Forest Research

Quantifying the sustainable forestry carbon cycle

Summary Report

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The Research Agency of the Forestry Commission

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Table of Contents

Summary

The UK has a commitment to reach 'net-zero' greenhouse gas (GHG) emissions by 2050, and significant tree planting targets have been proposed in each of the countries to help achieve this through the carbon sequestration that woodlands and forestry can provide. There is therefore a need to understand the latest evidence on forestry, carbon and GHG balances, to enable policy making to effectively manage forest carbon alongside other benefits as part of sustainable forest management.

This report was commissioned to estimate and compare the potential for carbon sequestration (net CO_2 uptake) and GHG emissions avoided by the use of harvested wood products in place of other materials, that could be realised by creating different types of woodlands. A more comprehensive evaluation of the role of woodlands in the carbon balance is presented in a full Assessment Report[1].

The analysis assesses the influence of different species, site and management factors, including the eventual use of harvested wood, on the potential net CO_2 uptake and GHG emissions, at the scale of an individual forest stand (i.e. in terms of quantities of carbon per hectare), and for notional woodland creation programmes of 1 hectare per year for 1 year and over 10 and 25 years.

A model-based approach has permitted the systematic, integrated and consistent assessment of different options for woodland creation and management, from the perspective of their potential for CO_2 uptake and avoiding GHG emissions.

The main modelling outputs of the assessment can be accessed using an Excel software tool, which facilitates the rapid assessment and comparison of different woodland options.

Evidence available from published field studies generally supports the estimates developed in this assessment. However, uncertainties must be acknowledged in estimates of soil carbon stock changes in early years following woodland establishment. There is also some uncertainty in estimates of carbon stocks in tree roots and branches, and in projections of carbon sequestration for woodland management options that differ significantly from the main types of productive woodland and management systems practised in the UK in the past century.

The modelling outputs have been used to assess the climate change mitigation potential of 12 "illustrative woodland options". These were selected to represent contrasting examples of possible types of woodlands that could be created in the UK. The 12 options have been characterised using short descriptive names (Table S1).

[1] Matthews, R.W., Morison, J.I.L., Henshall, P.A., Beauchamp, K., Hogan, G.P., Baden, R., Mackie, E.D. Vanguelova, E., Perks, M., Gruffudd, H. and Sayce, M. (2022) *Quantifying the sustainable forestry carbon cycle: Assessment Report.* Forest Research: Farnham, in preparation.

Table S1 Selected illustrative woodland options

Name	Yield class[2]	Summary management
Broadleaves, light management	4	Regular but low intensity thinning (continuous cover), also areas left unthinned/unmanaged
Natural recolonisation, rapid	4	
Natural recolonisation, gradual	4	
Production broadleaves	4	Regular thinning (continuous cover)
Production pine	8	Thinning, final felling with restocking
Moderate growing conifer unthinned	12	No thinning, final felling with restocking
Fast growing conifer unthinned	18	
Moderate growing conifer thinned	12	Thinning, final felling with restocking
Fast growing conifer thinned	18	
Fast growing Sitka spruce thinned	24	
Conifer mixture	14	Regular thinning, patch felling (continuous cover)
Complex conifer/broadleaf mixture	14 and 6	

The yield classes assigned to woodlands were assumed to remain constant over time. However, rising concentrations of CO_2 and related climatic changes can influence the growth and development of woodlands both positively and negatively. These impacts were allowed for implicitly in the selection of tree species and growth rates represented in different woodland options. Soil carbon dynamics in broad-leaved woodland options were represented by combining results for woodlands for mineral soils previously under grass and crops. The pine option was represented by combining results for mineral and organo-mineral soils previously under grass and crops. The other coniferous options were represented by combing results for organo-mineral soils previously under grass, crops and moorland (not cropland in the case of fast growing Sitka spruce). Results were calculated for each of the above illustrative woodland options, for four reporting periods of 2022-2050, 2022-2100, 2051-2100 and 2101-2150, and for three woodland creation scenarios:

- 1 hectare created in 2022
- 1 hectare per year created for 10 years starting in 2022
- 1 hectare per year created for 25 years starting in 2022.

This gave 12 sets of results, which are included in the full Assessment Report.

An example of a key set of results is shown in Figure S1 and Tables S2a & S2b, for 1 ha of each woodland option created in 2022, showing GHG emissions mitigated during the period 2022 to 2100.

[2] The growth rates of woodlands are represented using the British yield class system (see Matthews *et al.*, 2016a). Yield class is defined as the maximum average rate of cumulative stemwood volume production in a woodland over an optimal rotation. The actual average rate of production will vary with the specified rotation. As a convention, yield classes take even whole numbers, e.g. 4, 6, 8… $m^3\ ha^{-1}\ yr^{-1}$.

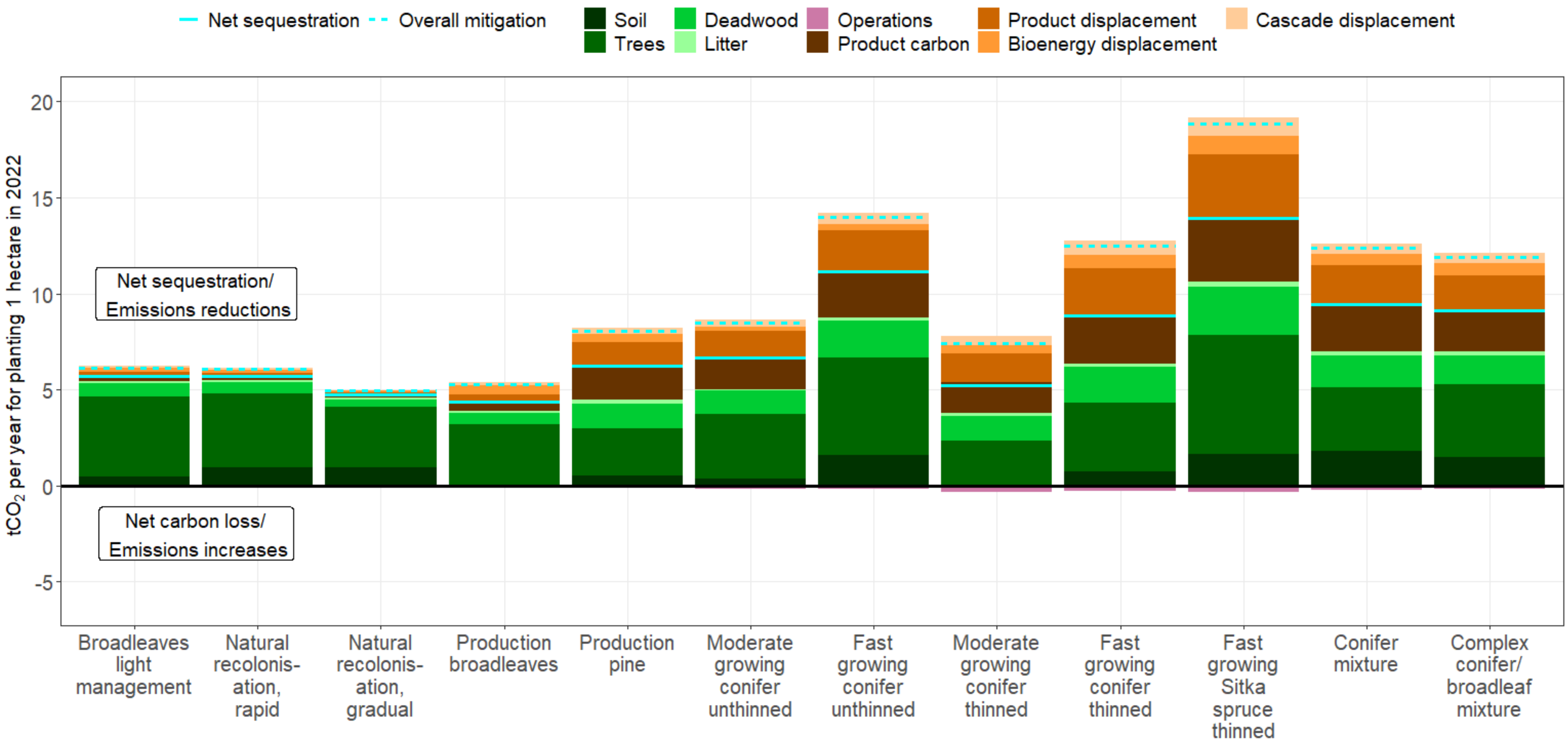

Figure S1. Annualised CO_2 uptake and GHG emissions avoided, estimated over the period 2022 to 2100 for 12 illustrative woodland options, assuming 1 hectare of woodland planted in 2022.

Table S2a Carbon sequestration by woodland options (2022-2100): 1 ha created in 2022

Woodland option	Annualised net carbon stock change ($tCO_2\ ha^{-1}\ yr^{-1}$)						
	Trees	**Deadwood**	**Litter**	**Soil**	**Total woodland**	**Wood products**	**All carbon pools**
Broadleaves light management	4.2	0.7	0.1	0.4	5.4	0.2	5.7
Natural recolonisation, rapid	3.9	0.6	0.1	0.9	5.5	0.2	5.7
Natural recolonisation, gradual	3.2	0.4	0.1	0.9	4.6	0.2	4.7
Production broadleaves	3.1	0.6	0.1	0.1	3.9	0.5	4.4
Production pine	2.4	1.3	0.2	0.5	4.5	1.7	6.2
Moderate growing conifer unthinned	3.3	1.2	0.1	0.4	5.0	1.6	6.7
Fast growing conifer unthinned	5.1	1.9	0.1	1.6	8.7	2.4	11.1
Moderate growing conifer thinned	2.3	1.3	0.1	-0.1	3.6	1.6	5.2
Fast growing conifer thinned	3.6	1.9	0.1	0.7	6.3	2.5	8.9
Fast growing Sitka spruce thinned	6.2	2.5	0.3	1.7	10.6	3.4	14.0
Conifer mixture	3.3	1.7	0.2	1.8	7.0	2.5	9.4
Complex conifer/ broadleaf mixture	3.8	1.5	0.2	1.5	7.0	2.1	9.1

Table S2b GHG emissions mitigation by woodland options (2022-2100): 1 ha created in 2022

Woodland option	GHG emissions mitigation (tCO_2-eq. ha^{-1} yr^{-1})					
	All carbon pools	**Forest operations (emissions)**	**Wood product substitution**	**Bioenergy (wood fuel) substitution**	**Cascade substitution**	**Net GHG emissions mitigation**
Broadleaves light management	5.7	-0.1	0.2	0.2	0.1	6.2
Natural recolonisation, rapid	5.7	0.0	0.2	0.2	0.1	6.1
Natural recolonisation, gradual	4.7	0.0	0.1	0.1	0.0	5.0
Production broadleaves	4.4	-0.1	0.4	0.4	0.2	5.3
Production pine	6.2	-0.2	1.3	0.4	0.3	8.0
Moderate growing conifer unthinned	6.7	-0.2	1.4	0.2	0.4	8.5
Fast growing conifer unthinned	11.1	-0.2	2.1	0.3	0.6	14.0
Moderate growing conifer thinned	5.2	-0.2	1.5	0.4	0.5	7.4
Fast growing conifer thinned	8.9	-0.3	2.5	0.7	0.8	12.5
Fast growing Sitka spruce thinned	14.0	-0.3	3.3	0.9	1.0	18.9
Conifer mixture	9.4	-0.2	2.1	0.6	0.6	12.4
Complex conifer/ broadleaf mixture	9.1	-0.2	1.8	0.7	0.5	11.9

For the carbon pools of trees, deadwood, litter, soil and wood products, results are shown in Figure S1 and Tables S2a & S2b for annualised carbon stock changes (equivalent to net CO_2 uptake or loss) over the specified reporting period, expressed in units of tonnes CO_2 per year (tCO_2 yr^{-1}). Annualised values are calculated by finding the average annual value over the specified reporting period. Estimates in Figure S1 and Table S2b for GHG emissions from forest operations and emissions avoided by wood product substitution impacts are also presented as annualised results over the specified reporting period, expressed in units of tonnes CO_2-equivalent per year (tCO_2-eq. yr^{-1}). Results with a positive sign indicate carbon stock increases (net carbon sequestration) or GHG emissions avoided, and those with a negative sign indicate carbon stock losses or net GHG emissions increases. The results in Figure S1 are shown as stacked bars, giving annualised carbon gains or losses for the specified period:

- Green shaded bars show the contributions made by woodland carbon pools (trees, deadwood, litter and soil).
- A purple bar shows the GHG emissions from forest operations (e.g. site preparation including herbicides, harvesting machinery, transport), up to the "mill gate". These emissions are generally relatively very small.
- A dark brown bar shows the contribution made by carbon retained in the wood products carbon pool (denoted "Product carbon" in the key to the figures).
- Lighter brown bars show the contributions potentially made by wood product substitution effects, consisting of wood products displacing non-wood materials, wood fuel (bioenergy) displacing other fuels and wood product cascading effects. These contributions are denoted "Product displacement", "Bioenergy displacement" and "Cascade displacement", respectively.
- The net result for carbon stock changes in all carbon pools (woodland and wood products) is indicated for each result with a solid cyan coloured line ("Net sequestration"). The net result also allowing for GHG emissions from forest operations and emissions avoided by wood product substitution impacts is indicated by a dashed cyan coloured line ("Overall mitigation").

1 hectare created in 2022: time horizon 2022 to 2050

Results for this woodland creation scenario and timescale are presented in Figure 2.2 and Tables 2.2a & 2.2b, in Section 2.5 of this report.

Differences in the modelled estimates of CO_2 uptake rates of woodland options are more apparent over shorter timescales such as between 2022 and 2050, when compared to the longer timescale illustrated in Figure S1. This is because outcomes over shorter timescales are more sensitive to variations in tree growth rates, silvicultural practices (thinning) and soil carbon stock changes related to woodland establishment.

Nearly all of the woodland options provide net CO_2 uptake in the period from 2022 to 2050; none result in significant net GHG emissions during this period. However, where they occur, soil carbon losses can offset carbon sequestration in other carbon pools.

