment. The biomass removed during hedgerow trimming and rejuvenation is not included in sequestration estimates, as the majority is lost through decay or burning, and displacement effects for wood fuel are out of scope. It is also assumed that the incremental increase in size also occurs in the biomass regrowth.

- Surveys show 50% of hedgerows across Wales are well managed (Maskell *et al.,* 2025). There are no data available for the management history of specific hedgerows, therefore rates for managed and unmanaged hedgerows are averaged and applied across all farms.
- Hedgerow sequestration rates are higher in the ~12 years following planting than once established and lowest in old hedgerows (Biffi *et al.,* 2023). For managed hedgerows, we exclude the establishing period and assume hedgerows have not reached maximum carbon stocks.
- Hedgerow rejuvenation through laying or coppicing is recommended every 20-30 years to retain a dense structure (PTES, 2026), though in practice rejuvenation may not occur this frequently across all farms. Rejuvenation removes a portion of the aboveground biomass, which would result in in-year emissions followed by regrowth. There are currently insufficient data to reflect the effects on rejuvenation on hedgerow carbon sequestration. It is assumed the effects of rejuvenation on hedgerow size are embedded within mean changes in height and width, and rejuvenation will not take place between LiDAR and the year following application of this method.
- Hedgerow soil sequestration rates for established hedgerows are applied, and it is assumed soil carbon stocks have not yet reached equilibrium. There is insufficient evidence to derive a relationship for soil carbon sequestration rates with hedgerow height, for managed vs. unmanaged hedgerows, nor to account for differences in soil type, though it is assumed soils are not organic.

4.3.2 Hedgerow Biomass

4.3.2.1 Hedgerow Aboveground Biomass

The carbon stocks in the biomass of one metre lengths of hedgerow are calculated from hedgerow size attributes and estimates of growth, and published values of carbon density, that is the carbon stocks per cubic metre of hedgerow biomass. Annual sequestration rates are derived from the change in carbon stocks over time.

Hedgerow Growth Increment

Between surveys in 2016 and 2022, mean hedgerow width across Wales increased from 2.10 to 2.29 m and mean height increased from 1.86 to 2.03 m (Maskell *et al.*, 2025). This equates to an annual average increase of 0.032 m in width (Wi) and 0.028 m in height (Hi), including managed and unmanaged hedgerows.

Managed hedgerows are assumed to be incrementally trimmed every 3 years, following agri-environment scheme requirements not to trim the hedgerow in successive years. Mean annual increments equal to one third of the 3-yearly increment, assuming one third of farm hedgerows are trimmed each year (Figure 4-11). Incremental trimming is recommended, which allows hedgerow height and width to increase by 5-10 cm every trim to prevent the formation of knuckles and sustain dense biomass (Figure 4-10). Without incremental trimming, sequestration rates would likely slow over time. The mean annual increment from Maskell *et al.* (2025) is equivalent to an increase in width of 9.5 cm and in height of 8.5 cm over the 3-year trimming interval, within the recommended range for incrementally trimmed hedgerows, but at the upper end.



Figure 4-10. Hedgerow cross section, showing size increase with incremental trimming (PTES, 2026).

For unmanaged hedgerows the growth increment is not dependent on trimming, and is instead dependent on variables including site conditions, species, and age. There are insufficient data for the rate of growth for unmanaged hedgerows across site types. The same increment as for managed hedgerows is applied, but with a lower carbon density.

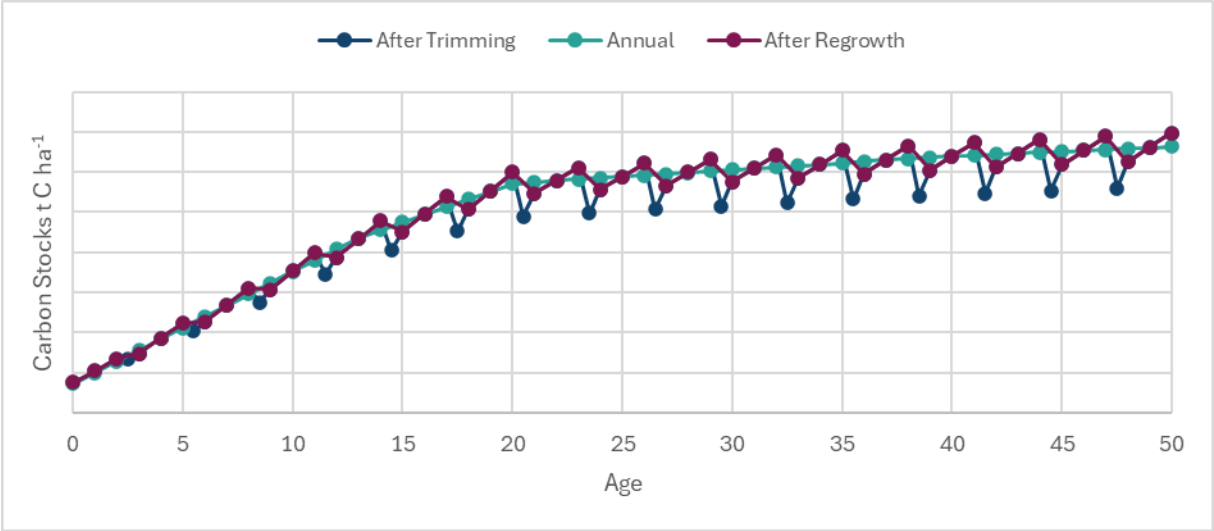


Figure 4-11. Example of aboveground biomass carbon stocks for hedgerows managed with trimming every 3-years, showing stocks after trimming, after regrowth, and annual averages

The initial hedgerow width (W1) and height (H1) are assumed to be those measured during the LiDAR survey in metres. Hedgerow width after one year (W2) is equal to the initial width plus the annual width increment (Wi), likewise height (H2) is equal to the starting height plus the annual height increment (Hi). Initial hedgerow volume (V1) is equal to the product of the initial height, width and section length (1 metre) [V1 = L*W1*H1], with volume after the mean annual increment (V2) equal to the product of the height and width after the incremental growth and length of 1 metre (V2 = L*W2*H2).

The average annual increase in hedgerow volume (Vi) for one metre of hedgerow (in $m^3\ m^{-1}$), is the volume after the incremental increase less the initial hedgerow volume [Vi = V2 – V1]. The annual rate of sequestration per metre of hedgerow length (kg $CO_2\ m^{-1}\ yr^{-1}$) is equal to the mean annual increase in hedgerow volume per metre (Vi, $m^3\ m^{-1}$) multiplied by carbon density.

Carbon Density

Mean carbon density values for hedgerows in the literature are 1.42 kg C m^{-3} (5.21 kg CO_2 m^{-3}) for managed hedgerows and 0.97 kg C m^{-3} (3.56 kg CO_2 m^{-3}) for unmanaged overgrown hedgerows (Biffi *et al.*, 2023, Beauchamp *et al., in preparation*). Carbon density is lower in unmanaged hedgerows which are not regularly trimmed because the lower branches become shaded leading to fewer branches at the base of the hedge, and greater branching and splaying in the upper portion of the hedge. Carbon density values for over trimmed hedgerows in poor condition are not available, and the value for unmanaged hedgerows is applied.

Hedgerow Sequestration Rates

Sequestration rates by the aboveground biomass ranged from 0.16 to 1.57 t CO_2 km^1 yr^{-1} for managed hedgerows, and from 0.11 to 1.06 t CO_2 km^{-1} yr^{-1} for unmanaged hedgerows. Using the assumption that approximately 50% of hedgerows in Wales are managed and in good condition, rates for managed and unmanaged hedgerows were averaged to derive values to be applied locally without knowing hedgerow management condition. Average values ranged from 0.13 to 1.31 t CO_2 km^{-1} yr^{-1} according to hedgerow size, see Figure 4-12.

4.3.2.2 Hedgerow Belowground Biomass

Destructive assessments of belowground hedgerow biomass are limited, and root to shoot ratios are typically applied to aboveground biomass estimates to derive belowground carbon stock and sequestration rates. Root:shoot ratios for hedgerows are higher than for trees and forests, which is theorised as being due to regular trimming promoting belowground biomass whilst constraining the aboveground biomass (Axe *et al.*, 2017). Belowground biomass does not decline with trimming or rejuvenation by laying or coppicing to the same extent as aboveground biomass (Axe *et al.,* 2017).

BGB:AGB ratios for hedgerows ranged from 0.16 to 0.94 (Axe *et al.*, 2017, Black *et al*., 2023, Drexler *et al.,* 2023). The highest ratio of 0.94 (Axe et al., 2017) included biomass in the coppice stool in the belowground estimate. Black *et al.,* (2023) found ratios of 0.16 to 0.74, with higher ratios in more intensely managed hedgerows, whilst younger and unmanaged hedgerows are likely to have lower ratios. Ratios have been reported for trees between 0.2 - 0.33, for shrubs of 0.5 (Mokany *et al*., 2006), and mature hedgerows of 0.7 (Drexler *et al.,* 2024). In this methodology, a central root to shoot ratio of 0.5 was applied, as hedgerows are assumed not to be mature or newly planted, and hedgerow condition varies, with half in good condition. Belowground carbon stocks are approximately half that of the aboveground carbon stocks, therefore carbon sequestration rates by the belowground biomass are calculated as half that of the aboveground biomass.

Sequestration by the belowground biomass ranged from 0.08 to 0.78 t CO_2 km^{-1} yr^{-1} for managed hedgerows, from 0.05 to 0.53 t CO_2 km^{-1} yr^{-1} for managed hedgerows and from 0.07 to 0.66 t CO_2 km^{-1} yr^{-1} for average hedgerows, see Figure 4-12.