Minimising disturbance to soil and existing vegetation on land where woodlands are being created may be identified as a critical factor for achieving early carbon sequestration. This is particularly the case for organo-mineral soils and woodlands where the trees have relatively slow growth rates.

With the exception of the woodland options involving natural recolonisation, the modelling of soil carbon dynamics assumed that scarification of sites would be carried out in advance of tree planting. This is assumed to remove one third of the pre-existing vegetation on the site, with a commensurate reduction in the inputs of carbon to soil from this source. Inputs of carbon from non-tree vegetation are then further reduced over time as the trees become established and compete with other vegetation on the site. Eventually, the reduced input of carbon from non-tree vegetation is compensated for by inputs from litter and fine roots, as the trees grow and accumulate biomass. The modelling of woodland creation with tree planting thus involves the assumptions of substantial reductions in inputs of carbon to the soil initially, but then recovery of soil carbon inputs (and eventually larger inputs than originally) once trees become established on the site.

The modelling of soil carbon accumulation following abandonment of land and allowing woodland to develop through natural colonisation is based on available estimates reported from long-term trials.

The rate of net CO_2 uptake in the period from 2022 to 2050 is strongly correlated with the growth rate of the trees forming the woodland. Growth rate not only relates to carbon sequestration by trees but also to inputs of carbon from the trees to the soil, which can increase soil carbon stocks or compensate for any initial losses during site preparation and woodland establishment. Faster growth rates are generally associated with coniferous tree species but outcomes for individual sites and climatic conditions will be very variable.

Removal of some trees by thinning attenuates rates of woodland carbon sequestration, but this is partially compensated for by carbon retained in wood products and relatively modest contributions from wood product substitution effects in early decades. Thinning can also improve the quality of woodlands by removing damaged and diseased trees and allowing the remaining better quality trees to grow faster, and produce better quality sawlogs more quickly, which can be used to manufacture longer lived wood products. Decisions about silvicultural practices such as thinning are likely to be determined by wider objectives for woodland management, rather than exclusively in terms of carbon sequestration.

In the period 2022 to 2050, the magnitude of total woodland carbon sequestration (in the carbon pools of trees, deadwood, litter and soil) in the broad-leaved woodland options created in 2022 is in the range 0.9 to 1.6 tCO_2 ha^{-1} yr^{-1}; for the coniferous woodland options the range is 1.8 to 12.0 tCO_2 ha^{-1} yr^{-1}. If carbon retained in wood products is also included, the upper-range estimate for net carbon sequestration over this period for coniferous woodland options increases to 14.5 tCO_2 ha^{-1} yr^{-1}.

1 hectare per year created for 25 years starting in 2022: time horizon 2022 to 2050

Results for this woodland creation scenario and timescale are presented in Figure 2.3 and Tables 2.3a & 2.3b, in Section 2.5 of this report.

For a programme of creating 1 ha of woodland per year over 25 years, the magnitude of annualised total woodland CO_2 uptake (sequestered in the carbon pools of trees, deadwood, litter and soil) in the broad-leaved woodland options in the period 2022 to 2050 is in the range -0.7 to 16.2 tCO_2 yr^{-1}; for the coniferous woodland options the range is -2.5 to 103.2 tCO_2 yr^{-1}. If carbon retained in wood products is also included, the lower range estimate over this period for broad-leaved woodland options over this period changes to -0.1 tCO_2 yr^{-1}, whilst the upper range estimate for coniferous woodland options increases to 118.2 tCO_2 yr^{-1}.

Effects of initial soil carbon losses offsetting carbon sequestration in other carbon pools are particularly noticeable in woodland creation programmes over longer periods (25 years), where carbon stocks in the woodlands created later in the programme do not have enough time to recover losses of soil carbon before 2050.

Longer time horizons

Figure S1 and Tables S2a & S2b show results for net CO_2 uptake rates and GHG emissions avoided during the period 2022 to 2100 by creating 1 ha of each woodland option in 2022. Over longer time horizons (e.g. 2022 to 2100) total net CO_2 uptake (all carbon pools) in the different woodland options are closer to one another. This occurs because most of the faster growing woodlands are assumed to be under management for production and areas of trees are being felled by thinning or clearfelling, diminishing the rate of carbon sequestration in these woodlands when this occurs. However, the slower growing and relatively lightly managed broad-leaved woodland options continue to grow and sequester carbon in later decades during this period. Often, broadleaves are slower growing than conifers but broad-leaved trees are also longer lived and more enduring, so that carbon sequestration in broad-leaved woodlands can eventually ‘catch up’ with coniferous woodlands.

It should also be noted that the harvesting of trees will result in net losses of carbon from individual managed woodland stands in some years. These losses will eventually be recovered when the successor stands of trees become established, but by this stage carbon stocks in the woodland are cycling between gains and losses, with the result that additional carbon sequestration can be modest from this point onwards. Losses of carbon stocks from harvesting in individual woodlands are not apparent in Figure S1 because the effects of harvesting and tree growth/regrowth are evened out by averaging over quite long timescales (i.e. calculating mean rates in woodlands for the period 2022 to 2100).

1 hectare created in 2022: time horizon 2022 to 2100

In the period 2022 to 2100 (Figure S1 and Tables S2a & S2b), the net rate of CO_2 uptake in all woodland carbon pools (not including wood products) in the broad-leaved woodland options created in 2022 is in the range 3.9 to 5.5 tCO_2 ha^{-1} yr^{-1}; for the coniferous woodland options the range is 3.6 to 10.6 tCO_2 ha^{-1} yr^{-1}. If carbon retained in wood products is allowed for, these ranges change to 4.4 to 5.7 ha^{-1} yr^{-1} and 5.2 to 14.0 tCO_2 ha^{-1} yr^{-1}, respectively.

1 hectare per year created for 25 years starting in 2022: time horizon 2022 to 2100

Results for this woodland creation scenario and timescale are presented in Figure 2.5 and Tables 2.5a & 2.5b, in Section 2.5 of this report.

For a programme of creating 1 ha of woodland per year over 25 years, the net rate of CO_2 uptake in all carbon pools (not including wood products) in the broad-leaved woodland options in the period 2022 to 2100 is in the range 81 to 114 tCO_2 yr^{-1}; for the coniferous woodland options the range is 73 to 185 tCO_2 yr^{-1}. If carbon retained in wood products is allowed for, these ranges change to 86 to 119 yr^{-1} and 116 to 266 tCO_2 yr^{-1}, respectively.

Wood product carbon and substitution effects

Wood products can provide a significant store of carbon and can avoid emissions when they substitute for other materials. These effects are most apparent for new coniferous woodlands managed for production over longer timescales (2022 to 2100), when these woodlands start to produce timber. If these contributions are also included in mitigation estimates for this period, the magnitude of the total GHG mitigation estimated for the managed coniferous woodland options created in 2022 increases to between 7.4 and 18.9 tCO_2 ha^{-1} yr^{-1}. For a programme of creating 1 ha of managed coniferous woodland per year over 25 years, these estimates are between 161 and 364 tCO_2 yr^{-1}. The substitution effects of wood products were modelled as diminishing over time, on the assumption that the wider economy would become decarbonised. However, if this happens, harvested wood will continue to provide a low-carbon source of materials and energy.

Comparing woodland options

It must be stressed that these woodland options are not interchangeable in the same locations or on the same sites within the UK. Rather, different options will be better suited to different regions of the UK and particular site types. For this reason, care must be taken when interpreting simple comparisons of the climate change/GHG mitigation potential of the different woodland options.

The model-based assessment above suggests a number of conclusions about options for creating and managing woodlands with the aim of sequestering carbon and/or mitigating GHG emissions:

- All of the example woodlands considered deliver substantial carbon sequestration over the period up to 2100.
- When the example woodlands are compared, there are differences in the rates of net CO_2 uptake, and how the rates develop over time. In shorter timescales (e.g. up to 2050), a fast growing Sitka spruce plantation can exhibit the highest uptake rates. In contrast, CO_2 uptake in broad-leaved woodlands created by natural colonisation may be relatively modest initially. However, over longer timescales, the assessment suggests that the CO_2 uptake rates and wider GHG emissions mitigation contributed by different woodland options become closer to one another. In terms of CO_2 uptake directly in woodlands, contributions from a range of woodland options could work together to deliver sustained carbon sequestration at all stages during the period up to 2100. This conclusion is supported by detailed analysis in the full Assessment Report.
- Net CO_2 uptake rates and their development over time depend on certain factors related to how woodlands are created on different sites and on how the woodlands are managed once established, e.g. with thinning or felling or with the avoidance of such interventions.
- The different rates and patterns of CO_2 uptake and GHG emissions avoided estimated for different woodland types provide some flexibility when planning woodlands to allow for wider objectives for woodland creation and management (e.g. recreation and wellbeing, biodiversity, water protection, timber and biomass supply), alongside delivering overall long-term carbon benefits.

Supporting evidence from field studies and other assessments

Experimental measurements of woodland carbon stock changes and CO_2 fluxes show reasonable consistency with the modelled estimates forming the basis of this assessment and the detailed assessments in the full Assessment Report.

When comparing modelled estimates with field estimates derived from long-term monitoring plots and chronosequence studies, uncertainties must be acknowledged in both field-based and model-based estimates of soil carbon stock changes in early years following woodland establishment and in carbon sequestration in trees following land abandonment to allow natural recolonisation.

Given the very different methods used to produce direct measurements of CO_2 fluxes and model-based estimates of carbon stock changes, there is remarkable agreement between these two types of estimates.

There are very few other examples of published assessments of the GHG emissions mitigation potentials of different woodland options relevant to the UK. The two main recent studies of interest have been reviewed and their findings are consistent with those produced in this assessment, when methodological differences between the studies are allowed for.

1 Introduction

1.1 Context and purpose

The UK has a commitment to reach 'net-zero' greenhouse gas (GHG) emissions by 2050, and significant tree planting targets have been proposed in each of the countries to help achieve this through the carbon sequestration that woodlands and forestry can provide. There is therefore a need to understand the latest evidence on forestry and carbon and GHG balances, to enable policy making to effectively manage forest carbon alongside other benefits and as part of sustainable forest management.

This report was commissioned to estimate and compare the potential for carbon sequestration (net CO_2 uptake) and GHG emissions avoided by the use of harvested wood products in place of other materials, that could be realised by creating different types of woodlands. A more comprehensive evaluation of the role of woodlands in the carbon balance is presented in a full Assessment Report[3].

The analysis assesses the influence of different species, site and management factors, including the eventual use of harvested wood, on the potential net CO_2 uptake and GHG emissions, at the scale of an individual forest stand (i.e. in terms of quantities of carbon per hectare), and for notional woodland creation programmes of 1 hectare per year over 10 years and over 25 years.

The rates of CO_2 uptake and GHG emissions of woodlands can vary considerably over time. Such time-dependent variability following woodland creation is of particular importance for this report. Given that policies aim to achieve net-zero emissions within a relatively short timescale, and also to sustain net-zero or net-negative emissions in the longer term, this assessment also considers the timescales over which CO_2 uptake and GHG emissions reductions can be contributed by newly created woodlands. A key aim of this assessment has been to provide consistent evidence on the potential of different options for woodland creation and management in the UK for mitigating climate change.

1.2 Report structure

A systematic model-based assessment is needed to evaluate how GHG mitigation potentials can vary with different options for woodland creation and management. The modelling methodology adopted in this assessment is outlined in Section 2. A simple Excel software tool is also described, which permits different options for woodland creation and management to be assessed and compared, in terms of

[3] Matthews, R.W., Morison, J.I.L., Henshall, P.A., Beauchamp, K. Hogan, G.P., Baden, R., Mackie, E.D. Vanguelova, E., Perks, M., Gruffudd, H. and Sayce, M. (2022) *Quantifying the sustainable forestry carbon cycle: Assessment Report*. Forest Research: Farnham, in preparation.

their potential for carbon sequestration and/or reducing GHG emissions. The software tool enables easy access to, and comparison of, more complete and detailed results for the carbon and GHG impacts arising from creating different forestry systems, modelled using the Forest Research CARBINE forest sector carbon accounting model. The modelling outputs are used to assess the climate change mitigation potential of 12 contrasting examples of “illustrative woodland options” relevant to the UK.

Section 2 also offers some conclusions and key messages drawn from the results, and briefly outlines some of the implications for implementing woodland creation with GHG emissions mitigation as an objective.

Section 3 reviews the main relevant sources of supporting evidence available from field studies and other published assessments of forestry carbon balances. Field-based estimates of rates of woodland carbon sequestration are compared with the model-based estimates developed for this assessment.

A glossary of technical terms and units of measurement is given in Appendix 1 of the full Assessment Report.

2 Assessment of woodland options

This section presents a summary assessment of the GHG emissions mitigation potential of a set of illustrative options for creating woodlands in the UK. A brief description is also given of a simple MS Excel tool that has been developed to assist with such assessments. The modelling methods applied in producing the estimates and the Excel tool are also outlined. More information on the modelling methods, their potential application and example results can be found in Section 2 of the full Assessment Report.

2.1 Scope of assessment

The contribution of woodlands and the forest-based sector to climate change mitigation is multi-faceted, involving numerous flows of carbon and GHGs, as illustrated in Figure 2.1.