4.3.2.3 Hedgerow Total Biomass

The total sequestration by the biomass is the combination of aboveground and belowground rates. Average values which will be applied for aboveground, belowground and total biomass are shown in Figure 4-12.

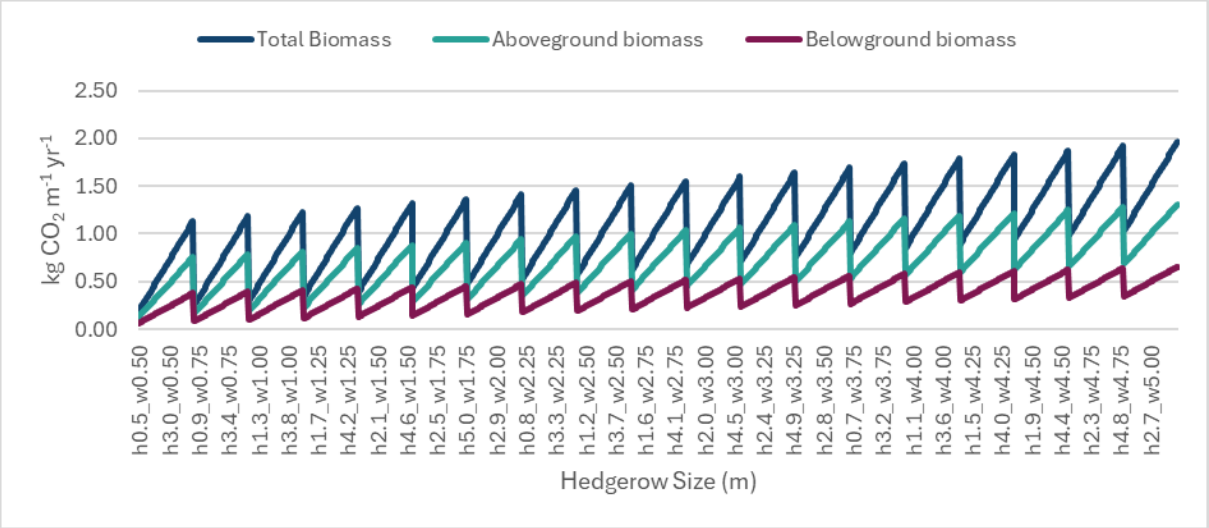


Figure 4-12. Biomass sequestration by size for average hedgerows, for one metre length of aboveground biomass, belowground biomass and total biomass.

Total biomass sequestration by hedgerow size for one metre lengths of managed, unmanaged and average hedgerows, with 3-year increments of 8.5 cm increase in height and 9.5 cm increase in width are shown in Figure 4-13.

Total biomass sequestration for managed hedgerows ranged from 0.24 to 2.35 t CO_2 km^{-1} yr^{-1} and for unmanaged hedgerows from 0.16 to 1.59 t CO_2 km^{-1} yr^{-1}. The mean values which will be applied range from 0.20 to 1.97 t CO_2 km^{-1} yr^{-1}.

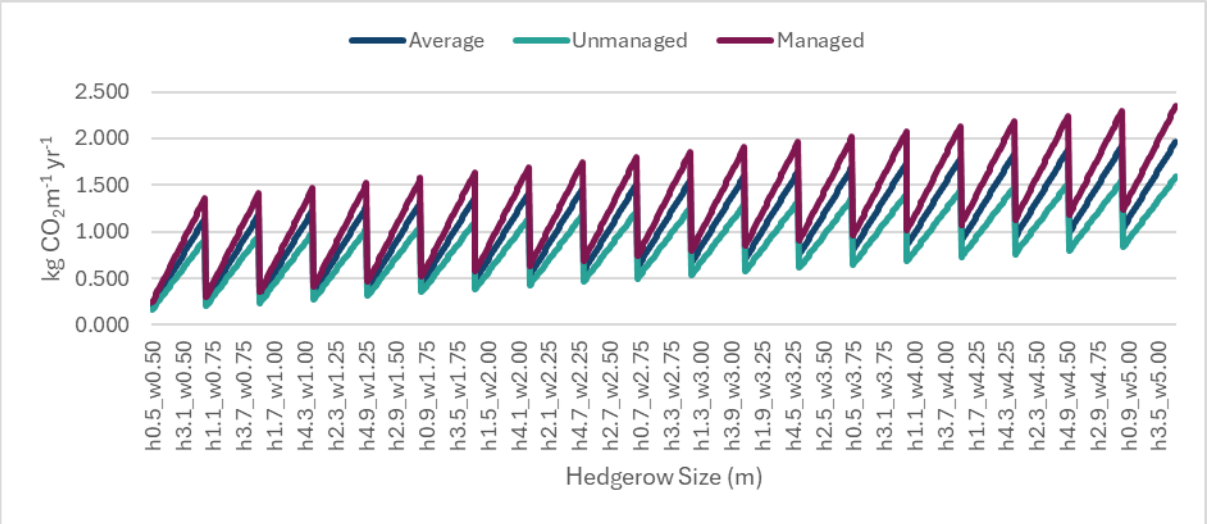


Figure 4-13. Total hedgerow biomass sequestration rates by hedgerow size, for one metre length of well-managed, unmanaged and average hedgerows.

Total biomass sequestration for managed hedgerows ranged from 0.24 to 2.35 t CO_2 km^{-1} yr^{-1} and for unmanaged hedgerows from 0.16 to 1.59 t CO_2 km^{-1} yr^{-1}. The mean values which will be applied range from 0.20 to 1.97 t CO_2 km^{-1} yr^{-1}.

4.3.3 Hedgerow Biomass Uncertainty

A standard error or confidence interval was not available for surveyed hedgerow size increment, or the carbon density values used to calculate carbon sequestration. As an

alternative, an uncertainty for mean hedgerow biomass sequestration was derived using sequestration rates and a 95% confidence interval from Biffi *et al.,* (2023) for 39-year-old hedgerows of 3.14 (1.82–4.47) t CO_2 ha^{-1} yr^{-1}. This gives a percentage uncertainty of ±42%, which was then applied to the sequestration rate calculated for each height and width value. See Figure 4-14.

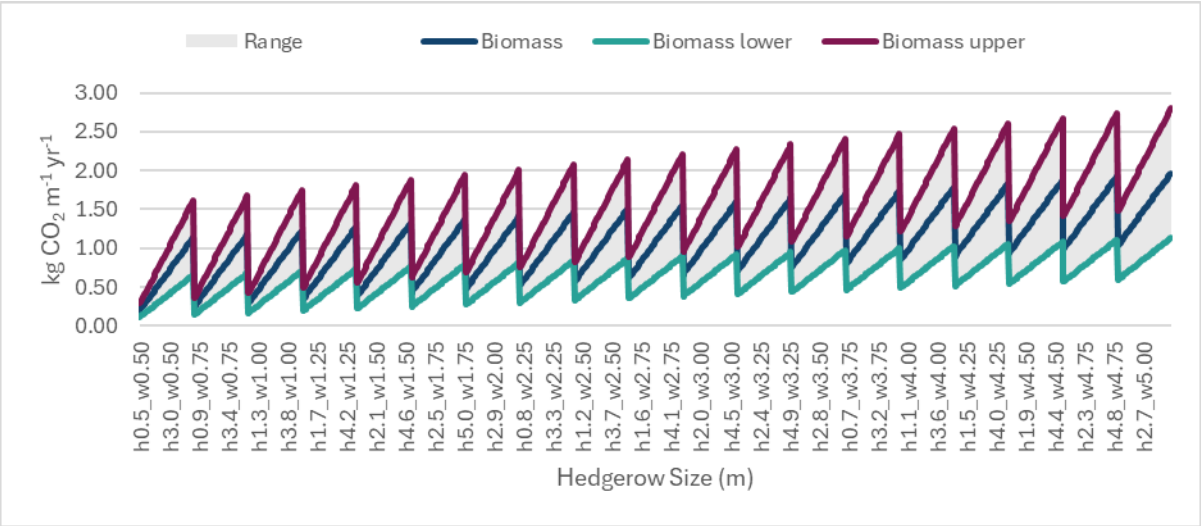


Figure 4-14. Uncertainty estimates for hedgerow biomass sequestration rates for one metre length of hedgerow, by hedgerow size.

4.3.4 Hedgerow Soil Sequestration

Carbon sequestration for soils under hedgerows was calculated from published per-hectare rates and converted to be applied to hedgerow width and length, to enable integration with the Welsh Government hedgerow map. Sequestration rates of 1.47 t CO_2 ha^{-1} yr^{-1} were reported in managed hedgerows 20-40 years old in a chronosequence where 81.1% of sites were on grassland and 18.9% were on cropland (Biffi *et al.,* 2025). Rates of 2.38 ± 2.02 t CO_2 ha^{-1} yr^{-1} were found on cropland (Drexler and Don, 2024), though rates were derived through comparison to surrounding land rather than from a chronosequence. Both studies demonstrate that sequestration can continue for decades after hedgerow creation. The lower rate of 1.47 t CO_2 ha^{-1} yr^{-1} was applied for all hedges, as the rate of soil carbon sequestration with age is non-linear, and the lower value for mature hedgerows is most relevant to the assumptions of this application.

This sequestration rate was converted to kilograms per square meter, equivalent to 0.147 kg CO_2 m^{-2}. The per m^2 squared value was then used to calculate the sequestration at a given width for each one-meter length of hedgerow. For example, a 1 m length of hedge that is 2 m wide has an area of 2 m^2, with an equivalent sequestration rate of 0.298 kg CO_2 m^{-1}. An adjustment was made also to account for the expected growth increment in hedgerow width. A width increment equivalent to the average annual increase of 0.032 m, reflecting the surveyed change in hedgerow size by Maskell *et al.*, (2025). Sequestration rates ranged from 0.078 to 0.738 kg CO_2 m^{-1} yr^{-1} (t CO_2 km^{-1} yr^{-1}) depending on hedgerow width (Figure 4-15).