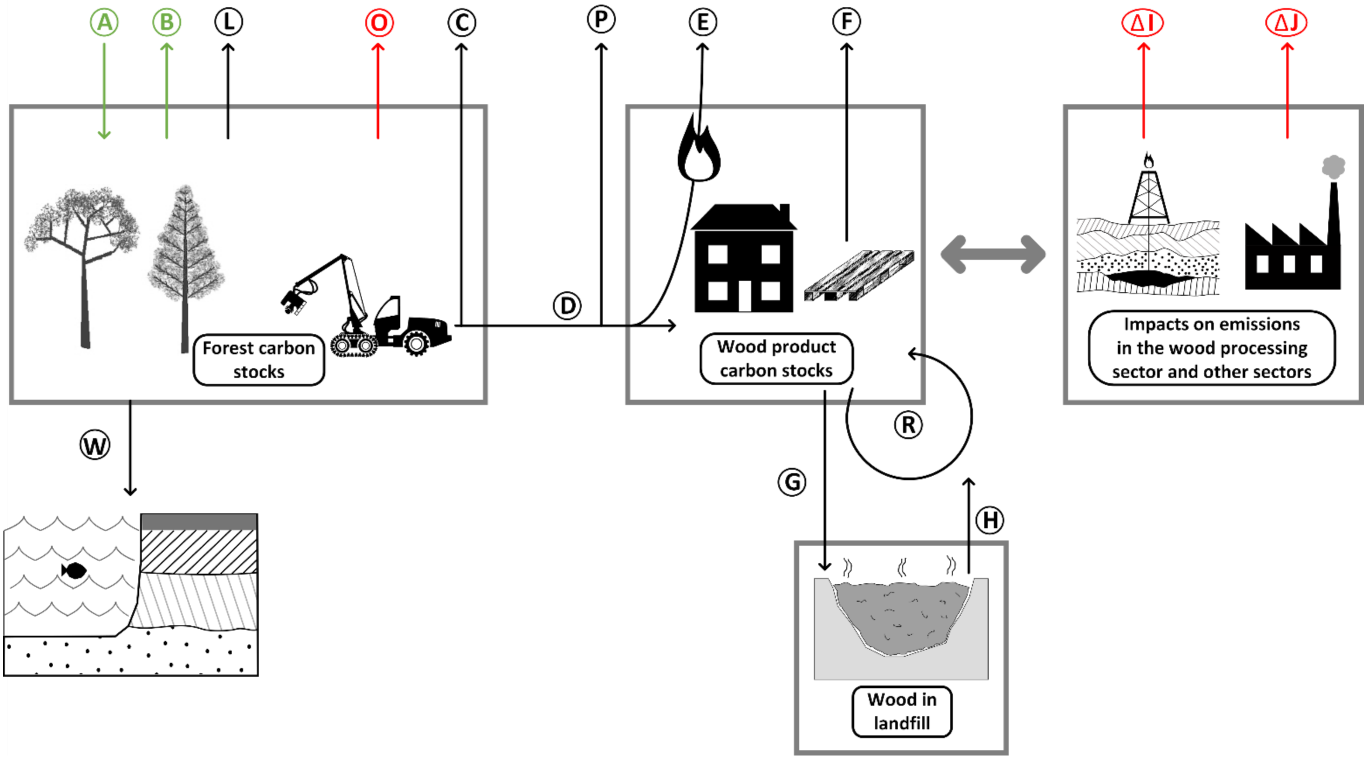

Figure 2.1. Scope of assessment of the contribution of woodlands and the forest-based sector to climate change mitigation. See Box 2.1 for an explanation of the various flows of carbon and GHGs. Note that the retention of carbon in aquatic systems and in wood discarded in landfill are outside the scope of this assessment. All other contributions are included in the scope.

Box 2.1 Key to CO_2 and GHG flows in Figure 2.1

Green arrows

A: Uptake and capture into woodland ecosystem by photosynthesis; B: Losses from forest through respiration. Note that the net result of A and B represents the input of carbon into the system.

Black arrows

L: Losses from the decay of vegetation that dies or is killed by natural disturbances; W: Losses of litter and soil carbon to aquatic systems; C: Losses from woodland arising from forest operations including (for example) losses of soil carbon from site disturbance during woodland establishment and losses through decay of forest residues arising from tree harvesting; D: Transfers out of the woodland in the form of extracted wood; P: Losses in the wood supply and processing chain including wood burnt to waste; E: Losses arising from burning wood as bioenergy including for process heat and power in wood processing mills; F: Losses arising from the decay or destruction of wood products at end of life; G: Transfers of carbon arising from disposal of wood products at end of life to landfill; H: Emissions (as carbon dioxide and methane) from discarded wood products in landfill; R: Reuse, repurposing and recycling of wood products.

Red arrows

O: Emissions of GHGs from use of machinery and materials in forestry operations; ΔI: Changes in GHG emissions from the extraction and consumption of non-wood fuels (e.g. fossil fuels) in response to bioenergy production; ΔJ: Changes in GHG emissions from the manufacture of wood products and non-wood products (e.g. made from steel, concrete, plastics) in response to supply of wood products.

The various flows in Figure 2.1 can be summarised as five main contributions:

1. Woodland ecosystems can accumulate a reservoir of carbon by removing CO_2 from the atmosphere through the process of photosynthesis and tree growth, releasing oxygen and retaining carbon in trees and other vegetation, deadwood, litter and soil. Tree mortality and natural disturbances can result in losses of carbon to the atmosphere as CO_2 and non-CO_2 GHGs. Tree harvesting also results in losses of carbon from woodland ecosystems. Carbon can also be lost when vegetation and soil are disturbed as part of site preparation for woodland creation; these losses can be very significant on highly organic soils (e.g. soils with an organic layer of at least 50 cm depth),

especially in cases where woodland establishment and growth leads to the drying and oxidation of peat.

2. There can be certain generally relatively small non-CO_2 GHG emissions, mostly methane (CH_4) but also nitrous oxide, associated with natural processes in woodland ecosystems, particularly for woodlands on highly organic wet soils (e.g. soils with an organic layer of at least 50 cm depth).
3. Wood harvested from woodlands can also retain carbon that was originally removed from the atmosphere by woodlands in the form of wood-based products; there are also emissions of GHGs from wood products when they are disposed of and destroyed at end of life, which can involve methane emissions under certain conditions if wood products are discarded in landfill.
4. Fuels, materials and machinery used in forestry operations such as mounding, scarifying, tree protection, thinning, felling and the extraction and transport of harvested wood result in emissions of CO_2 and non-CO_2 GHGs.
5. Using wood-based products and wood fuel can also be a way to avoid using alternative non-wood products and energy sources, whose manufacture and use may involve higher GHG emissions, compared with the equivalent wood products; these contributions can be referred to as the "substitution" effects of using wood products

When assessing the climate change mitigation potential of woodlands, it is necessary to be clear about which of the above contributions are considered in the scope of the assessment. This study is concerned with all five contributions above, encompassing all potential impacts on carbon and GHGs associated with woodlands and the forest-based sector. However, note that the retention of carbon in aquatic systems and in wood discarded in landfill are outside the scope of this assessment. The results of assessments are broken down to show the individual contributions made to the carbon balance by woodlands, wood product carbon stocks and wood product substitution effects.

Woodlands can also influence climate in other ways, by affecting the reflectivity of the land surface (albedo), contributing to rates of water evapotranspiration and by releasing certain aerosols that affect climate. These effects are not considered within the scope of this assessment.

The accumulation of carbon from (and loss to) the atmosphere by woodlands as a result of tree growth can be a complex process, influenced by several natural and anthropogenic factors. Firstly, woodlands are biological and ecological systems. As trees grow and are lost through mortality, they both remove CO_2 from the atmosphere and also emit CO_2, resulting in a variable balance between CO_2 removals and emissions over time. Secondly, the management of woodlands by humans can have a profound impact on CO_2 emissions and removals, both immediately and over time. However, the natural processes of woodland growth, mortality and carbon cycling in woodland ecosystems can only ever be partially under human control. Thirdly, rising concentrations of CO_2 and related climatic changes can influence the growth and development of woodlands both positively and negatively, with consequent impacts on CO_2 emissions and removals in woodlands. These conditions are partially the result of the impacts of human activities on atmospheric chemistry and physics, but they are mediated by the natural processes of tree growth and mortality. Only the first two of these contributions to the GHG balances of woodlands described here are explicitly considered within the scope of this assessment. The third contribution is allowed for implicitly in the selection of tree species and growth rates represented in different woodland options.

2.2 Modelling methods

The modelling methods consisted of the following steps:

- Step 1: Defining a set of scenarios for new woodlands and their management
- Step 2: Modelling the scenarios using the Forest Research CARBINE model
- Step 3: Post-processing of outputs of CARBINE for each scenario, including some supplementary calculations.

The post-processed results were incorporated into an MS Excel tool.

2.2.1 Step 1: Specification of scenarios

Scenarios for woodland creation were defined according to the following characteristics:

- Country (England, Scotland, Wales and Northern Ireland)
- Climate zones representative of different conditions in the UK, based on the Forest Research Ecological Site Classification system (seven zones)[4]
- Soil, defined principally in terms of soil texture and/or the presence of a substantial organic matter layer, which are the main soil characteristics determining soil carbon (sand, loam, clay, organo-mineral, organic)
- Two possible types of previous land use (permanent cropland, permanent pasture/moorland)

[4] The ESC decision support tool has not been deployed in Northern Ireland but 3 of the climatic zones represented in ESC were characterised for Northern Ireland, namely, ‘warm-dry’, ‘warm-moist’ and ‘warm-wet’.

- Tree species (19 species, based on those available in the Forest Research Forest Yield software tool; Matthews *et al.*, 2016a, b)
- Woodland growth rate (all yield classes represented for a given tree species in the Forest Yield software tool)
- Woodland management (10 options, including no management, no thinning or thinning, clearfelling or continuous cover).

It should be noted that several of the tree species included in Forest Yield are now of less relevance in the UK because of significant issues with tree pests and/or diseases. Also, the growth models in Forest Yield have recently been superseded by those available in a new model developed by Forest Research. However, these new growth models have not yet been integrated into the CARBINE model.

2.2.2 Step 2: Modelling scenarios with CARBINE

The CARBINE model was used to estimate the development of carbon stocks and levels of wood production for each of the woodland scenarios defined above.

The CARBINE forest sector carbon accounting model was first developed by Forest Research in 1988 and has been under continuous development since then. CARBINE is now one of several forest carbon accounting models that have been developed worldwide. The general purpose of the CARBINE model is to address questions about the carbon and GHG balances of forestry systems, and to inform the development of forest policy and practice, particularly with regard to the goal of climate change mitigation.

All the CARBINE simulations were run for a functional unit of 1 hectare (net area) of woodland, so that the results were expressed per hectare of woodland. The simulation period was from 1 year before tree planting (to capture soil carbon stocks under the previous land use) up to 300 years after initial tree planting, allowing for the felling and restocking of trees in relevant scenarios. Results for soil carbon stocks were reported to a depth of 1 m.

2.2.3 Step 3: Post-processing of CARBINE outputs

The outputs of the CARBINE model for each woodland scenario were processed to produce a set of results of interest for this assessment. Supplementary results were calculated for GHG emissions associated with certain forestry operations such as timber transportation and GHG emissions avoided through the substitution impacts of wood products. The substitution impacts of wood products (and wood fuel) were modelled as diminishing over time, on the assumption that the wider economy would become decarbonised. However, if this happens, harvested wood will continue to represent a low carbon source of materials and energy. When wood products come to the end of their service lives, instead of discarding them in landfill or incinerated as waste, they can be reused, repurposed, recycled or burnt with energy recovery. These actions, which are sometimes described collectively as 'wood product cascading' or 'biomass cascading', can have further carbon impacts. Frequently, the impacts of biomass cascading are not represented in assessments of woodland and forestry systems. For this assessment, the possibility of cascading effects was allowed for by assuming that 80% of the wood in products at end of life was burnt with energy recovery, that is, utilised as wood fuel.

2.2.4 Presenting results for periods and woodland creation programmes

The annual estimates of carbon stock changes in woodland carbon pools and wood products, and of GHG emissions from forestry operations and emissions avoided through substitution impacts of wood products, were summarised into mean (annualised) gains or losses (GHG removals or emissions) for a set of four specified periods:

- 2022 to 2050 (assuming that woodland creation started in 2022)
- 2022 to 2100
- 2051 to 2100
- 2101 to 2150.

Annualised values are calculated by finding the average annual value over the specified reporting period.

Two further sets of results were produced based on the above reporting periods, but assuming that woodland creation was carried out at a rate of 1 hectare per year for a period of 10 years and for a period of 25 years. These results enable the assessment of the potential contribution to mitigating GHG emissions made by woodland creation programmes over these timescales.

2.3 Incorporation of results into software tool

The modelling described above produced a very large body of estimates of carbon gains and losses for a wide range of possible options for woodland creation and management. A simple MS Excel software tool was developed to permit easy and understandable access to these estimates. Functionality was included in the Excel tool to permit the selection and comparison of results.

Two versions of the software tool were produced, one containing results for a single hectare of woodland created in 2022, and the other containing results for the notional 25 year planting programme.

2.4 Assessment of illustrative woodland options

The modelling outputs were used to assess the climate change mitigation potential of 12 "illustrative woodland options". These were selected to represent possible types of woodlands of interest to stakeholders. The example woodlands were defined in consultation with forestry policy analysts in England, Scotland, Wales and Northern Ireland. Table 2.1 gives a summary of the 12 options.

Several options represent broad-leaved woodlands with minimal management of trees. Although there is interest in unmanaged woodlands, in reality all woodlands require some management, even if just to remediate damage, e.g. from storms. This was represented by including continuous cover forest management (CCF, essentially continuous thinning without clearfelling) in a proportion of the area of the woodlands, also reflecting management in at least some parts of the woodland to meet amenity/ecological objectives. Other woodland options represent coniferous woodlands with management consistent with conventional approaches over the last century, whilst two options represent tree species mixtures with more complex management. Coniferous woodland options involving management with clearfelling and restocking were assumed to be managed on a rotation consistent with maximum mean annual stem volume production.

The growth rates (yield classes[5]) assumed were consistent with those observed for the tree species according to statistics available from the GB National Forest Inventory. Broadleaves typically have yield classes of 4 or 6. The mean yield class of conifers is around 12 to 14. The yield classes of Sitka spruce woodlands can be much higher than 14 if planted on suitable sites, whilst stands of genetically improved Sitka spruce can exceed yield class 24.