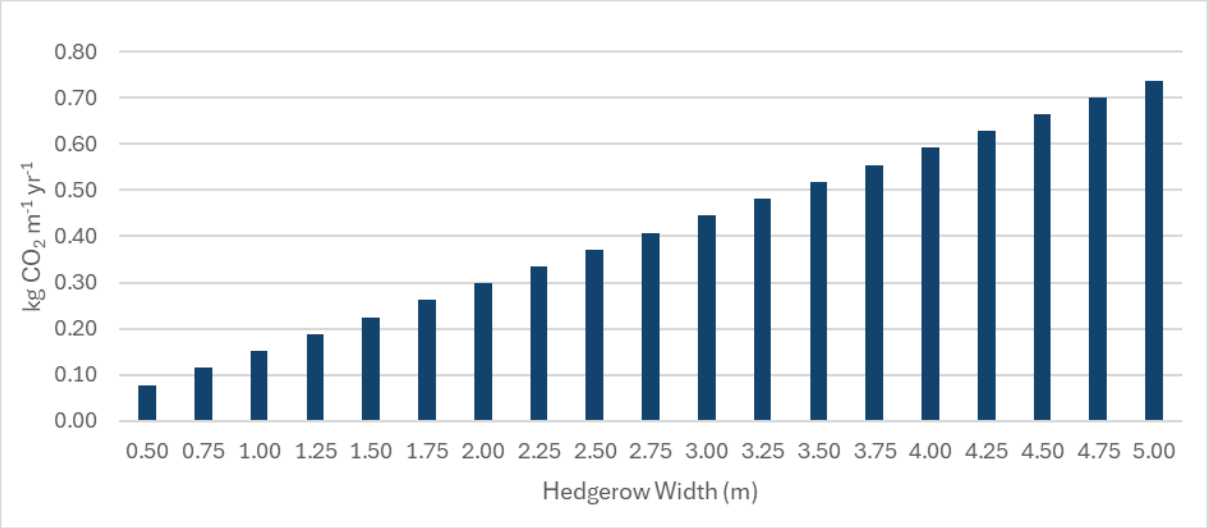


Figure 4-15. Sequestration rates by hedgerow soils by hedgerow width, for one metre of length.

4.3.5 Hedgerow Soil Uncertainty

A standard error or confidence interval was not available for surveyed hedgerow size increment or the soil carbon sequestration rate for the 20-40-year-old hedgerows used to calculate carbon sequestration. As an alternative, an uncertainty for mean hedgerow soil carbon sequestration was derived using sequestration rates and a 95% confidence interval from Biffi *et al.,* (2025) for old hedgerows of 0.8 (0.4–1.21) t CO_2 ha^{-1} yr^{-1}. This gives a percentage uncertainty of ±51%, which was then applied to the sequestration rates calculated for each hedgerow width value. See Figure 4-16.

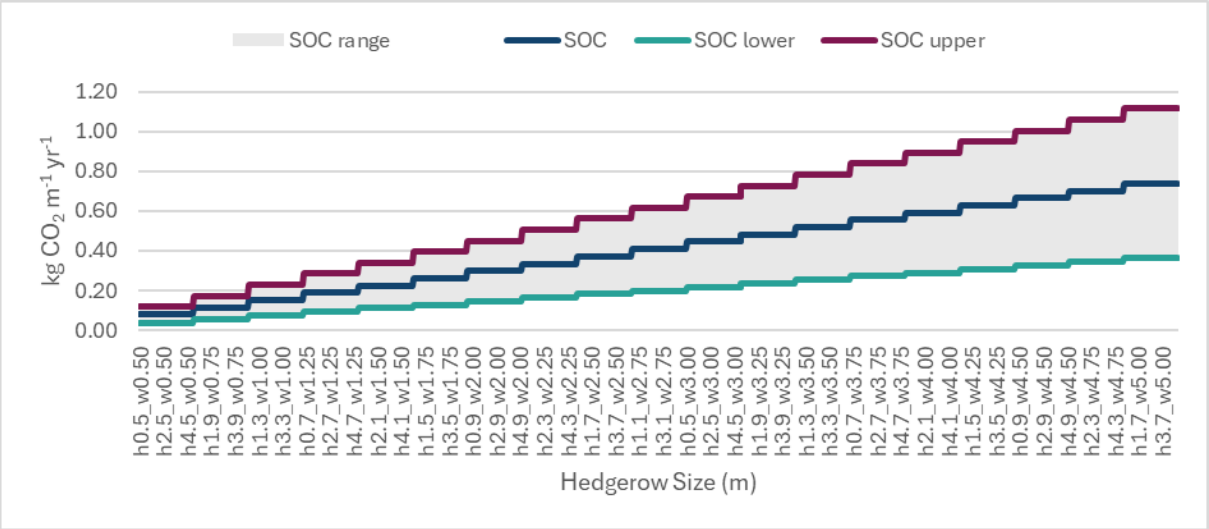


Figure 4-16. Uncertainty estimates for hedgerow soil carbon sequestration for one metre length of hedgerow, by hedgerow size.

4.3.6 Validation: Published Sequestration Rates for Hedgerows

Appendix 1 includes a summary table of sequestration rates from the published literature by aboveground hedgerow biomass, belowground hedgerow biomass and hedgerow soils. Here we compare published values with modelled estimates.

4.3.6.1 Hedgerow Aboveground Biomass

In published studies, measured sequestration rates of aboveground biomass for managed hedgerows ranged from 1.56 to 8.29 t CO_2 ha^{-1} yr^{-1}, with higher rates for newly planted hedges for the first 12 years, and lowest rates for mature hedgerows 13-40 years (Biffi *et al.*, 2023). Crossland (2015) presents a modelled minimum estimate of 0 t CO_2 ha^{-1} yr^{-1} for managed hedgerows. Hedgerow age, size, management, and growth rate all affect sequestration rates.

Modelled sequestration rates by the aboveground biomass of managed hedgerows were calculated as 1.48 t CO_2 ha^{-1} yr^{-1}, for unmanaged hedgerows as 1.00 t CO_2 ha^{-1} yr^{-1}, and average hedgerows as 1.24 t CO_2 ha^{-1} yr^{-1}. Sequestration rates applied in this method are just lower than the published range, as we are representing established hedgerows, are including 50% unmanaged hedgerows, and are representing national average changes in hedgerow size.

4.3.6.2 Hedgerow Belowground Biomass

For average hedgerows, sequestration rates by the belowground biomass were 0.62 t CO_2 ha^{1} yr^{-1}. Published rates for sequestration by belowground biomass are derived from root:shoot ratios, as with this method.

4.3.6.3 Hedgerow Total Biomass

For the average of managed and unmanaged hedgerows, total sequestration rates by the biomass were 1.85 t CO_2 ha^{-1} yr^{-1}. Including the uncertainty estimate, the upper rate of total biomass sequestration was 2.64 t CO_2 ha^{-1} yr^{-1}, and the lower rate 1.07 t CO_2 ha^{-1} yr. Estimates are at the conservative end of the range of published values, as we are representing established hedgerows, including both managed and unmanaged.

4.3.6.4 Hedgerow Soils

Sequestration rates of soils under managed hedgerows ranged from 1.47 to 27.87 t CO_2 ha^{-1} yr^{-1}, with higher rates for newly planted hedgerows and lower rates in established and mature hedgerows (Biffi *et al.*, 2022; Biffi *et al.*, 2025; Drexler and Don, 2024). Sequestration rates of 1.47 t CO_2 ha^{-1} yr^{-1} were reported in managed hedgerows 10-40 years of age (Biffi *et al.,* 2025), which most closely match the assumptions of this analysis. Including uncertainty estimates, a lower rate of 0.72 t CO_2 ha^{-1} yr^{-1} and an upper rate of 2.21 t CO_2 ha^{-1} yr^{-1} were calculated. Sequestration by hedgerow soils is thought to continue for decades after hedgerow creation, therefore is assumed to be ongoing in this methodology.

4.3.7 Validation: Hedgerow and Woodland Sequestration

During implementation, boundary vegetation greater than 5 m in width or height would be classified as small broadleaf woodlands rather than hedgerows. Figure 4-17 compares per-hectare sequestration rates by height for hedgerows and broadleaf woodland. There is good continuity between estimates at 5 m of height where the transition would occur.

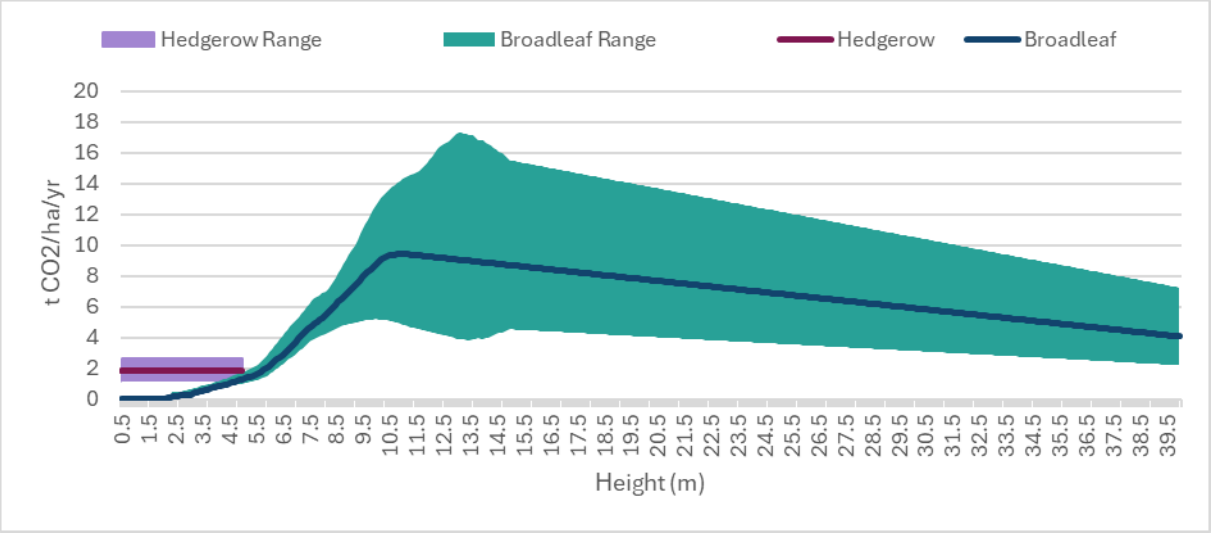


Figure 4-17. Hedgerow and broadleaf woodland sequestration rates per-hectare by height

4.4 Uncertainty (All Vegetation Types)

An uncertainty range is provided for each vegetation type. This is intended to represent the upper and lower range of where we expect the mean sequestration value to be. It does not account for uncertainty in the LiDAR data or in local variation in sequestration rates that may occur at very fine resolution arising, for example, from species and management differences. It is possible for sequestration rates for individual land parcels or tree polygons to vary outside of this range.

5 IMPLEMENTATION GUIDANCE

5.1 Prepare Spatial Input Datasets

The following spatial datasets are required as input to the calculations:

- Canopy height model (1 m pixels)
- Welsh TOW map
- Welsh NFI map
- Conifer, broadleaf classification map
- Farm boundaries
- Welsh Government Hedgerow map

The Welsh TOW map identifies areas of tree canopy outside of woodland and classifies them into small woodlands, groups of trees, lone trees and NFI Over-Hanging Canopy (OHC).

The hedgerow map is a new product, which may be further refined, but in its current iteration (June 2026) areas of hedge overlap with features in both the Welsh TOW map and NFI map. To avoid double counting, the following hierarchy is proposed for calculating sequestration for each vegetation type:

NFI woodland / Small woods / Small groups of trees > Lone trees > Hedgerows

Placing hedgerows lowest in the hierarchy may result in the treatment of features which might be hedgerows as TOW. This classification will act to give a conservative estimate of overall Farm Carbon Sequestration; more carbon would be expected to be sequestered in hedgerow features than areas of hedgerow-sized (<5 m in height) woodland. It should be noted that, if subdividing contributions to Farm Carbon Sequestration from different categories of features, this method's hierarchy is likely to under-represent the contribution from hedgerows.

Hedgerows in the context of this study have the following thresholds applied: <5 m in height and <5 m in width.

To aid classification of vegetation features to the hedgerow dataset, it is recommended to prepare and use the following temporary layers:

- NFI buffer layer
  - NFI woodland polygons are buffered by 1-2 m. This is recommended to minimise the possibility of including returns from low sections of tree canopy where no hedge is present.
- TOW buffer layer
  - TOW map polygons are buffered by 1-2 m. This is recommended to minimise the possibility of including returns from low sections of tree canopy where no hedge is present.

Where the hedgerow layer (a point layer) overlaps with the NFI woodland or TOW buffered layers, remove hedgerow points within the buffered layers. This will produce the hedge point dataset filtered to only non-overlapping points which the look-up table can be applied to. The hedgerow point dataset should further be filtered to remove sections of hedge less than 0.5m in width and/or greater than 0.5m maximum height and those wider than 5m and/or taller than 5m (regardless of whether these areas overlap with any area of other vegetation or not).

These measures are proposed to avoid double counting or complexity in correctly classifying overlapping vegetation types. It should be possible to develop a more nuanced approach that better classifies these vegetation types or accounts for small hedgerows under TOW trees, but this would require further testing.

5.2 Calculate Sequestration for Each Vegetation Type

5.2.1 Woodland, Small Woods and Small Groups of Trees

1. Extract the canopy height model for each vegetation type

Mask the canopy height model with the following vegetation map layers and extract the canopy height model for each separately.

- Conifer woodland NFI
- Broadleaf woodland NFI
- "Modified" small woodlands TOW
    - Small woodlands layer from TOW map, modified to merge small groups of trees connected to small woodlands into small woodlands
- "Modified" small groups of trees TOW
    - Small groups of trees layer from TOW map, modified to merge small groups of trees connected to small woodlands into small woodlands

Areas of NFI woodland that do not have a conifer or broadleaf classification available, should be treated as broadleaf woodland. Small woodland and small groups of trees can be extracted directly from the TOW map.

Note that NFI Overhanging canopy area, reported in the TOW map, is excluded from the calculation. This is because the CARBINE yield tables relate to the net stocked area of woodland.

2. Prepare canopy height model data

Round the canopy height model values to the nearest 0.1m. Apply a minimum height threshold to the canopy height model of 2.2m for vegetation using the broadleaf lookup table and 2m for the conifer lookup table. This is the minimum value that the lookup tables can be applied to. Apply a maximum height threshold in the canopy height model of 40m, this is the maximum value that the lookup tables can be applied to (for both broadleaved and conifer).

3. Convert canopy height model values pixels to top height values (for woodland)

Pixel top height is calculated as the 95th percentile of the height values within each 30m grid cell (Suárez & Rosette, 2013). Aggregate the 1m pixels to a 30m pixel and calculate the 95th percentile height value.

The 30m pixels now need to be converted back to the 1m canopy pixel areas. Apply a mask for the original canopy height model to assign the new 'pixel top height values' for each 1m cell. This will give a 'pixel' top height value for each 1m cell.

4. Apply the sequestration values to the canopy height model map (Woodland)

Convert the carbon sequestration in tonnes per hectare (t C ha^{-1}) to kg per meter square (kg m^{-2}) by dividing the value by 10. Assign carbon sequestration values to each 1m pixel, by joining by the 'top height' values.

Do this for the relevant table and canopy height model for:

- Conifer lookup table – apply to conifer woodland
- Broadleaf lookup table – apply to broadleaf woodland, unclassified woodland, small woodland, and small groups of trees.

This will provide a map of the sequestration per m^2 square of canopy area for each vegetation type.

5.2.2 Lone Trees

1. Prepare lone tree map data

Lone tree calculation needs can be applied directly from the TOW map rather than from the canopy height model. The TOW map should be filtered to 'Lone Tree' in the 'Woodland type' column. To prevent overlap with hedgerows, lone trees in the TOW map should be intersected with the hedgerow as described in section 5.1. In the remaining lone tree features dataset, some lone tree features may contain multiple polygons representing the same tree, with each polygon indicating a different height class of canopy of that tree. All polygons associated with one lone tree feature should be merged, retaining the maximum height for that feature. The maximum height value should be capped at 40m as the biomass equation cannot predict beyond this value.

2. Calculate lone tree sequestration

Apply the carbon sequestration lookup table to the maximum height value for each lone tree. This will provide a map of lone tree sequestration per tree (kg C $tree^{-1}$ $year^{-1}$)).

5.2.3 Hedgerows

1. Prepare hedgerow map

The Welsh Government Hedgerow map is to be used as a basis for this calculation. Hedgerows wider than 5m or greater than 5m tall, should not be included, and treated as a TOW category instead, based on the methodology set out in section 5.1.

2. Calculate sequestration per length of hedge

Hedgerow length is considered to be along the boundary, with width perpendicular to length. Biomass sequestration rates are provided for hedgerows between 0.5 m and 5 m in height and between 0.5 m and 5 m in width. LiDAR derived height values should be rounded to the nearest 0.1 m. Width and length measurements are provided in 0.25 m width buckets. Height and width measurements are assumed to be to the outer edge of the hedgerow biomass.

Hedgerow gaps should be excluded.

Sequestration rates are provided in kg CO_2 m^{-1} yr^{-1} (equivalent to t CO_2 km^{-1} yr^{-1}). Sequestration by hedgerow biomass can be calculated by looking up hedgerow width and height in the table and multiplying value this by the length in metres to derive values in kg CO_2 m^{-1} yr^{-1} or by length in km to derive rates in t CO_2 km^{-1} yr^{-1}.

Values can be applied to features with consistent width, or for metre of hedgerow length, using a height value representative of the top of the hedge (for example, the 95^{th} percentile of top return points). Application to features with consistent height using mean width may increase the error as the width resolution is lower and width buckets larger.

Soil sequestration rates are provided for hedgerows between 0.5 m and 5 m in width. Sequestration by hedgerow soils is independent of hedgerow height and is calculated by

looking up the value in the table for width and multiplying this by the length in metres to derive values in kg CO_2 yr^{-1} or by length in km to derive rates in t CO_2 yr^{-1}.

5.3 Calculate On-Farm Sequestration

1. Calculate individual farm sequestration

Intersect the sequestration maps with each farm boundary and sum the values to calculate the total on-farm sequestration.

Sum the carbon sequestration maps for each vegetation type together to get total biomass sequestration for woody vegetation. This will comprise:

- Sequestration in kg C per m^2 value for each m^2 pixel of canopy (for woodland, small woods and small groups of trees).
- Sequestration in kg C per tree for each individual lone tree.
- Sequestration per metre of hedgerow length, in kg CO_2 m^{-1} yr^{-1}

Sequestration rates can be converted from kilograms of carbon (kg C) to tonnes carbon dioxide (t CO_2) by multiplying by the relevant molecular weights:

$$t\ CO_2 = 44 / 12 \times 0.1 \times kg\ C$$

2. Uncertainty

An uncertainty value is provided for each lookup table, as an upper and lower value. The upper and lower value for the total sequestration in each farm can be calculated by repeating each step, but using the upper and the lower sequestration value, rather than the mean sequestration value, for each height bin.