With the exception of the woodland options involving natural recolonisation, the modelling of soil carbon dynamics on establishment of the illustrative woodland options involved the assumption that scarification of sites would be carried out in advance of tree planting. This is assumed to remove one third of the pre-existing vegetation on the site, with a commensurate reduction in the inputs of carbon to soil from this source. Inputs of carbon from non-tree vegetation are then further reduced over time as the trees become established and compete with other vegetation on the site. Eventually, the reduced input of carbon from non-tree vegetation is compensated for by inputs from litter and fine roots, as the trees grow and accumulate biomass. The modelling of woodland creation with tree planting thus involves the assumptions of substantial reductions in inputs of carbon to the soil initially, but then recovery of soil carbon inputs (and eventually larger inputs than originally) once trees become established on the site. The modelling of soil carbon accumulation following abandonment of land and allowing woodland to develop through natural colonisation is based on available estimates reported from long-term trials.

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[5] The growth rates of woodlands are represented using the British yield class system (see Matthews *et al*., 2016a). Yield class is defined as the maximum average rate of cumulative stemwood volume production in a woodland over an optimal rotation. The actual average rate of production will vary with the specified rotation. As a convention, yield classes take even whole numbers, e.g. 4, 6, 8… $m^3\ ha^{-1}\ yr^{-1}$.

Table 2.1 Summary of illustrative woodland options

Woodland option name	Description
Broadleaves, light management	Birch and oak, yield class 4, 50% no management and 50% continuous cover (CCF) management (thinning every 5 years and gradual regeneration). Soil carbon represented by results for woodlands planted on mineral soil, formerly under cropland.
Natural recolonisation, rapid	Birch and oak, yield class 4. Management and soil carbon represented as above, but woodland created by allowing natural recolonisation of abandoned cropland (mineral soil). 'Rapid' natural recolonisation by trees was assumed to start 10 years after the time of land abandonment.
Natural recolonisation, gradual	Birch and oak, yield class 4. Management and soil carbon represented as above. 'Gradual' recolonisation by trees was assumed to start 25 years after the time of land abandonment.
Production broadleaves	Birch and oak, yield class 4, with CCF management. Soil carbon represented by results for woodlands planted on mineral soil, formerly under cropland.
Production pine	Mainly Scots pine, yield class 8, managed with a combination of thinning and clearfelling and some CCF managed areas. Also, a smaller area of birch with no management (amenity/ecological objectives). Soil carbon represented by combining results for woodlands planted on mineral and organo-mineral soils, formerly under grassland, scrub, moorland and cropland.
Moderate growing conifer unthinned	Conifers (represented by Sitka spruce), yield class 12, managed with clearfelling but with no thinning. Also, a smaller area of birch with no management (amenity/ecological objectives). Soil carbon represented as above.
Fast growing conifer unthinned	Conifers, (represented by Sitka spruce), yield class 18, managed with clearfelling but with no thinning. Also, a smaller area of birch with no management (amenity/ecological objectives). Soil carbon represented as above.

Table 2.1 (continued) Summary of illustrative woodland options

Woodland option name	Description
Moderate growing conifer thinned	Conifers (represented by Sitka spruce), yield class 12, managed with clearfelling and with thinning. Also, a smaller area of birch with no management (amenity/ecological objectives). Soil carbon represented by combining results for woodlands planted on organo-mineral soil, formerly under grassland, scrub, moorland and cropland.
Fast growing conifer thinned	Conifers, (represented by Sitka spruce), yield class 18, managed with clearfelling and with thinning. Also, a smaller area of birch with no management (amenity/ecological objectives). Soil carbon represented as above.
Fast growing Sitka spruce thinned	Sitka spruce, yield class 24, managed with clearfelling and with thinning. Also, a smaller area of birch with no management (amenity/ecological objectives). Soil carbon represented by results for woodlands planted on organo-mineral soil, formerly under grassland, scrub and moorland.
Conifer mixture	Mixture of Douglas fir, Sitka spruce and Western red cedar, all yield class 14, managed with clearfelling on variable rotations and with thinning. Also, a smaller area of birch with no management (amenity/ecological objectives). Soil carbon represented by combining results for woodlands planted on mineral and organo-mineral soils, formerly under grassland, scrub, moorland and cropland.
Complex conifer/broadleaf mixture	Mixture of Douglas fir, Sitka spruce and Western red cedar, all yield class 14, managed with clearfelling on variable rotations and with thinning, also with oak and a small area of beech, both yield class 6. All species managed with CCF methods. Soil carbon represented as above.

2.5 Results for illustrative woodland options

Results for climate change mitigation potential were calculated for each of the illustrative woodland options in Table 2.1. Separate results were produced for each of the four reporting periods defined in Section 2.2.4, and for three scenarios representing woodland creation programmes:

- 1 ha created in 2022
- 1 hectare per year created for 10 years starting in 2022
- 1 hectare per year created for 25 years starting in 2022.

This gave a total of 12 sets of results, which are included in the full Assessment Report. A selection of four key sets of results is presented and discussed below:

- 1 ha created in 2022, results for the period 2022 to 2050 (Figure 2.2)
- 1 hectare per year created for 25 years starting in 2022, results for the period 2022-2050 (Figure 2.3)
- 1 hectare created in 2022, results for the period 2022 to 2100 (Figure 2.4, also Figure S1 in the Summary)
- 1 hectare per year created for 25 years starting in 2022, results for the period 2022-2100 (Figure 2.5).

For the carbon pools of trees, deadwood, litter, soil and wood products, results are shown in each figure for annualised carbon stock changes over the specified reporting period, expressed in units of tonnes CO_2 per year ($tCO_2\ yr^{-1}$). As discussed previously, annualised values are calculated by finding the average annual value over the specified reporting period. Estimates for GHG emissions from forest operations and emissions avoided by wood product substitution impacts are also presented as annualised results over the specified reporting period, expressed in units of tonnes CO_2-equivalent per year (tCO_2-eq. yr^{-1}). Results with a positive sign indicate carbon stock increases (net carbon sequestration) or GHG emissions avoided, and those with a negative sign indicate carbon stock losses or net GHG emissions increases.

All results are given on a net-area basis. Hence, they must be adjusted to allow for any areas of open ground within forest areas.

The values for individual contributions in Figures 2.2 to 2.5 are also given in Tables 2.2a & 2.2b to 2.5a & 2.5b. Subtotals are also shown for all woodland carbon pools, all carbon pools including wood products, and for total GHG emissions mitigation.

Note that estimates can be calculated for a notional programme of woodland creation of ‘X ha per year over 25 years’ by multiplying the results in Tables 2.3a & 2.3b and 2.5a & 2.5b by the value of X.

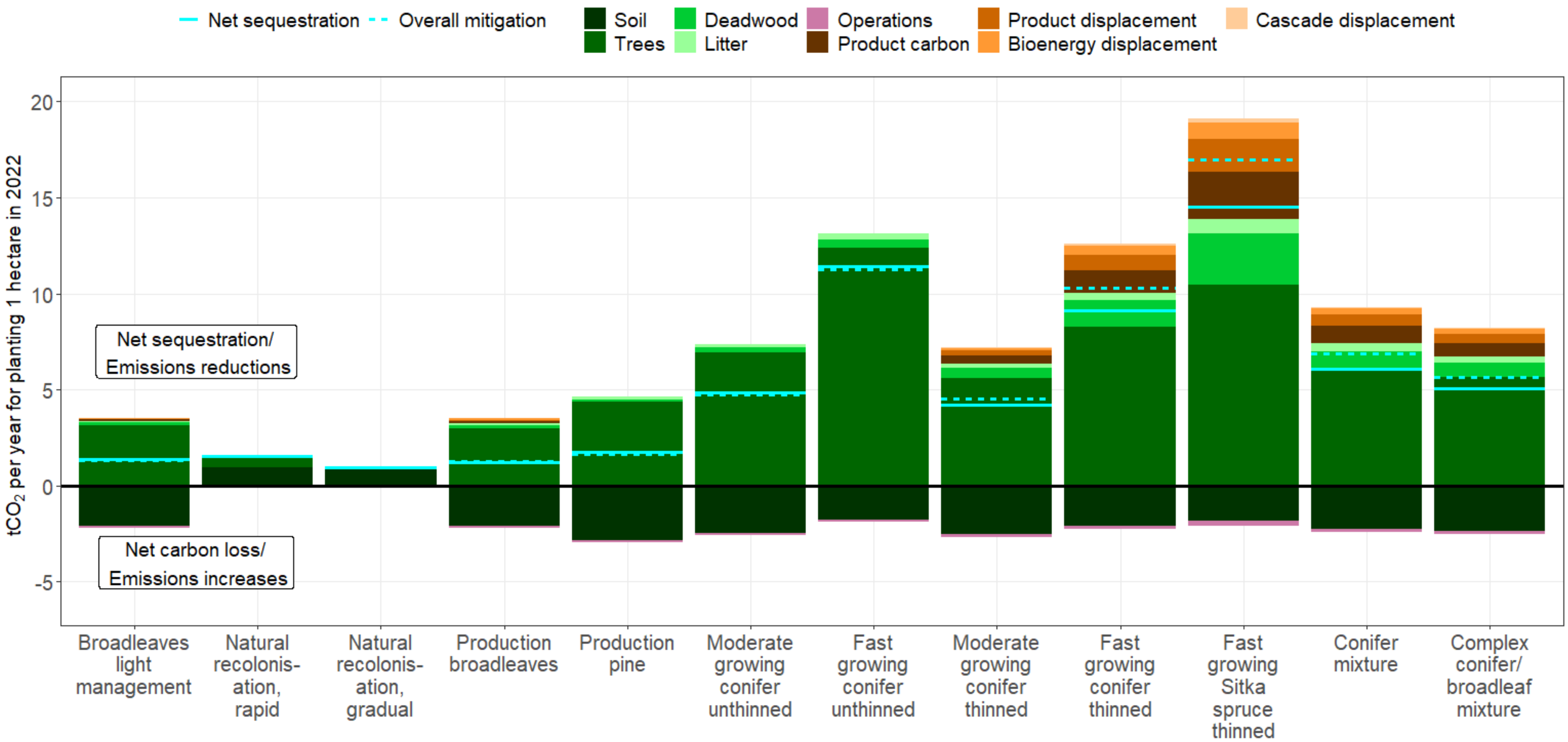

Figure 2.2. Annualised CO_2 uptake and GHG emissions avoided, estimated over the period 2022 to 2050 for 12 illustrative woodland options, assuming 1 hectare of woodland planted in 2022.

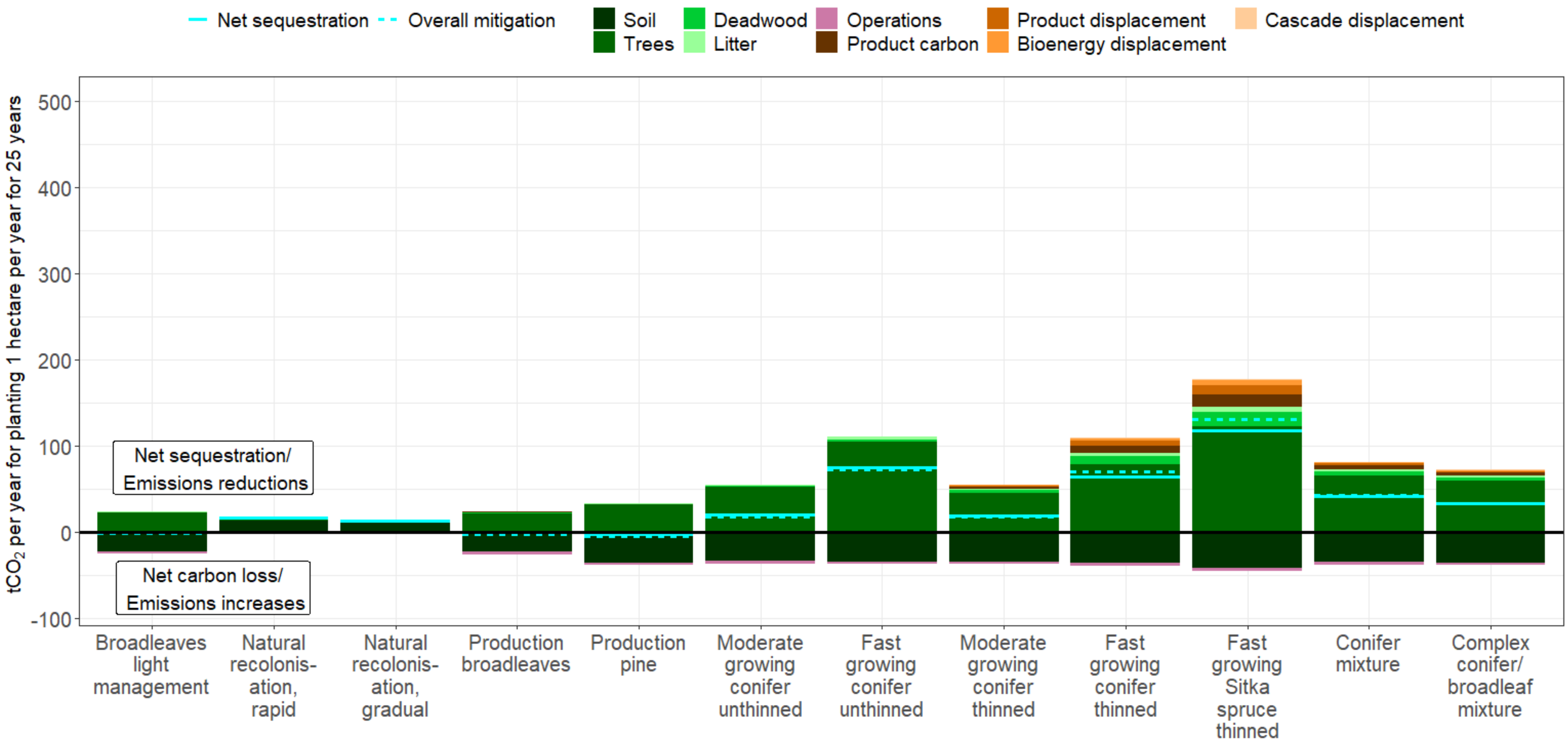

Figure 2.3. Annualised CO_2 uptake and GHG emissions avoided, estimated options over the period 2022 to 2050 for 12 illustrative woodland options, assuming 1 hectare of woodland planted per year for 25 years, starting in in 2022.