6 LIMITATIONS AND CAVEATS

Caveats and limitations associated with the methodology developed for each vegetation type are outlined below. Due to the requirement to enable sequestration to vary by height, and limited additional information, such as tree, species, management, age, there is relatively high uncertainty, especially when applied at a granular resolution. We advise caution in interpreting these estimates as definitive, particularly when applying them to local-scale areas such as individual farm parcels. It is likely that sequestration estimates will change as better data becomes available in the future.

A limitation affecting all vegetation features is that application of the look-up tables is dependent on the accuracy of tree/hedge identification from the LiDAR data and then classification in woodland, TOW and hedgerow features. Therefore, some tree or hedge features may be entirely missed in the dataset, misclassified or incorrectly measured (height and/or canopy area). For example, orchard trees, which are not in scope of this methodology, may not be identified, or may be misclassified as a group of trees or small woodland.

6.1 Woodland, Small Woods and Small Groups of Trees

- Deriving top height from LiDAR, may not provide a direct match and is subject to uncertainty. The method to do this was developed for Sitka Spruce (Suarez & Rosette, 2013). An alternative percentile (to 95%) may be more appropriate for certain species. However, this is an area for further work.
- The following limitations apply to the calculation of the weighted mean yield tables.
    - The yield tables assume all woodland is managed as no-thin-no-fell. This means that any carbon losses due to management of these trees (e.g. selective thinning or felling) will not be included.
    - The weighting applied for all private woodlands in Wales is unlikely to be representative of on-farm woodlands, which were assumed to be managed as no-thin-no-fell in this analysis.
    - The weighting applied is based on the 2011 NFI, as this is the data that is readily available as an input into the UK GHGI. This is now 15 years out of date and may influence the weighting of the yield tables calculated.
    - Applying a total mean-based yield table will be subject to high uncertainty. This could be improved by identifying the individual species.
- The yield tables applied assume all woodland is managed as no-thin-no-fell. This means that any carbon losses due to management of these trees (e.g. selective thinning or felling) will not be included. Even a small area of felling can result in large carbon losses.
- Disturbances such as pest & disease impacts (e.g. Ash dieback) or windblow are not included.
- Applying CARBINE to small groups of trees is unlikely to be representative of these tree types. However, it was the only available method to apply to the areas of small groups of trees and small woodlands, while taking into account their height.
- Additional carbon pools (litter, deadwood, soil) were not included.

6.2 Lone Trees

- Lack of height-based growth data: There is limited growth data for individual, isolated trees. There is even less data available which provides growth in relation to tree height (it is normally related to trunk diameter). Only one paper was found which provided height

growth information for lone trees – Vaz Monteiro *et al.* (2017). Therefore, the height growth increment used here was based on a limited dataset, which was biased to larger stature species growing in an urban environment and in good condition.

- Lack of information of species and condition of lone farmland trees: Lone trees on-farmland could be highly variable in species and management. For example, a 10m lone tree could be a veteran apple tree with slow growth, or a young oak tree with vigorous growth. Each tree would have very different sequestration rates, but using this approach based on height alone would give the same sequestration rate. Information on the composition of species, condition and management across Welsh farms, could have enabled some weighting to be applied to the sequestration rate applied here, similar to the approach used for woodland trees.
- Lack of lone tree biomass data: Most biomass data available has been recorded on forest-grown trees, while trees growing in more isolated conditions will likely have very different biomass allometry, making use of TOW specific data preferrable for lone trees. In this study we made use of a recently generated TOW specific biomass dataset, but this still had relatively few data points. This meant that only a general TOW equation could be generated to predict biomass from height, and couldn't be derived for trees of different stature or condition. Further, the dataset only included three conifer trees, and therefore a conifer specific equation could not be created.
- Large uncertainty: Given the limitations in the data described above, the sequestration rates should be treated as having a large uncertainty. The lower and upper estimates provided in the lookup table represent 95% confidence intervals. These reflect the confidence that the mean value of sequestration rate for trees at that height bin are within that range. The uncertainty for predicting the sequestration rate any single tree would be much higher than the range given by the confidence interval.

In this method it is assumed that:

- All lone tree polygons represent a single tree only (no misclassification in Woodland type in TOW map)
- All lone trees are broadleaf tree species
- All are in good condition and under no intensive management regimes. No impact of pest and diseases, such as ash dieback, are accounted for.

6.3 Hedgerows

This method applies within the limits of the data available. The key limitations include:

- There is a time delay between LiDAR data collection and the application of this method, therefore the data do not reflect current conditions. Data collection across Wales was carried out over a period of years, and there is variation in the delay across locations.
- Validation of the LiDAR derived hedgerow attributes, including height, width and length, with ground measurements have not been carried out. This is necessary to ensure consistency between values and definitions of height and width and provide estimates of uncertainty.
- Data resolution for hedgerow width and length are to the nearest 0.25 m. Height values are per pixel at 0.5 m^2 resolution. Lookup tables are provided at 0.1 m height increments.
- Sequestration rates by hedgerow biomass are affected by: hedgerow condition and management history, including frequency and nature of trimming, and the nature of and time since last rejuvenation; hedgerow species; site climatic conditions; and hedgerow age. Sequestration rates by hedgerow soils are also affected by: soil type and previous land use. As repeat assessments of carbon stocks over time are not available, nor are

these attributes, assumptions have been made to represent average conditions and recommended management.

- Data availability for the contribution of hedgerow litter and deadwood to carbon stocks and sequestration rates is limited, therefore it has not been possible to include these carbon partitions.
- The evidence base for UK hedges is small but growing, yet values have good comparability.
- The assumptions implemented to address these limitations are outlined in Section 4.

7 Comparison to Commercial Carbon Calculators

A number of carbon calculators are available to farmers to assess greenhouse gas emissions on a farm scale, and it is likely that in some cases carbon sequestration results from commercial offerings will be compared to Carbon Baseline carbon sequestration values provided to farmers using the methodology detailed in this report. Summary overviews of UK and international carbon calculators are provided below in Section 7.1. Detailed comparison of commercially available tools for agriculture and discussion of their harmonisation has been made in a report published by DEFRA in 2023 (ADAS, 2023). Rather than repeating the work of this detailed comparison, we place the methodology in this report in context with selected commercial calculators by comparing the calculated 'woody elements' component of greenhouse gas emissions (as t CO_2e yr^{-1}) from three 'model farms' in Section 7.2.

7.1 Overviews of UK and International Calculators

Summary overviews of UK commercial carbon calculators and international government-developed tools are presented in Tables 7-1 and 7-2. Modern carbon calculators increasingly integrate Optical EO imagery (vegetation cover, NDVI), SAR radar (structure, cloud-independent biomass), LiDAR (3D vegetation structure, canopy height), and GIS datasets (land parcels, soils) in order to carry out biomass estimation, carbon stock mapping and change over time monitoring. International options for carbon sequestration in agriculture and rural landscapes are typically quantified through MRV systems (Monitoring, Reporting, Verification) which combine field data (soil sampling, vegetation surveys), farm management data, models (biogeochemical, empirical), remote sensing (EO satellites, LiDAR, SAR) and national inventory methods to quantify soil organic carbon (SOC), biomass carbon, and Greenhouse Gas (GHG) fluxes (CO_2, CH_4, N_2O) (Batjes *et al.*, 2024).

Table 7-1: Summary of commercial carbon calculator tools available for the UK.

TOOL	UK use	Caveats / Notes	Homepage URL
Agrecalc	Widely used in UK programmes and supply chains; recognised in DEFRA harmonisation work and used for farm audits since ~2016 [nueleg.org], [agritradenews.co.uk]	Strong on emissions (IPCC Tier 1/2), weaker on **dynamic sequestration modelling** (soil C module improving but still model-based) Comparability issues vs other tools (known divergence in DEFRA study)	https://www.agrecalc.com/
Cool Farm Tool (Cool Farm Alliance)	UK-developed (University of Aberdeen) and widely used in UK & global supply chains	Widely used in the UK; limited detail for hedgerows and small woodlands.	https://coolfarmtool.org

Regrow	Yes	Requires calibration to UK soils, crops, and management practices	https://www.regrow.ag
CIBO Technologies	Yes	Needs UK soil, weather, and land-use datasets configured	https://www.cibotechnologies.com
Eggbase Carbon Calculator	Used in UK poultry sector (e.g. farms in programmes and commercial use cases)	Highly sector-specific (eggs/poultry only) → not transferable to whole farm systems - Focus on emissions not sequestration (limited soil carbon relevance)	https://eggbase.co.uk/carbon-footprinting-with-eggbase/
EarthOptics	Yes (limited)	Technically usable; UK service availability and cost may limit scale	https://earthoptics.com
Farm Carbon Toolkit (Farm Carbon Calculator)	Widely used across UK farming sector; "trusted and used… across UK supply chain"	Includes sequestration estimates (soil, hedges) but: - High uncertainty in soil carbon modelling - Results dependent on assumptions and emission factors	https://farmcarbontoolkit.org.uk/
Trinity AgTech "Sandy"	Used in UK supply chains (e.g. potato sector partnerships)	"natural capital" model → high complexity and black-box risk - Combines carbon, biodiversity, water → harder to isolate sequestration assumptions - Relies on model–data fusion	https://www.trinityagtech.com/
Solagro Farm Carbon Calculator	Used in EU research / policy contexts (developed for European Commission/JRC)	Spreadsheet-based tool. less user-friendly / scalable - Primarily emissions diagnostic → limited dynamic sequestration modelling - Requires manual data handling → higher risk of inconsistency	https://solagro.org/carbon-calculator

Nadar	Yes	EO and LiDAR work globally; UK hedge accuracy improves with ground truthing	https://www.nadar.earth
Lens for Carbon (Upstream Tech)	Yes	Strong for woodland and tree carbon; not farm-management focused	https://www.upstream.tech
NCX	Partially	Primarily US-focused forestry markets; UK applicability still emerging	https://www.ncx.com
SilviaTerra	Yes	Usable in UK forestry; needs alignment with UK forest inventory standards	https://silviaterra.com
Verra-aligned platforms	Yes	Usable but costly and complex; overkill for simple farm baselines	https://verra.org
Gold Standard providers	Yes	Suitable for project-level carbon credits, not lightweight baselining	https://www.goldstandard.org

Table 7-2: Summary of most common overseas Government-developed tools.