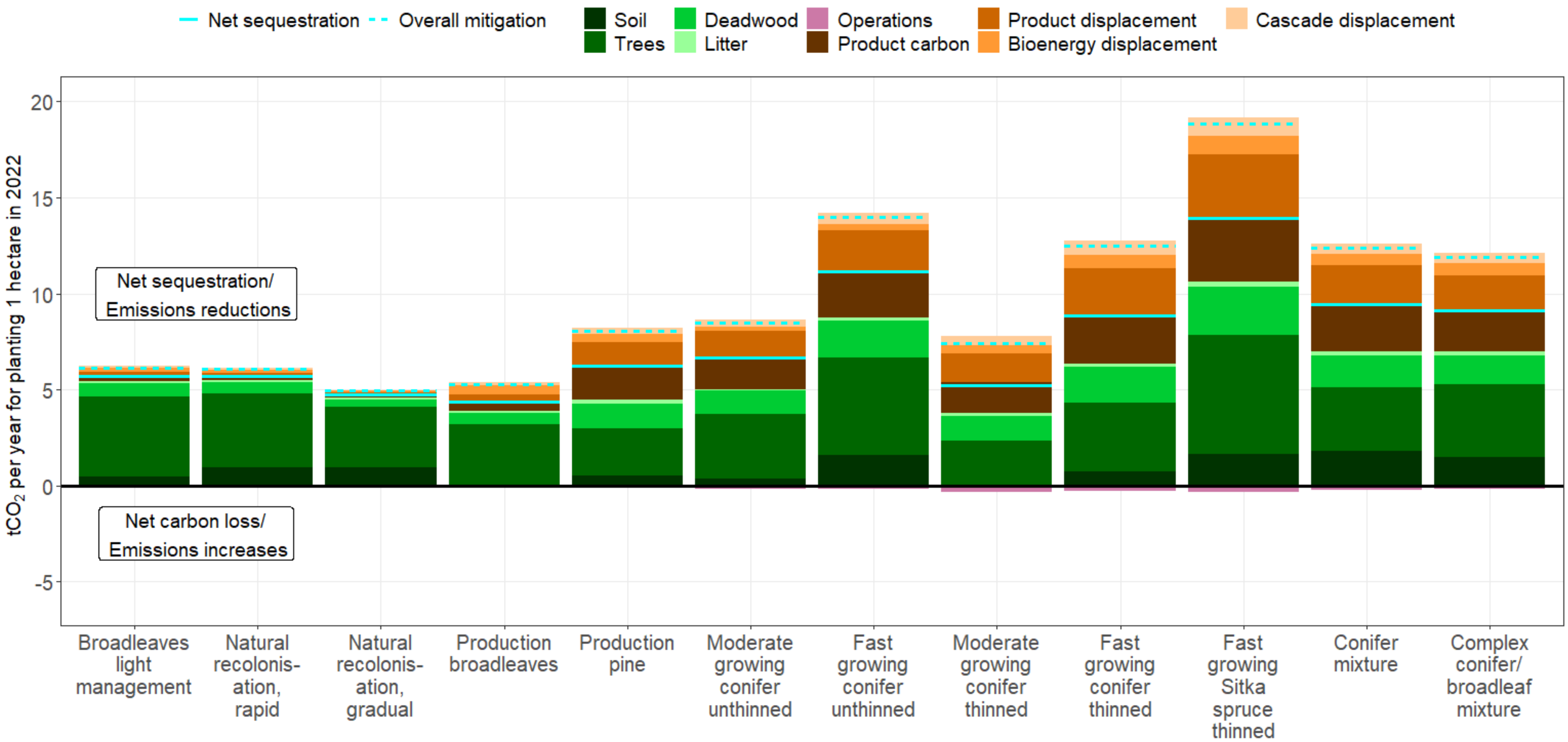

Figure 2.4. Annualised CO_2 uptake and GHG emissions avoided, estimated over the period 2022 to 2100 for 12 illustrative woodland options, assuming 1 hectare of woodland planted in 2022.

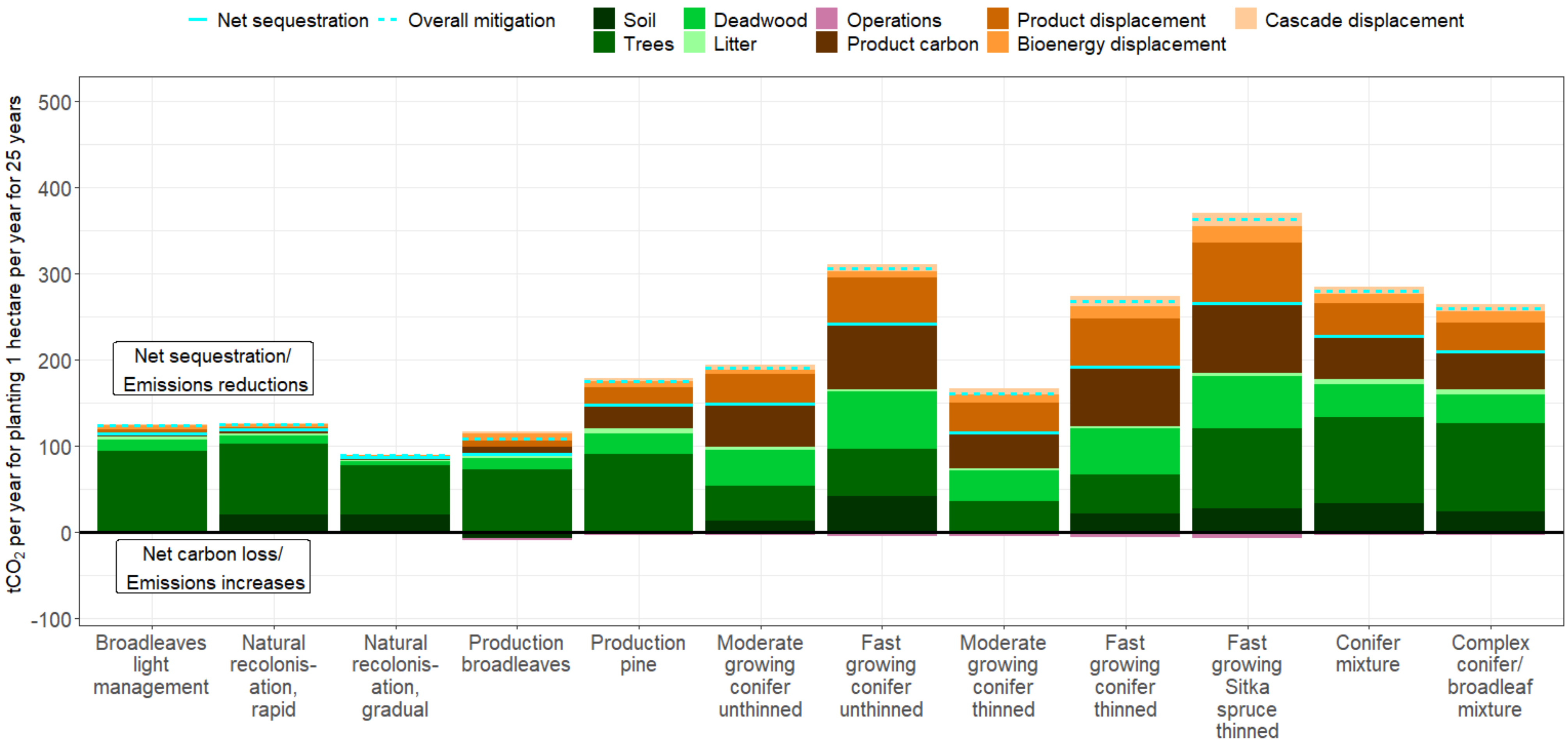

Figure 2.5. Annualised CO_2 uptake and GHG emissions avoided, estimated options over the period 2022 to 2100 for 12 illustrative woodland options, assuming 1 hectare of woodland planted per year for 25 years, starting in in 2022.

Table 2.2a Carbon sequestration by woodland options (2022-2050): 1 ha created in 2022

Woodland option	Annualised net carbon stock change (tCO_2 ha^{-1} yr^{-1})						
	Trees	**Deadwood**	**Litter**	**Soil**	**Total woodland**	**Wood products**	**All carbon pools**
Broadleaves light management	3.2	0.1	0.1	-2.1	1.3	0.1	1.3
Natural recolonisation, rapid	0.6	0.0	0.0	0.9	1.6	0.0	1.6
Natural recolonisation, gradual	0.0	0.0	0.0	0.9	0.9	0.0	0.9
Production broadleaves	3.0	0.2	0.1	-2.1	1.1	0.1	1.2
Production pine	4.4	0.1	0.1	-2.8	1.8	0.0	1.8
Moderate growing conifer unthinned	7.0	0.2	0.2	-2.5	4.9	0.0	4.9
Fast growing conifer unthinned	12.4	0.5	0.3	-1.8	11.4	0.0	11.4
Moderate growing conifer thinned	5.6	0.6	0.2	-2.6	3.8	0.4	4.2
Fast growing conifer thinned	8.3	1.4	0.3	-2.1	7.9	1.2	9.1
Fast growing Sitka spruce thinned	10.4	2.7	0.7	-1.8	12.0	2.4	14.5
Conifer mixture	6.1	0.9	0.4	-2.3	5.1	0.9	6.1
Complex conifer/ broadleaf mixture	5.6	0.7	0.3	-2.4	4.3	0.7	5.0

Table 2.2b GHG emissions mitigation by woodland options (2022-2050): 1 ha created in 2022

Woodland option	GHG emissions mitigation (tCO_2-eq. ha^{-1} yr^{-1})					
	All carbon pools	**Forest operations (emissions)**	**Wood product substitution**	**Bioenergy (wood fuel) substitution**	**Cascade substitution**	**Net GHG emissions mitigation**
Broadleaves light management	1.3	-0.1	0.0	0.0	0.0	1.3
Natural recolonisation, rapid	1.6	0.0	0.0	0.0	0.0	1.6
Natural recolonisation, gradual	0.9	0.0	0.0	0.0	0.0	0.9
Production broadleaves	1.2	-0.1	0.1	0.1	0.0	1.3
Production pine	1.8	-0.1	0.0	0.0	0.0	1.7
Moderate growing conifer unthinned	4.9	-0.1	0.0	0.0	0.0	4.7
Fast growing conifer unthinned	11.4	-0.1	0.0	0.0	0.0	11.2
Moderate growing conifer thinned	4.2	-0.1	0.3	0.2	0.0	4.5
Fast growing conifer thinned	9.1	-0.2	0.9	0.5	0.1	10.4
Fast growing Sitka spruce thinned	14.5	-0.2	1.9	0.9	0.2	17.1
Conifer mixture	6.1	-0.2	0.6	0.3	0.1	6.9
Complex conifer/ broadleaf mixture	5.0	-0.2	0.5	0.3	0.0	5.7

Table 2.3a Carbon sequestration by woodland options (2022-2050): 25 year programme

Woodland option	Annualised net carbon stock change ($tCO_2\ yr^{-1}$)						
	Trees	**Deadwood**	**Litter**	**Soil**	**Total woodland**	**Wood products**	**All carbon pools**
Broadleaves light management	22.0	0.7	0.5	-23.2	0.0	0.3	0.3
Natural recolonisation, rapid	2.7	0.0	0.0	13.4	16.2	0.0	16.2
Natural recolonisation, gradual	0.0	0.0	0.0	13.4	13.4	0.0	13.4
Production broadleaves	21.1	0.9	0.5	-23.2	-0.7	0.6	-0.1
Production pine	31.6	0.6	0.9	-35.7	-2.5	0.0	-2.5
Moderate growing conifer unthinned	52.1	1.3	1.2	-34.2	20.4	0.0	20.4
Fast growing conifer unthinned	104.6	3.0	2.6	-34.8	75.4	0.0	75.4
Moderate growing conifer thinned	45.6	3.2	1.5	-34.2	16.0	2.2	18.2
Fast growing conifer thinned	78.5	9.9	3.5	-35.7	56.1	8.2	64.4
Fast growing Sitka spruce thinned	122.0	17.4	5.6	-41.9	103.2	15.0	118.2
Conifer mixture	65.5	4.5	2.6	-35.4	37.2	4.1	41.4
Complex conifer/ broadleaf mixture	59.5	3.7	2.2	-35.7	29.7	3.3	33.0

Table 2.3b GHG emissions mitigation by woodland options (2022-2050): 25 year programme

Woodland option	GHG emissions mitigation (tCO_2-eq. yr^{-1})					
	All carbon pools	**Forest operations (emissions)**	**Wood product substitution**	**Bioenergy (wood fuel) substitution**	**Cascade substitution**	**Net GHG emissions mitigation**
Broadleaves light management	0.3	-2.6	0.2	0.2	0.0	-1.8
Natural recolonisation, rapid	16.2	0.0	0.0	0.0	0.0	16.2
Natural recolonisation, gradual	13.4	0.0	0.0	0.0	0.0	13.4
Production broadleaves	-0.1	-2.9	0.4	0.4	0.0	-2.1
Production pine	-2.5	-2.8	0.0	0.0	0.0	-5.3
Moderate growing conifer unthinned	20.4	-2.8	0.0	0.0	0.0	17.6
Fast growing conifer unthinned	75.4	-2.8	0.0	0.0	0.0	72.6
Moderate growing conifer thinned	18.2	-2.9	1.4	0.8	0.1	17.6
Fast growing conifer thinned	64.4	-3.2	5.9	3.1	0.3	70.5
Fast growing Sitka spruce thinned	118.2	-3.6	11.4	5.7	0.7	132.5
Conifer mixture	41.4	-3.0	2.7	1.5	0.2	42.8
Complex conifer/ broadleaf mixture	33.0	-3.1	2.1	1.2	0.1	33.4