Tool	Description	Inputs	Use Cases
COMET-Farm (USA)	Whole-farm GHG accounting tool based on USDA methodologies	Farm management (tillage, crops, livestock), soil type, climate data, land use	Farm carbon baselines, conservation planning, carbon credits
COMET-Planner (USA)	Simplified version using regional averages	Basic land use inputs	Early-stage policy/scenario screening
IPCC National Inventory Methods	Tier 1–3 methodologies for GHG inventories	Activity data, emission factors, national datasets	National reporting, policy modelling
EU LULUCF & CAP MRV frameworks	EU-level carbon accounting standards	Land use, EO data, inventories	Compliance, subsidy frameworks
FAO GSOC MRV frameworks	Soil carbon monitoring systems	Soil sampling + modelling inputs	Global soil carbon monitoring

7.2 Comparison of Model Farm Results

Commercially available carbon calculators account for a much broader range of emissions categories than the methodology detailed in this report; these include crop residues, enteric emissions, embedded emissions associated with the production of pesticides and/or feed, fertiliser application, Scope 1, 2, and 3 emissions related to energy use, and others, including for some calculators carbon stock change across the farm system due to land use changes and soil management practices (ADAS, 2023). Carbon sequestration from land use (including sequestration from carbon stock change associated with woody elements) is, however, typically presented as its own category in the outputs of commercial tools, allowing values from our methodology to be compared with just this component of the outputs of commercial tools.

The 'woody elements' component of greenhouse gas emissions (as t CO_2e yr^{-1}) on three 'model farms' was calculated using commercially available carbon calculators and compared to carbon sequestration (t CO_2 yr^{-1}) calculated with this report's methodology. The carbon calculators examined in this report (Farm Carbon Calculator v3.6, Trinity AgTech's Natural Capital Navigator Sandy, Solagro v3.1) were among those identified as most relevant or widely used in a 2023 report which analysed the functionality of commercially available carbon calculators (ADAS, 2023). Analysis results are anonymised with respect to carbon calculator, and no endorsement of any particular carbon calculator is made.

Choice of model farms

Three 1 km squares containing varying amounts of woodland, hedgerows and trees outside woodland (Table 7-3) were used as 'model farms' to compare carbon sequestration methods. Areas of woodland, woody linear features (WLF) such as hedgerows and lines of trees, and trees outside woodland (TOW) were mapped within 1 km squares as part of the ERAMMP National Field Survey; features as mapped by surveyors, and their recorded characteristics, were used as input into carbon calculators.

Table 7-3: Summary statistics of woody features (woodland, woody linear features and trees outside woodland) in 'model farms' used to compare carbon sequestration values from different calculators. For better comparison between commercial calculators and the methodology presented in this report, which uses a maximum cut-off height of 5 m for hedges, woody linear features are subdivided into '<5 m hedge'-type and 'trees'-type (e.g. belts of trees, >5m unmanaged hedgerows). 'Model farms' are based on surveyed squares from the ERAMMP National Field Survey.

Square ID	Woodland area (ha)	WLF – <5 m hedge length (km)	WLF – trees length (km)	TOW – small woods and groups of trees	TOW – lone trees
DDLYPR	1.61	9.45	5.82	28	6
IDHJID	19.55	1.98	1.85	4	36
PBHRYW	64.66	0	0	3	4

Comparison of commercial carbon accounting tools and this report's methodology

Differences in carbon sequestration values calculated using different tools and using the method presented in this report arise from:

a. differences in what inputs can be entered into each carbon calculator,
b. what assumptions are made, and
c. the emissions factors used to calculate carbon sequestration from those inputs.

Factors contributing to differences between commercial tools, and between commercial tools and the methodology presented in this report, are discussed below.

Difference in scope of calculators: inclusion of woodland

Difference in system boundaries has been identified as a driver in overall differences in emissions estimates between commercial calculators, which can be extensive (ADAS, 2023). Not all commercial calculators accommodate calculation of carbon sequestration from woody elements (ADAS, 2023), and within those that do there are differences in which woody elements are included. All examined calculators, as well as the methodology presented in this report, calculate carbon sequestration due to hedges and in-field trees, but calculator A did not include trees in woodland (Table 7-4). The methodology presented in this report includes the calculation of carbon sequestration in woodland; when compared to a commercial calculator in which woodland is not in scope, this report's methodology is likely to return a larger carbon sequestration value.

Table 7-4: Comparison of scope of carbon calculators with respect to 'woody elements': woodland, hedgerows and Trees Outside Woodland.

Carbon Calculator	Woodland	Hedgerows	Trees Outside Woodland
A	out of scope	in scope (carbon in wood + soil)	in scope (carbon in wood + soil)
B	in scope (carbon in wood)	in scope (carbon in wood + soil)	in scope (carbon in wood)
C	in scope (carbon in wood)	in scope (carbon in wood)	in scope (carbon in wood)
this report	in scope (carbon in wood)	in scope (carbon in wood + soil)	in scope (carbon in wood)

Data entry factors: mapping of woody features.

Commercial carbon calculators require a data gathering phase in which farmers assemble information about their farms, including areas and dimensions of woody features (e.g. areas of woodland, width and length of hedges and number and size of in-field trees). Some commercial calculators, such as calculator C, have the ability to develop methods to available data such as LiDAR, though standard models are designed to be used by landowners and land managers. For the comparison presented above, data entered into commercial calculators was collected on the ground by ERAMMP National Field Survey Surveyors, who mapped areas of woodland, hedgerow extent, and the position of lone trees.

In the methodology presented in this report, the positions of small areas of woodland and lone trees are determined using the Earth Observation-derived Trees Outside Woodland map of Wales. Metrics such as the exact canopy extent of a woodland or small group of

trees, or width of a section of hedge are determined using LiDAR which allows mapping on a much more granular scale, though changes to woody features may have occurred between the years of LiDAR collection (2020-2022) and 2026 (the year of presentation of Farm Carbon Baseline to farmers). Ground surveying also allows hedgerows underneath canopies to be recorded; these are excluded in the methodology presented in this report.

Differences in data collection may contribute to differences between carbon sequestration values calculated using the method in this report, and those arrived at by the use of carbon accounting tools by farmers, though these differences are unlikely to be systematically in one direction.

Data entry factors: difference in granularity and assumptions

Other farmer-collected information which may inform carbon sequestration estimates in commercial calculators includes: details of woodland age, yield class, woodland species, and woodland management, and differentiation between managed and unmanaged hedgerows. Commercial calculators differ from one another and from the methodology presented in this report in the amount of granularity possible when reporting and modelling on-farm woody elements.

The methodology presented in this report uses height of woodland and lone trees and dimensions of hedgerows to inform the calculation of carbon sequestration rates. Some commercial calculators (e.g. B, C) allow input of woodland age, if known, for a similar effect. However, as information on woodland age was not collected during the field surveys, this input could not be included in carbon sequestration calculations by commercial calculators for the 'model farm' comparison – analogous to a situation in which a landowner did not know the age of their on-farm woodland. The data gap in this comparison introduces uncertainty into carbon sequestration estimates from commercial calculators that use woodland models dependant on stand age; calculators provided assumptions for woodland age under these circumstances.

Calculators B and C also allows input of details of woodland management. Model farm PBHRYW contained some areas of managed (thinned) woodland. Calculations of carbon sequestration in this report's methodology assume that all woodland is unmanaged; this may result in over-estimation of carbon sequestration on farms containing managed woodland.

Where detailed input is not used in a calculator, or information (e.g. woodland age) is not known, assumptions must be made. If making assumptions on woodland management, commercial calculators tend to assume that woodland is not thinned or harvested (ADAS, 2023); this is also an assumption made in this report's methodology.

In addition to those mentioned above, the methodology in this report uses assumptions based on national averages for Wales for the proportion of managed hedgerows, representative species distribution and yield class in private broadleaf and conifer woodland. It is possible that the private woodland composition in Wales, in terms of species and yield class, differs from that found on farmland, and may result in an overestimate of tree growth. On the scale of an individual farm, particularly one that differs from national averages by, for example, thinning its woodland, differences in granularity of input, and assumptions and default values between calculators could lead to noticeable differences in calculated carbon sequestration values.

Difference in emissions factors used by calculators.

No single approach to assessing carbon sequestration from vegetation is taken by commercial calculators (ADAS, 2023). Most of the carbon calculators identified in the analysis of ADAS (2023) as most relevant or widely used (including this report's calculator B

and C) are, when calculating emissions factors for woodland, aligned in some way with the Woodland Carbon Code, which uses a consistent underlying model theory to Forest Research's CARBINE model (Woodland Carbon Code, 2025). The methodology presented in this report to calculate carbon sequestration from woodland is likewise aligned with Forest Research's CARBINE model, so is underpinned by the same carbon accounting model, though different calculators may use different levels of detail and default values, with the biggest difference being inclusion of stand age (see above).