Table 2.4a Carbon sequestration by woodland options (2022-2100): 1 ha created in 2022

Woodland option	Annualised net carbon stock change (tCO_2 ha^{-1} yr^{-1})						
	Trees	Deadwood	Litter	Soil	Total woodland	Wood products	All carbon pools
Broadleaves light management	4.2	0.7	0.1	0.4	5.4	0.2	5.7
Natural recolonisation, rapid	3.9	0.6	0.1	0.9	5.5	0.2	5.7
Natural recolonisation, gradual	3.2	0.4	0.1	0.9	4.6	0.2	4.7
Production broadleaves	3.1	0.6	0.1	0.1	3.9	0.5	4.4
Production pine	2.4	1.3	0.2	0.5	4.5	1.7	6.2
Moderate growing conifer unthinned	3.3	1.2	0.1	0.4	5.0	1.6	6.7
Fast growing conifer unthinned	5.1	1.9	0.1	1.6	8.7	2.4	11.1
Moderate growing conifer thinned	2.3	1.3	0.1	-0.1	3.6	1.6	5.2
Fast growing conifer thinned	3.6	1.9	0.1	0.7	6.3	2.5	8.9
Fast growing Sitka spruce thinned	6.2	2.5	0.3	1.7	10.6	3.4	14.0
Conifer mixture	3.3	1.7	0.2	1.8	7.0	2.5	9.4
Complex conifer/ broadleaf mixture	3.8	1.5	0.2	1.5	7.0	2.1	9.1

Table 2.4b GHG emissions mitigation by woodland options (2022-2100): 1 ha created in 2022

Woodland option	GHG emissions mitigation (tCO_2-eq. ha^{-1} yr^{-1})					
	All carbon pools	Forest operations (emissions)	Wood product substitution	Bioenergy (wood fuel) substitution	Cascade substitution	Net GHG emissions mitigation
Broadleaves light management	5.7	-0.1	0.2	0.2	0.1	6.2
Natural recolonisation, rapid	5.7	0.0	0.2	0.2	0.1	6.1
Natural recolonisation, gradual	4.7	0.0	0.1	0.1	0.0	5.0
Production broadleaves	4.4	-0.1	0.4	0.4	0.2	5.3
Production pine	6.2	-0.2	1.3	0.4	0.3	8.0
Moderate growing conifer unthinned	6.7	-0.2	1.4	0.2	0.4	8.5
Fast growing conifer unthinned	11.1	-0.2	2.1	0.3	0.6	14.0
Moderate growing conifer thinned	5.2	-0.2	1.5	0.4	0.5	7.4
Fast growing conifer thinned	8.9	-0.3	2.5	0.7	0.8	12.5
Fast growing Sitka spruce thinned	14.0	-0.3	3.3	0.9	1.0	18.9
Conifer mixture	9.4	-0.2	2.1	0.6	0.6	12.4
Complex conifer/ broadleaf mixture	9.1	-0.2	1.8	0.7	0.5	11.9

Table 2.5a Carbon sequestration by woodland options (2022-2100): 25 year programme

Woodland option	Annualised net carbon stock change ($tCO_2\ yr^{-1}$)						
	Trees	**Deadwood**	**Litter**	**Soil**	**Total woodland**	**Wood products**	**All carbon pools**
Broadleaves light management	93.9	13.5	2.8	-0.7	109.5	5.3	114.8
Natural recolonisation, rapid	82.3	10.3	2.4	19.4	114.4	4.4	118.8
Natural recolonisation, gradual	57.7	5.0	1.7	19.4	83.7	2.5	86.2
Production broadleaves	72.4	13.3	2.4	-7.3	80.8	10.0	90.9
Production pine	90.1	24.6	6.0	-1.0	119.6	28.0	147.6
Moderate growing conifer unthinned	40.6	41.9	3.1	12.7	98.2	50.2	148.4
Fast growing conifer unthinned	54.7	66.9	3.0	41.4	165.9	76.2	242.2
Moderate growing conifer thinned	35.9	35.1	2.5	-0.8	72.7	43.0	115.7
Fast growing conifer thinned	45.1	53.7	2.8	20.9	122.4	69.6	192.0
Fast growing Sitka spruce thinned	93.0	60.2	4.4	27.2	184.8	80.8	265.6
Conifer mixture	100.5	37.5	6.5	33.0	177.5	50.1	227.6
Complex conifer/ broadleaf mixture	102.9	33.6	5.8	23.5	165.8	44.0	209.8

Table 2.5b GHG emissions mitigation by woodland options (2022-2100): 25 year programme

Woodland option	GHG emissions mitigation (tCO_2-eq. yr^{-1})					
	All carbon pools	**Forest operations (emissions)**	**Wood product substitution**	**Bioenergy (wood fuel) substitution**	**Cascade substitution**	**Net GHG emissions mitigation**
Broadleaves light management	114.8	-1.4	4.1	4.5	1.4	123.4
Natural recolonisation, rapid	118.8	-0.4	2.9	3.3	0.9	125.6
Natural recolonisation, gradual	86.2	-0.2	1.4	1.6	0.3	89.4
Production broadleaves	90.9	-1.9	7.8	8.4	2.7	107.8
Production pine	147.6	-2.8	19.1	6.9	4.4	175.2
Moderate growing conifer unthinned	148.4	-4.5	35.0	5.3	5.4	189.6
Fast growing conifer unthinned	242.2	-5.9	52.9	8.0	8.1	305.3
Moderate growing conifer thinned	115.7	-4.7	34.0	9.0	7.0	161.0
Fast growing conifer thinned	192.0	-6.4	56.4	14.1	11.5	267.6
Fast growing Sitka spruce thinned	265.6	-7.6	70.9	18.9	16.0	363.7
Conifer mixture	227.6	-4.4	38.3	10.9	8.0	280.4
Complex conifer/ broadleaf mixture	209.8	-4.1	33.6	13.0	7.7	260.1

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2.6 Key findings of assessment of woodland options

The results in Figures 2.2 to 2.5 are shown as stacked bars, giving annualised carbon gains or losses for the specified period:

- Green shaded bars show the contributions made by woodland carbon pools (trees, deadwood, litter and soil).
- A purple bar shows the GHG emissions from forest operations (e.g. site preparation including herbicides, harvesting machinery, transport), up to the "mill gate". These emissions are generally relatively very small.
- A dark brown bar shows the contribution made by carbon retained in the wood products carbon pool (denoted "Product carbon" in the key to the figures).
- Lighter brown bars show the contributions potentially made by wood product substitution effects, consisting of wood products displacing non-wood materials, wood fuel (bioenergy) displacing other fuels and wood product cascading effects. These contributions are denoted "Product displacement", "Bioenergy displacement" and "Cascade displacement", respectively.
- The net result for carbon stock changes in all carbon pools (woodland and wood products) is indicated for each result with a solid cyan coloured line ("Net sequestration"). The net result also allowing for GHG emissions from forest operations and emissions avoided by wood product substitution impacts is indicated by a dashed cyan coloured line ("Overall mitigation").

1 hectare created in 2022: time horizon 2022 to 2050

Results for this woodland creation scenario and timescale are presented in Figure 2.2 and Tables 2.2a & 2.2b.

Differences in the modelled estimates of carbon sequestration rates of woodland options are more apparent over shorter timescales such as between 2022 and 2050, when compared to results for longer timescales (see subsequent discussion of longer time horizons in this section). This is because outcomes over shorter timescales are more sensitive to variations in tree growth rates, silvicultural practices (thinning) and soil carbon stock changes related to woodland establishment.

Nearly all of the woodland options provide net GHG mitigation benefits in the period from 2022 to 2050; none result in significant net GHG emissions during this period. However, where they occur, soil carbon losses can offset carbon sequestration in other carbon pools.

Minimising disturbance to soil and existing vegetation on land where woodlands are being created may be identified as a critical factor for achieving early carbon sequestration. This is particularly the case for woodlands where the trees have relatively slow growth rates.

Assumptions made in the modelling of soil carbon dynamics during woodland establishment have been discussed in Section 2.4. With the exception of the woodland options involving natural recolonisation, the modelling of soil carbon dynamics on woodland establishment assumed that scarification of sites would be carried out in advance of tree planting. This is assumed to remove one third of the pre-existing vegetation on the site, with a commensurate reduction in the inputs of carbon to soil from this source. Inputs of carbon from non-tree vegetation are then further reduced over time as the trees become established and compete with other vegetation on the site. Eventually, the reduced input of carbon from non-tree vegetation is compensated for by inputs from litter and fine roots, as the trees grow and accumulate biomass. The modelling of woodland creation with tree planting thus involves the assumptions of substantial reductions in inputs of carbon to the soil initially, but then recovery of soil carbon inputs (and eventually larger inputs than originally) once trees become established on the site.

The modelling of soil carbon accumulation following abandonment of land and allowing woodland to develop through natural colonisation is based on available estimates reported from long-term trials.

The rate of CO_2 uptake, and hence carbon sequestration, in the period from 2022 to 2050 is strongly correlated with the growth rate of the trees forming the woodland. Growth rate not only relates to carbon sequestration by trees but also to inputs of carbon from the trees to the soil, which can increase soil carbon stocks or compensate for any initial losses during site preparation and woodland establishment. Faster growth rates are generally associated with coniferous tree species but outcomes for individual sites and climatic conditions will be very variable.

Removal of some trees by thinning attenuates rates of woodland carbon sequestration, but this is partially compensated for by carbon retained in wood products and relatively modest contributions from wood product substitution effects in early decades. Thinning can also improve the quality of woodlands by removing damaged and diseased trees and allowing the remaining better quality trees to grow faster, and produce better quality sawlogs more quickly, which can be used to manufacture longer lived wood products. Decisions about silvicultural practices such as thinning are likely to be determined by wider objectives for woodland management, rather than exclusively in terms of carbon sequestration.

In the period 2022 to 2050, the magnitude of total woodland carbon sequestration (in the carbon pools of trees, deadwood, litter and soil) in the broad-leaved woodland options created in 2022 is in the range 0.9 to 1.6 $tCO_2\ ha^{-1}\ yr^{-1}$; for the coniferous woodland options the range is 1.8 to 12.0 $tCO_2\ ha^{-1}\ yr^{-1}$.

If carbon retained in wood products is also included, the upper-range estimate for net carbon sequestration over this period for coniferous woodland options increases to 14.5 tCO_2 ha^{-1} yr^{-1}.

1 hectare per year created for 25 years starting in 2022: time horizon 2022 to 2050

Results for this woodland creation scenario and timescale are presented in Figure 2.3 and Tables 2.3a & 2.3b.

For a programme of creating 1 ha of woodland per year over 25 years, the magnitude of total woodland carbon sequestration (in the carbon pools of trees, deadwood, litter and soil) in the broad-leaved woodland options in the period 2022 to 2050 is in the range -0.7 to 16.2 tCO_2 yr^{-1}; for the coniferous woodland options the range is -2.5 to 103.2 tCO_2 yr^{-1}.

If carbon retained in wood products is also included, the lower-range estimate over this period for broad-leaved woodland options over this period changes to -0.1 tCO_2 ha^{-1} yr^{-1}., whilst the upper-range estimate for coniferous woodland options increases to 118.2 tCO_2 ha^{-1} yr^{-1}.

Effects of initial soil carbon losses offsetting carbon sequestration in other carbon pools are particularly noticeable in woodland creation programmes over longer periods (25 years), where carbon stocks in the woodlands created later in the programme do not have enough time to recover losses of soil carbon before 2050.

Longer time horizons

Over longer time horizons (e.g. 2022 to 2100) carbon sequestration (all carbon pools) in the different woodland options are closer to one another (see Figures 2.4 and 2.5 and Tables 2.4a & 2.4b and 2.5a & 2.5b). This occurs because most of the faster growing woodlands are assumed to be under management for production and areas of trees are being felled by thinning or clearfelling, diminishing the rate of carbon sequestration in these woodlands when this occurs. At the same time, the slower growing and relatively lightly managed broad-leaved woodland options continue to grow and sequester carbon in later decades during this period. Often, broadleaves are slower growing than coniferous trees, but broad-leaved trees are also longer lived and more enduring, so that carbon sequestration in broad-leaved woodlands can eventually ‘catch up’ with coniferous woodlands.

It should also be noted that the harvesting of trees will result in net losses of carbon from individual managed woodland stands in some years. These losses will eventually be recovered when the successor stands of trees become established, but by this stage carbon stocks in the woodland are cycling between gains and losses, with the result that additional carbon sequestration can be modest from this point onwards. Losses of carbon stocks from harvesting in individual woodlands are not apparent in Figures 2.2 to 2.5 because the effects of harvesting and tree growth/regrowth are evened out by averaging over quite long timescales (i.e. calculating mean rates in woodlands for the period 2022 to 2100).

1 hectare planted in 2022: time horizon 2022 to 2100

Results for this woodland creation scenario and timescale are presented in Figure 2.4 and Tables 2.4a & 2.4b.

In the period 2022 to 2100, the magnitude of carbon sequestration in all woodland carbon pools (not including wood products) in the broad-leaved woodland options created in 2022 is in the range 3.9 to 5.5 tCO_2 ha^{-1} yr^{-1}; for the coniferous woodland options the range is 3.6 to 10.6 tCO_2 ha^{-1} yr^{-1}. If carbon retained in wood products is allowed for, these ranges change to 4.4 to 5.7 ha^{-1} yr^{-1} and 5.2 to 14.0 tCO_2 ha^{-1} yr^{-1}, respectively.

1 hectare per year planted for 25 years starting in 2022: time horizon 2022 to 2100

Results for this woodland creation scenario and timescale are presented in Figure 2.5 and Tables 2.5a & 2.5b.