Commercial carbon calculators may calculate emissions factors for hedgerows from a synthesis of data from published studies (such as those summarised in Appendix 1, Table A1-1). Data for the lookup table for hedgerows in this report are based on growth models validated against emissions factors from published studies. Section 4.3.6 provides a more detailed discussion of validation of the hedgerow growth model presented in this report against data from published studies.

Data for the lookup table for lone trees in this report is based on a lone tree-specific growth model. Lone trees are expected to have higher per-tree carbon stocks than in forest-grown trees (Forrester *et al.,* 2017; Moeys *et al.,* 2025), so this report's method would be expected to estimate greater carbon sequestration from a lone tree than a calculator which uses woodland values.

Comparison of carbon sequestration in model farms

We would therefore expect there to be a change between carbon sequestration rates calculated using our methodology and those calculated using commercial calculators, particularly due to differences in scope and differences in granularity of input and assumptions. Changes observed between calculators are likely due to multiple factors operating at once.

A comparison of the resulting GHG sequestration values is presented in Figure 7-1. Calculation of on-farm carbon sequestration using this report's method is made using the average values of carbon sequestration presented in the lookup tables. Lower and upper confidence intervals on the values of carbon sequestration per metre^2/metre/tree from the lookup tables (see 'Uncertainty' sections in Section 4) are used to calculate upper and lower carbon sequestration estimates for each farm.

GHG sequestration values for model farms calculated using different commercial tools differ widely. Carbon sequestration values calculated using this report's methodology (using the lookups' average carbon sequestration values) are broadly similar to GHG sequestration values from commercial tools, and are not more different from commercial tools' estimates than commercial tools' estimates are from one another. The largest differences occur in the estimate of carbon sequestration in woodland; it should be noted that in calculators B and C carbon sequestration in woodland is sensitive to stand age, therefore the lack of stand age data for 'model farms' is likely to lead to large uncertainties in carbon sequestration values. Calculator C provided regionally and species-specific default values for stand age where woodland stand age was unknown; when calculating carbon sequestration in woodland of unknown age, calculator B provided an average value for each type of woodland over a 200 year average.

In the case of 'model farm' PBHRYW, difference between carbon sequestration values from commercial calculators and the method described in this report arises predominantly from data entry factors in mapping of woody features. The 1 km ERAMMP National Field Survey square PBHRYW contains the largest proportion of woodland (Table 7-4) and is the least representative of the composition of woody features of a typical farm; though illustrative,

more weight should be given to comparison of methods in the calculation of carbon sequestration for 'model farms' DDLYPR and IDHJID.

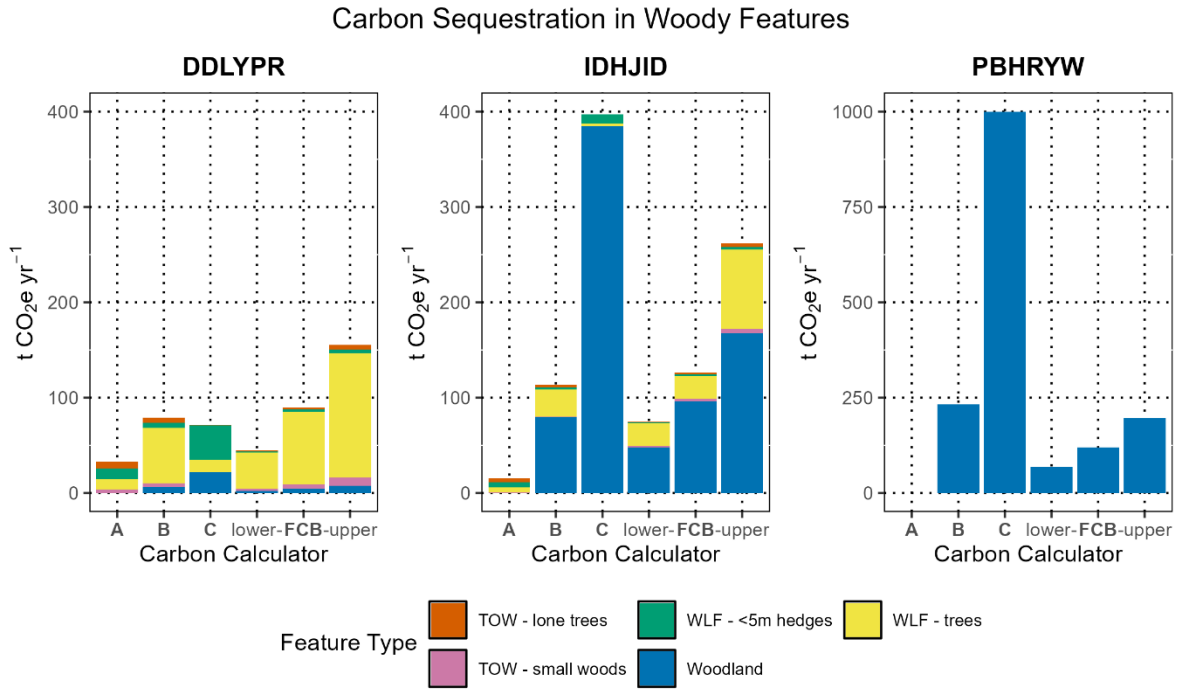


Figure 7-1: Comparison of carbon sequestration (t CO_2e yr^{-1}) in three model farms, calculated using carbon calculators A, B, and the method developed in this report, labelled 'FCB' (Farm Carbon Baseline) on the plot. Note the change in scale for plot PBHRYW. Calculation of on-farm carbon sequestration using this report's method is made using the average values of carbon sequestration presented in the lookup tables. Lower and upper confidence intervals on the values of carbon sequestration per hectare/metre/tree are used to calculate carbon sequestration estimates presented as separate bars labelled 'lower-' and '-upper' on the bar chart. It should be noted that, whilst commercial carbon calculators provide CO_2e, the FCB method includes only CO_2. The components of carbon sequestration due to Woodland, Trees Outside Woodland – small woods, Trees Outside Woodland – lone trees, Woody Linear Features – <5 m hedge and Woody Linear Features – trees are indicated by different colours. The method in this report calculates carbon sequestration in 'woodland, small woods, and small trees'; for better comparison on the plot, this category has been subdivided into Woodland, TOW – small woods, and WLF – trees (TOW features which intersect field boundaries). Carbon sequestration in Woodland was out of scope of calculator A, and the TOW – small woods category was excluded from the carbon calculation of calculator C.

The observed differences in carbon sequestration calculated on model farms using various commercial calculators highlights the importance of using a consistent method for all farms, to avoid variations solely due to method or tool selection, and of clear communication when presenting carbon sequestration values. Decisions on a) what is in scope to include in the calculations, b) which input data are used and c) what assumptions are made are guided in both the methodology presented in this report and in commercial carbon calculators by the purpose for which the carbon sequestration values were calculated. Therefore, different carbon sequestration values are likely to be obtained using different tools. It should be noted

also that if, for later time periods, a different approach for calculating on-farm carbon sequestration is adopted (see further discussion in Section 8), on-farm carbon sequestration estimates from different years calculated using different methods will not be directly comparable.

When reporting farm carbon sequestration values calculated using the methodology detailed in this report, including an accompanying description of the purpose and scope of sequestration estimates provides additional context to explain potential differences from values returned by commercial calculators. A similar recommendation to consider the purpose of carbon assessment when using carbon accounting tools was made in a previous report on harmonisation of carbon accounting tools for agriculture (ADAS, 2023).

8 FURTHER RECOMMENDATIONS

Potential recommendations to improve on-farm carbon sequestration estimates are discussed below. All suggestions require additional investment in data collection and/or method development.

8.1 Improvements to current approach

Apply a species breakdown for woodland

The identification of species would allow species specific yield tables to be applied. Emerging methods are using AI to enable species mapping of woodland sites, with two models currently in development at FR enabled species mapping of woodland sites. However, a remaining issue is that many areas of farm woodland are likely to be mixed species, which are not represented directly in CARBINE. Uncertainty or error in misclassifying species would also be a limitation, particularly for smaller woodland polygons.

Inclusion of deadwood, litter and soil carbon pools for woodland.

CARBINE also reports carbon stock change for deadwood, litter, and soil carbon pools. These pools were excluded from this methodology, as the sequestration rate is highly uncertain without additional information on stand age, rotation number, soil type, and previous land use (for soil carbon) (Matthews, 2020). It could be possible to include these carbon pools to provide a more complete picture of total woodland sequestration by providing an area-weighted lookup table that includes these carbon pools. A key distinction required for soil carbon would be to identify woodland on mineral, organo-mineral and organic soils. Mineral soils could be aggregated or into a single lookup table, or group separately. An assumption of previous land use would also be required.

If implementing this method, the soil type of a woodland parcel might be estimated using national-scale maps of soil type such as NATMAP, The National Soil Map for England and Wales (“National Soil Map of England and Wales”). Woodland on deep peat soils may be particularly important target for inclusion, as woodlands on deep peats with poor drainage can be significant sources of the greenhouse gas methane (Matthews, 2020). The Peatlands of Wales Map series (Welsh Government, 2022) is identified as a useful source for determining where areas of woodland occur on deep peat soil.

Refinement of assumptions

This methodology takes as a necessary assumption that unknown attributes of woody features (e.g. species, management practices) are represented by ‘national average’ values. Within the hedgerow growth model, the following areas require assumptions that are identified as targets for improvement: hedgerow growth rate and change in size over time for managed and unmanaged hedgerows, frequency of trimming and trimming practices across farms in Wales, the frequency and nature of rejuvenation across farms in Wales. Assumptions affecting mean hedgerow height and width include the rate of hedgerow transition to tree lines, the rate of hedgerow loss or removal, the frequency of hedgerow rejuvenation and rates of hedgerow creation. The data needed to refine these assumptions could be obtained from landowners and/or national survey data.

More site-specific input data

A key limitation of this study was the lack of site-specific data that is typically required to estimate woodland carbon sequestration, such as species, age and management.

Consequently, the method developed for woodland sites enabled a weighted national average sequestration rate to be applied. More site-specific information would improve the accuracy of this assessment. This could be acquired from farmer reporting or from Earth Observation techniques. The identification of species is discussed above.

Woodland stand age and management remain challenging to identify without ground level assessment. Satellite imagery could be used to identify if any recent felling has occurred on farmland trees. Farmer reporting could be used to gather information on woodland age (if known) and management. However, this would place a large burden on the farmer and require a more complicated method that would likely be challenging to combine with LiDAR derived spatial datasets and lookup tables.

Likewise, hedgerow sequestration estimates are limited by methods for the detection of hedgerow management stage and health from LiDAR data. Methods are being developed at Kew to assess hedgerow properties from LiDAR data, which could be applied to refine sequestration estimates.

Improvements to the resolution of hedgerow width to improve accuracy could be made through analysis of aerial imagery, such as was carried out by machine learning for England's hedgerow map (Forest Research, *in preparation*).

Refinement of hedgerow growth model

Hedgerow sequestration estimates are constrained by limited data availability, notably for: variation by hedgerow species; variation in growth rates across site types (soil, elevation, aspect, slope, temperature, rainfall, exposure) for both managed hedgerows between trims and for unmanaged hedgerows; the biomass remaining on site after hedgerow laying or coppicing; the effect of rejuvenation on subsequent growth and biomass density; sequestration rates by over-trimmed and declining hedgerows. Additional data collection would allow a more robust method to be developed.

Inclusion of carbon sequestration from woody perennials

This report presents a methodology for calculating the carbon sequestration component from trees, hedgerows and lone trees. Contributions to carbon sequestration from woody perennial crops such as orchards, vines and short rotation coppice were out of scope for this methodology. As perennial crop types can undergo regular harvest and replanting; they may be expected to have a low contribution to overall net biomass sequestration. If assuming their total area is in equilibrium, an assumption of zero net sequestration from biomass would be consistent with the tier 2 methodology applied in the UK GHGI (Brown *et al.*, 2026).

However, if estimates of carbon sequestration in woody perennials were pursued, it could be possible to derive sequestration rates from carbon stocks reported in the Cropland category of the UK Greenhouse Gas Inventory, for shrubby perennials, short rotation coppice, vines, and traditional and intensive orchards. A similar approach was applied for the UK Water Industry Research tool (UKWIR, 2022). This is an area of ongoing development, with perennial biomass carbon stock change estimates flagged as an area for improvement in the UK LULUCF GHGI Improvement list (Brown *et al.*, 2026).

Calculating on farm sequestration would still require spatial information for land parcels containing woody perennial crops and information on how these are being managed.Calculating on farm sequestration would still require spatial information for land parcels containing woody perennial crops and information on how these are being managed. Farmer-reported information gathered through Rural Payments Wales as part of farmers' applications for scheme payments is a possible source for these data. Overlap between the TOW map and areas of woody perennials such as orchards means, if carbon sequestration

in woody perennials were calculated through a per hectare method, woody features identified from the TOW map in land parcels containing woody perennials would have to be excluded from the calculations of carbon sequestration using LiDAR-derived metrics described in the body of this report to avoid double-counting.

8.2 Alternative Approaches

Assessing change in biomass over time

Repeat LiDAR surveys would enable the difference in carbon stocks between two timepoints to be calculated, to estimate carbon stock change. This approach would be particularly useful for TOW and hedgerows, which currently lack more sophisticated growth models (such as applied in CARBINE). Repeat LiDAR surveys would also effectively capture removal of vegetation from felling or other disturbances, providing a more comprehensive assessment of net carbon stock change.

The carbon stock difference between two points in time could also be applied to woodland, however, a methodology to estimate carbon stock directly from LiDAR data for woodland is still required. Alternatively, it may be possible to use the height increment from repeat surveys to map a specific yield class value, if the species is known. A programme of regular LiDAR survey would be required for this approach to be adopted.

Recent work at FR has developed a method to estimate TOW carbon stocks from LiDAR data, based on tree height and canopy area (Defra R&D project in 2026). Ongoing work at FR is now exploring how this could be combined with developing synthetic canopy height models, from historic aerial photography, to estimate national TOW carbon stock change. The use of synthetic canopy height models may enable spatially explicit carbon stock change estimates , without the need to wait for a repeat LiDAR surveys. This work is focused primarily on TOW trees. A similar method could be developed for woodland trees; however, this is not currently being directly addressed.

Including on-farm carbon sequestration from other sources

Contributions to carbon sequestration from areas of permanent grassland or net emissions associated with land use change were out of scope for this methodology's creation, but would provide a more total picture of on-farm sequestration.

Although substantial further commitment to model testing and validation would be required, use of a process-based model such as the Earth Observation data-driven modular ecosystem-scale carbon model under development by UKCEH (discussed in Section 3) would provide a possible avenue for widening the scope of the carbon sequestration component of the Carbon Baseline provided to farmers.

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10 APPENDIX 1: LITERATURE REVIEW OF HEDGEROW CARBON SEQUESTRATION

Table A1-1: Published sequestration rates for hedgerows per hectare (t CO_2 ha^{-1} yr^{-1}), divided into aboveground biomass (AGB), belowground biomass (BGB) and soil organic carbon (SOC).

Source	Hedge type	AGB Carbon sequestration (t CO_2 ha^{-1} yr^{-1})	BGB Carbon sequestration (t CO_2 ha^{-1} yr^{-1})	SOC Carbon sequestration (t CO_2 ha^{-1} yr^{-1})
Robertson, 2012	unmanaged hedgerows	5.06		
Robertson, 2012	tall hedgerows	1.87		
Robertson, 2012	medium hedgerows	0.95		
Robertson, 2012	short hedgerows	0.48		
Robertson, 2012 [1]	old hedgerows			1.99
Robertson, 2012 [1]	new hedgerows			1.67
Crossland, 2015 [2]	(modelled) unmanaged blackthorn, average rate over 100 years	22	4.03	7.7
Crossland, 2015 [2]	(modelled) managed blackthorn, average rate over 100 years	0	0.55	1.39
Crossland, 2015 [2]	(modelled) unmanaged hawthorn, average rate over 100 years	6.56	1.83	36.3
Crossland, 2015 [2]	(modelled) managed hawthorn, average rate over 100 years	0	0.73	1.58
Crossland, 2015 [2]	(modelled) unmanaged hazel, average rate over 100 years	4.58	1.80	3.67
Crossland, 2015 [2]	(modelled) managed hazel, average rate over 100 years	0	2.38	5.10
Biffi *et al.*, 2022 [1]	'typical' English species composition, 2–4-year-old hedge			8.36 (-19.54–36.23)
Biffi *et al.*, 2022 [1]	'typical' English species composition, 10-year-old hedge			6.67 (-2.16–15.55)
Biffi *et al.*, 2022 [1]	managed, 'typical' English species composition 37-year-old hedge			4.07 (1.91–6.20)
Biffi *et al.*, 2022 [1]	managed, 'typical' English species composition 'old' hedge, exact age unknown			3.12 (-0.18–6.38)
Biffi *et al.*, 2022 [2]	'typical' English species composition, 2–4-year-old hedge			13.60 (-7.63–34.83)
Biffi *et al.*, 2022 [2]	'typical' English species composition, 10-year-old hedge			9.86 (4.58–15.14)

Biffi *et al*., 2022 [2]	managed, 'typical' English species composition 37-year-old hedge			5.42 (2.71–8.14)
Biffi *et al*., 2022 [2]	managed, 'typical' English species composition 'old' hedge, exact age unknown			4.47 (1.39–7.55)
Biffi *et al*., 2023	'typical' English species composition, sequestration rate between 0–6 years	7.65 (2.86–12.45)		
Biffi *et al*., 2023	'typical' English species composition, sequestration rate between 6–12 years	8.29		
Biffi *et al*., 2023	managed, 'typical' English species composition, sequestration rate between 0–12 years	6.7 (2.76–10.64)		
Biffi *et al*., 2023	'typical' English species composition, sequestration rate between 12–39 years	1.58		
Biffi *et al*., 2023	managed, 'typical' English species composition, 'old' hedge, sequestration rate between 0–39+ years	3.14 (1.82–4.47)		
Drexler and Don, 2024 [1]	average from diverse German hedges			1.54±0.84
Drexler and Don, 2024 [3]	average from diverse German hedges			2.38±2.02
Biffi *et al*., 2025 [2]	'typical' North-Western Europe species composition, 2–5-year-old hedge			45.54 (31.94–59.11)
Biffi *et al*., 2025 [2]	'typical' North-Western Europe species composition, 10-year-old hedge			19.14 (7.37–30.91)
Biffi *et al*., 2025 [2]	managed, 'typical' North-Western Europe species composition, 20–30-year-old hedge			5.46 (3.41–7.52)
Biffi *et al*., 2025 [2]	managed, 'typical' North-Western Europe species composition, mature hedge >30yrs old			2.93 (1.47–4.44)

1 Soil depth 0–30 cm, 2 Soil depth 0–50 cm, 3 Soil depth 0–100cm

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