For a programme of creating 1 ha of woodland per year over 25 years, the magnitude of annualised carbon sequestration in all carbon pools (not including wood products) in the broad-leaved woodland options in the period 2022 to 2100 is in the range 81 to 114 tCO_2 yr^{-1}; for the coniferous woodland options the range is 73 to 185 tCO_2 yr^{-1}. If carbon retained in wood products is allowed for, these ranges change to 86 to 119 yr^{-1} and 116 to 266 tCO_2 yr^{-1}, respectively.

Wood product carbon and substitution effects

Wood products can provide a significant store of carbon and can avoid emissions when they substitute for other materials. These effects are most apparent for new coniferous woodlands managed for production over longer timescales (2022 to 2100), when these woodlands start to produce timber. If these contributions are also included in mitigation estimates for this period, the magnitude of the total GHG mitigation estimated for the managed coniferous woodland options created in 2022 increases to between 7.4 and 18.9 tCO_2 ha^{-1} yr. For a programme of creating 1 ha of managed coniferous woodland per year over 25 years, these estimates are between 161 and 364 tCO_2 yr^{-1} (again, over the period 2022-2100). As noted in Section 2.2.3, the substitution impacts of wood products (and wood fuel) were modelled as diminishing over time, on the assumption that the wider economy would become decarbonised. However, if this happens, harvested wood will continue to provide a low-carbon source of materials and energy.

Comparing woodland options

It must be stressed that these woodland options are not interchangeable in the same locations or on the same sites within the UK. Rather, different options will be better suited to different regions of the UK and particular site types. For this reason, care must be taken when interpreting simple comparisons of the climate change/GHG mitigation potential of the different woodland options such as those in Figures 2.2 to 2.5 and Tables 2.2a & 2.2b to 2.5a & 2.5b.

The model-based assessment above suggests a number of conclusions about options for creating and managing woodlands with the aim of sequestering carbon and/or mitigating GHG emissions:

- All of the example woodlands considered deliver substantial carbon sequestration over the period up to 2100.
- When the example woodlands are compared, there are differences in the rates of carbon sequestration, and how the rates develop over time. In shorter timescales (e.g. up to 2050), a fast-growing Sitka spruce plantation can exhibit the highest carbon sequestration rates. In contrast, carbon sequestration in broad-leaved woodlands created by natural colonisation may be relatively modest initially. However, over longer timescales, the assessment suggests that the carbon sequestration and wider GHG emissions mitigation contributed by different woodland options become closer to one another. In terms of carbon sequestration directly in woodlands, contributions from a range of woodland options could work together to deliver sustained carbon sequestration at all stages during the period up to 2100. This conclusion is supported by detailed analysis in Section 3.7 of the full Assessment Report.
- Carbon sequestration rates and their development over time depend on certain factors related to how woodlands are created on different sites and on how the woodlands are managed once established, e.g. with thinning or felling or with the avoidance of such interventions.
- The different rates and patterns of carbon sequestration estimated for different woodland types provide some flexibility when planning woodlands to allow for wider objectives for woodland creation and management (e.g. recreation and wellbeing, biodiversity, water protection, timber and biomass supply), alongside delivering overall long-term carbon benefits.

2.7 Implications for implementation

It is beyond the scope of this assessment to comment on how forest policy and practice should be developed to support woodland creation and management with GHG emissions mitigation as a key objective. However, from a purely technical standpoint, it is possible to identify some high-level principles for woodland and wood product management suggested by the assessment presented in this report.

This assessment has shown that different types of woodland and woodland management can contribute towards GHG emissions mitigation in different ways and over different timescales. The range of possible woodland options offers flexibility for matching tree species and management objectives to sites, climatic conditions and most importantly local and regional expectations for what woodlands will provide. This principle can be summarised as illustrated in Figure 2.6, which has been adapted from Matthews and Robertson (2006). The figure shows how there is, effectively, a continuous scale of woodland management options, from semi-natural woodlands managed minimally as biological reserves and for high carbon stocks, through other types of multipurpose managed woodlands that provide a mix of carbon sequestration, wood products and wood energy, to fast-growing forestry plantations managed for maximum timber and biomass production.

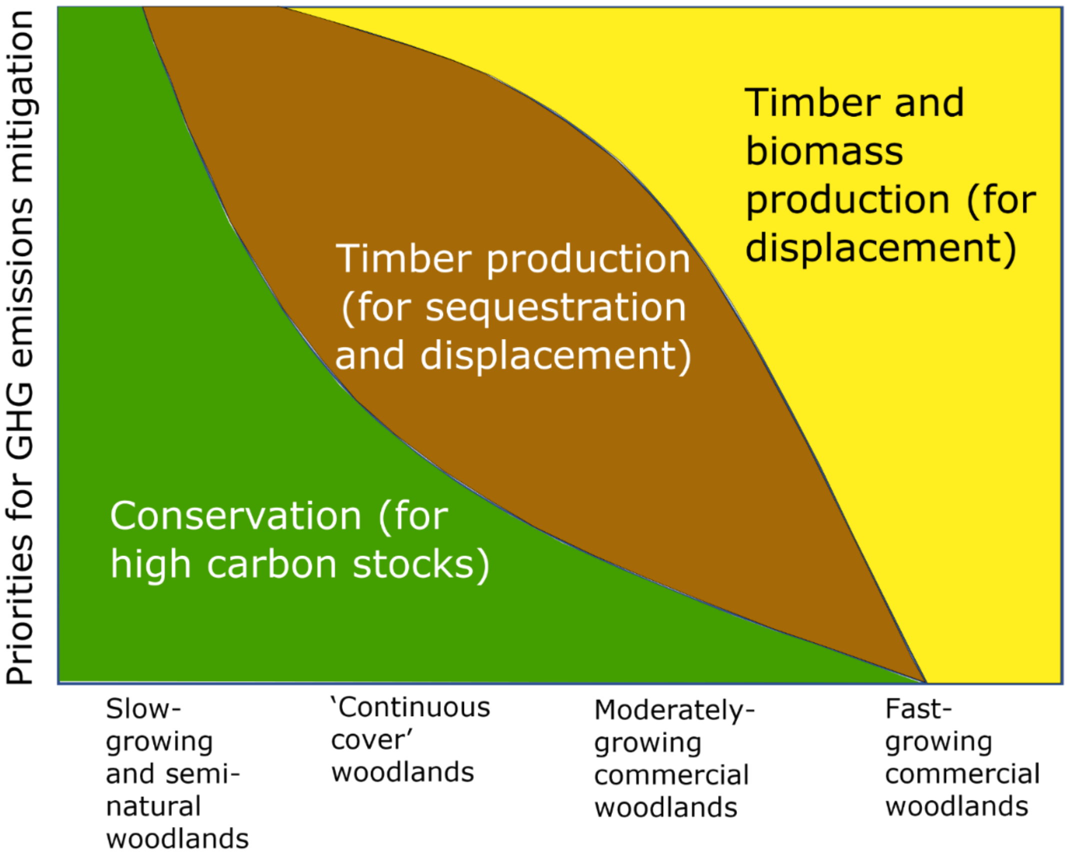

Figure 2.6. Relationships between woodland options and addressing GHG emissions mitigation. Adapted from Matthews and Robertson (2006) and based originally on the ideas of Bernhard Schlamadinger.

The diagram in Figure 2.6 illustrates the key interrelationship between the potential growth rates of trees (determined in many situations by site and climatic conditions) and the 'best fit' options for woodland management for mitigating GHG emissions. For example:

- Sites and climates that can support very fast growing trees provide opportunities to grow woody biomass rapidly to displace other products. Looking at the diagram the other way (y-axis), if a role is identified for creating a resource of fast growing forests in a particular locality, then sites that support fast tree growth will need to be available.

- On the other hand, sites and climates where trees are likely to grow slowly are well suited to the creation of woodland reserves and semi-natural woodlands, by establishing enduring broad-leaved tree species and managing them for high carbon stocks.
- Meanwhile, growing woodlands and managing them for commercial wood production, either involving clearfelling or continuous cover management practices, can support GHG emissions mitigation through a combination of enhanced carbon stocks and increased timber and wood energy supply.

As illustrated above, the diagram ‘works both ways’, in that:

- Particular types of sites and woodland (x-axis) tend to suggest management to contribute towards GHG emissions mitigation in different ways
- Equally, particular objectives for delivering GHG emissions mitigation (y-axis) tend to suggest certain types of sites woodlands (including tree species) and approaches to woodland management.

Whilst this simplistic illustration may help to visualise the potential contributions of different woodland options, it is important to recognise that this becomes a highly constrained problem when the theory meets reality, and when wider objectives for woodland creation and management are also considered.

3 Evidence from published field studies and assessments

The full Assessment Report includes a thorough review of evidence from published field studies and other assessments that have been made on forestry carbon balances. This section presents a summary of the essential evidence from other studies and analyses in support of the assessment in Section 2.

The two key sources of evidence from field studies are:

1. A synthesis of estimates of carbon stock changes occurring in woodlands over time derived from long-term monitoring plots and chronosequence studies in woodlands in Britain
2. Direct measurements of CO_2 fluxes in woodlands taken at a selection of sites in Britain and Ireland.

These evidence sources are discussed in Sections 3.1 and 3.2, respectively.

There are also two main recent examples of published assessments of the GHG emissions mitigation potentials of different woodland options relevant to the UK. These are discussed in Section 3.3.

3.1 Estimates of carbon stock changes in woodlands

The full Assessment Report describes how data from long term monitoring plots and chronosequence studies in woodlands were synthesised to assess how carbon stocks in woodlands develop over time.

The assessment examined the magnitudes and changes in carbon stocks that occur on an area of land over a period of 100 years from the time when a new woodland is created. A selection of woodland types relevant to UK conditions were assessed. All of the carbon pools in the woodland were covered, and carbon stocks in wood products were also included, where these were relevant. As far as possible, the results presented here are based on actual measurements taken over time in woodlands. Further details of methods are given in the full Assessment Report.

Nine examples of woodlands were selected, representing contrasting examples of tree species, site and soil types and woodland management, including:

- Oak woodlands on mineral soils in southeast England managed according to different thinning prescriptions
- Mixed broad-leaved woodlands on mineral soils in southeast England created by abandoning agricultural land and allowing trees to naturally recolonise the sites, with minimal subsequent management

- Spruce and pine forests on organo-mineral soils in northern England and northern Scotland, managed for wood production with thinning, and with clearfelling in the case of the example spruce woodland.

The main sources of data on tree carbon stocks were permanent mensuration sample plots maintained by Forest Research (Craig & Baden, 2020; Matthews & Mackie, 2004) and the periodic measurements taken in the Rothamsted classical experiments on natural recolonisation of agricultural land by trees (Harmer *et al.*, 2001; Poulton *et al.*, 2003; Poulton, 2006).

Data on litter and soil carbon were derived from chronosequence studies (Vanguelova *et al.*, 2019; Ražauskaitė, 2019; Ražauskaitė *et al.*, 2020).

Carbon stocks retained in wood products were modelled according to methods defined in IPCC (2019).

Estimates were compiled into consistent sets to represent the development of carbon stocks in the nine example woodland types. These are reported and discussed in detail in the full Assessment Report.

3.1.1 Pictorial representation of carbon stocks in example woodlands

Figures 3.1 to 3.2 provide pictorial illustrations of how carbon stocks and periodic carbon sequestration rates develop over time, for two examples of the woodlands covered in this assessment:

- “Straits” (Figure 3.1) – an oak woodland on a surface-water gley soil (previously grassland) in Alice Holt forest (southeast England), yield class 6, managed with thinning
- “Culbin” (Figure 3.2) – a Scots pine woodland on a peaty podzol (previously sand dunes) in Culbin forest (northeast Scotland), General Yield Class 8 (Local Yield Class 7), managed with thinning.

Forestry life cycle stages are illustrated in each figure for:

- Vegetation and soil that existed before the woodland was created (either by tree planting or by abandoning the previous land use and allowing natural colonisation with trees)
- “Young” woodland (represented notionally by the woodland 25 years after the time of initial creation)
- “Middle-aged” woodland (after 45 years)
- “Mature” woodland (after 100 years).

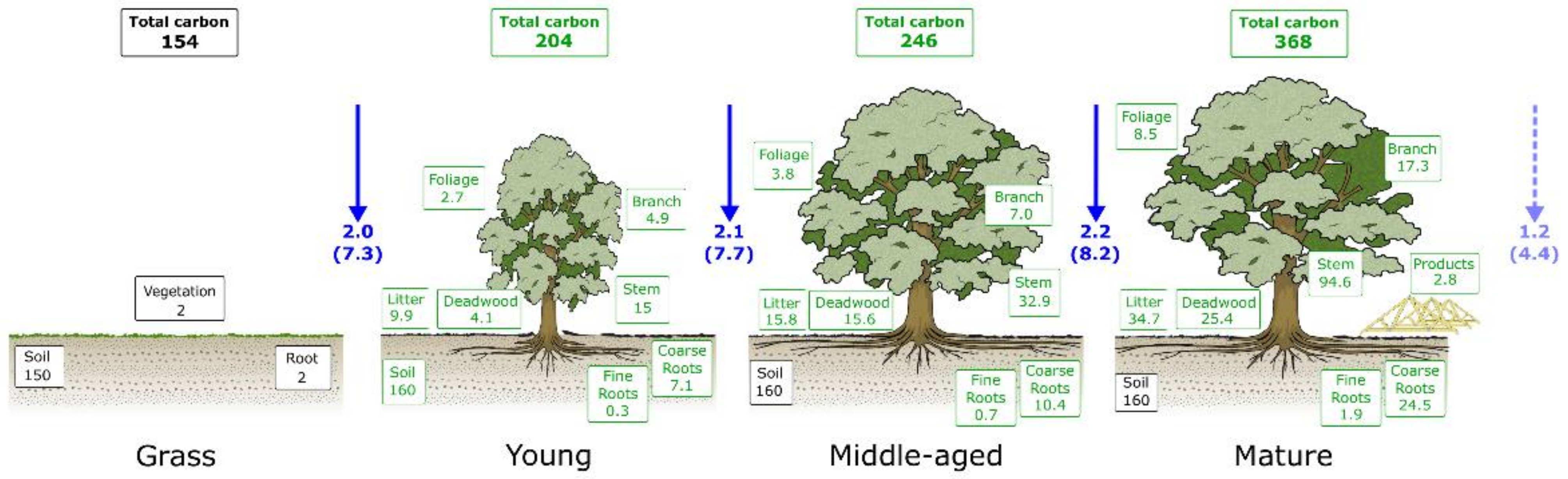

Figure 3.1. Straits – oak woodland planted on clay soil, standard thinning: Illustration of the development of carbon stocks over the life cycle of the first rotation of an oak woodland in southeast England, yield class 6, planted at approximately 1.2 m spacing, replacing grassland on a gley soil, regularly thinned with Standard thinning. Life cycle stages (young, middle-aged and mature) are represented by stand ages of 25, 45 and 100 years, respectively.

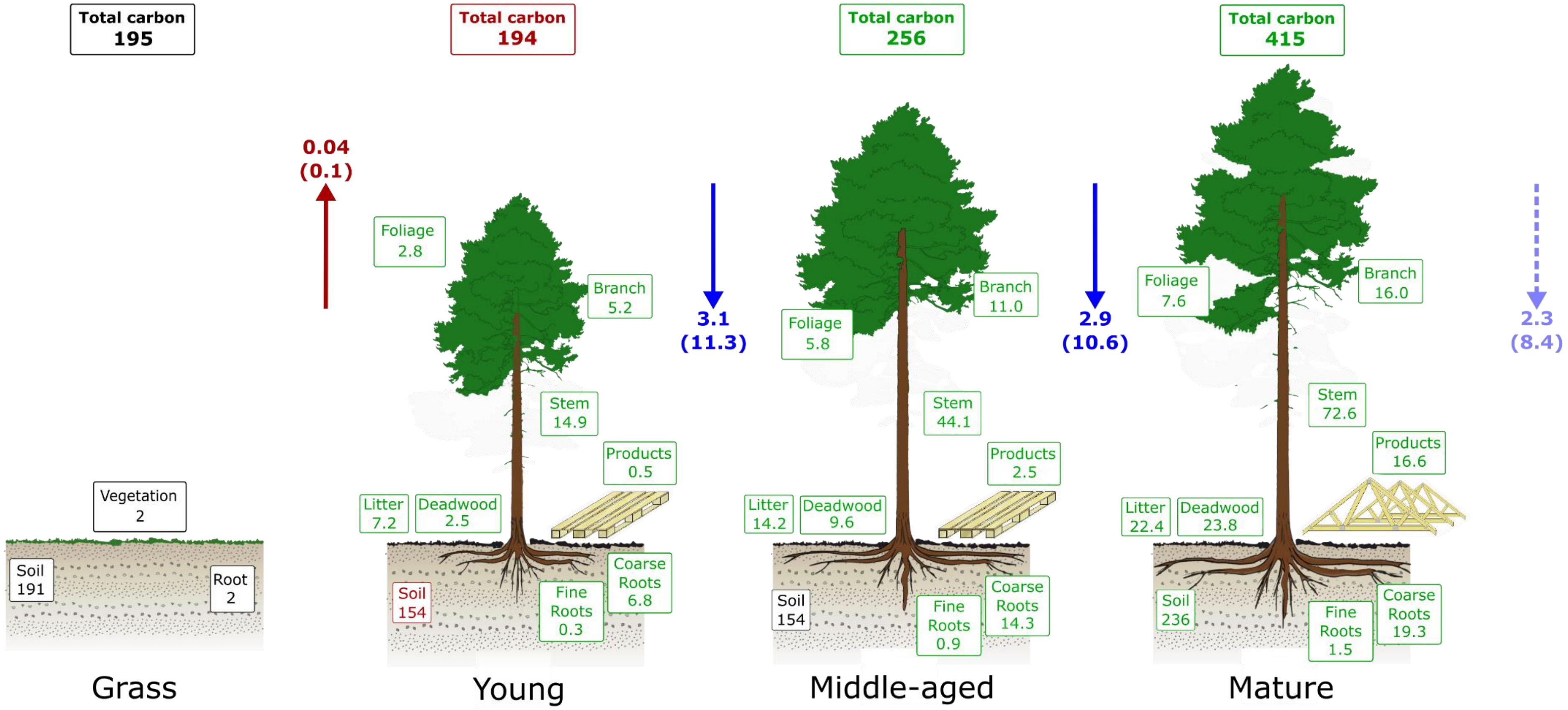

Figure 3.2. Culbin – Scots pine woodland planted on sandy soil, Standard thinning: Illustration of the development of carbon stocks over the life cycle of the first rotation of a Scots pine woodland in Northeast Scotland, yield class 7-8, planted at approximately 1.4 m spacing, replacing grassland on a peaty podzol soil, regularly thinned with Standard thinning. Life cycle stages (young, middle-aged and mature) are represented by stand ages of 25, 45 and 100 years, respectively.

For each life cycle stage in Figures 3.1 and 3.2, the carbon stocks in the various carbon pools are shown in boxes, in units of tC ha^{-1}. The total carbon stock is also shown in a box above each picture illustrating each stage. Green numbers in green boxes in the figures indicate that the carbon stock in a pool has increased at a given stage, compared with the previous stage. Red numbers in red boxes indicate a net loss of carbon stocks. Black numbers in black boxes indicate no change from one stage to the next.

Arrows between each stage indicate the rate of net periodic carbon sequestration by the system at each stage, compared with the previous stage, or the net carbon loss, as appropriate. These results are given in units of tC ha^{-1} yr^{-1} (and tCO_2 ha^{-1} yr^{-1} in brackets). A blue downward pointing arrow indicates net carbon sequestration, whilst a red upward arrow indicates net carbon loss.

At the far right of each figure, a dashed arrow gives a projected estimate of periodic carbon sequestration beyond 100 years. This has been calculated based on model projections of carbon stocks between 100 and 150 years. These estimates are speculative, and arrows associated with the estimates are dashed to highlight this.

3.1.2 Comparison with modelled estimates

The estimates of carbon stock changes derived from long-term measurements and chronosequence studies can be compared with the modelled estimates produced for this assessment. To allow such a comparison, results were selected from amongst specific woodland scenarios modelled for inclusion in the Excel software tool developed for this assessment, which were a good match for the nine woodlands represented in the field-based assessments. Estimates for two of the oak woodlands with non-standard thinning treatments were excluded because comparable scenarios are not included in the current version of the Excel software tool. One of the experiments at Rothamsted was also excluded because woodland consists of a narrow strip (<0.1 ha) and therefore may not be representative of a significant area of regenerated woodland. Further details of the methods used in the comparison are given in the full Assessment Report.

Figure 3.3 shows a comparison of the plot-based annualised estimates of carbon sequestration (all carbon pools) with the model-based estimates, for consistent time horizons of 0 to 25 years and 0 to 100 years from time of woodland creation.

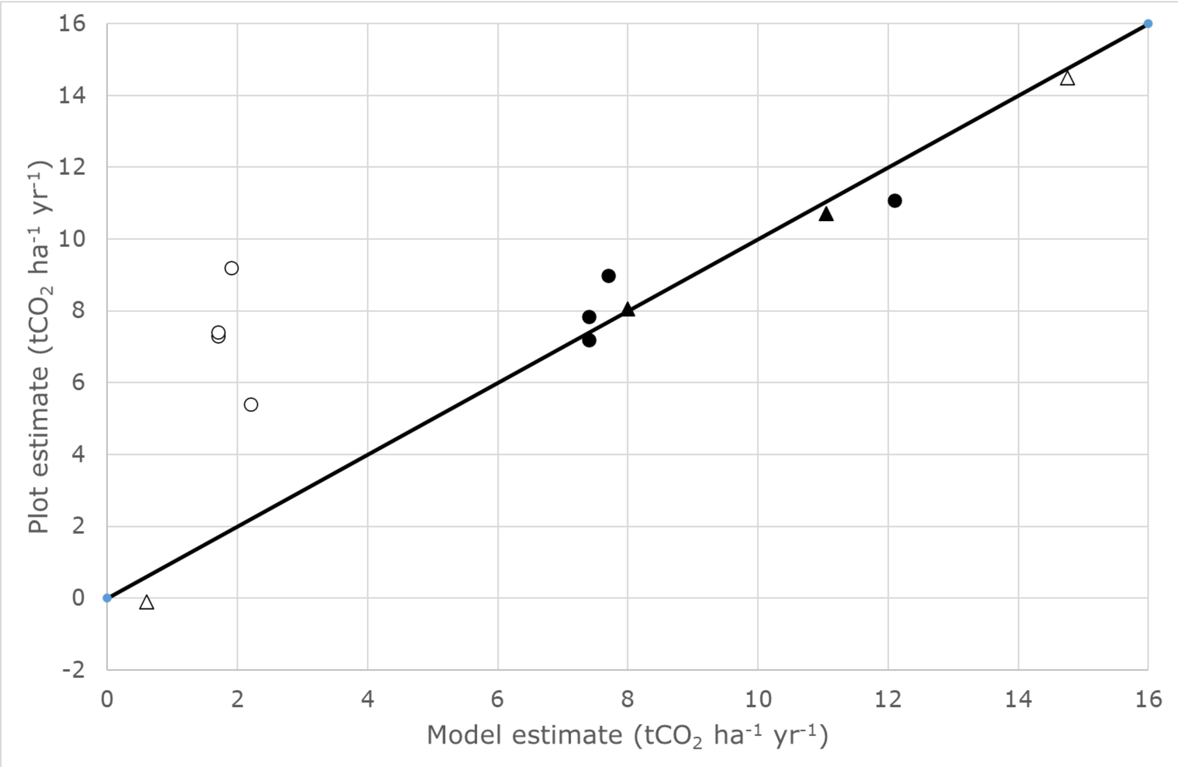

Figure 3.3. Comparison of field-based and model-based estimates of annualised rates of carbon sequestration (all woodland carbon pools). Open symbols: 25 year period from woodland creation; Filled symbols: 100 year period. Circles: broadleaf woodland; Triangles: coniferous woodland.

The results for the longer time horizon show remarkable agreement, with all of the estimates falling close to the "y = x" line. However, the outcome is different for the results for the shorter time horizon. Only the points for the two coniferous woodland examples show good agreement; for the broad-leaved woodland cases, the field-based results suggest higher rates of carbon sequestration, when compared with the model-based results.

In most cases (planted oak woodlands), the cause of the differences is mainly related to different assumptions about the response of soil carbon when establishing woodlands:

- In the modelling of scenarios it was assumed that some level of soil disturbance would occur, along with some removal of previous vegetation, resulting in losses of soil carbon in early years following woodland creation
- For the field-based assessments, for the broadleaf cases, data was taken from a field study that suggested a neutral response or increase of soil carbon when broad-leaved woodlands are established (Ražauskaitė, 2019).

For the purpose of the model-based assessment, cautious assumptions were made about the impacts of soil and vegetation disturbance on soil carbon during the initial stages of woodland creation.

For the example of a woodland created by natural colonisation at Rothamsted, assumptions about rates of soil carbon accumulation following land abandonment are based directly on rates observed in the Rothamsted trials. In this case, the difference between the model-based and field-based estimates for total carbon sequestration is related to the early development of tree carbon stocks. Measurements of tree carbon stocks in the Rothamsted experiments only started at a quite late stage of woodland development. The field-based estimates for tree carbon stocks in the woodland at Rothamsted in early years were based on backwards extrapolation and are uncertain. However, the model-based estimates are also uncertain; in this case they were derived by assuming a simple 10 year delay to the start of tree biomass development, compared to trees that are actively planted. More sophisticated modelling of tree biomass development in the Rothamsted trials has been presented in Section A1.3 (Appendix 1) of Matthews (2020). The results of that exercise suggest carbon sequestration in trees at a rate of under 0.2 tCO_2 ha^{-1} yr^{-1} in the first 25 years, consistent with a simple delay to the start of (planted) tree growth of at least 15 years.

3.2 Measurements of CO_2 fluxes in woodlands

Carbon stocks in woodlands are the results of gains and losses that take place over many years. Carbon stocks can be measured directly but the annual uptake or loss of carbon (or flux of carbon) is harder to estimate. Alternatively, at smaller scales, CO_2 fluxes associated with woodlands can be measured directly using specialist micrometeorological equipment.

The annual CO_2 uptake rates of individual woodland stands have been measured in a very few example woodlands in Britain and Ireland (Clement, Jarvis & Moncrieff, 2012; Saunders *et al.*, 2012; Thomas *et al.*, 2011; Xenakis *et al.*, 2021; Wilkinson *et al.*, 2012, updated). A summary of the results of these studies can be found in the full Assessment Report.

3.2.1 Comparison with modelled estimates

Micrometeorological measurements of woodland CO_2 fluxes register the short-term (e.g. annual) net carbon flow into woodlands but do not capture all of the carbon flows out of woodlands (e.g. they cannot register the episodic losses of carbon extracted as harvested timber). However, modelled estimates of carbon stock changes in woodlands can be calculated that are consistent with CO_2 flux measurements. Figure 3.4 shows the flux measurements for growing woodlands from published studies compared with modelled estimates from CARBINE that have been calculated on a consistent basis.

The lowest measured estimate in Figure 3.1 is for an ancient woodland (Wytham Woods, Oxfordshire; Thomas *et al.*, 2011). The CARBINE model does not currently include the features needed to accurately simulate the development of carbon stocks in ancient woodlands. As a proxy, tentative estimates were taken from long model runs for mixed broad-leaved woodlands with a complex tree structure (resulting from continuous cover forest management). These speculative model estimates are shown as a range in Figure 3.4 (dashed black line joining the minimum and maximum estimates).

Given the very different methods used to produce the CO_2 flux measurements and the model-based estimates in Figure 3.4, the agreement between the values for this small sample of woodlands is notable. This is the particularly the case considering that flux measurements will be influenced by significant variations in shorter term environmental conditions. Statistical tests indicate that the correlation between the two sets of results does not deviate significantly from the “y = x” line (black line in Figure 3.4).

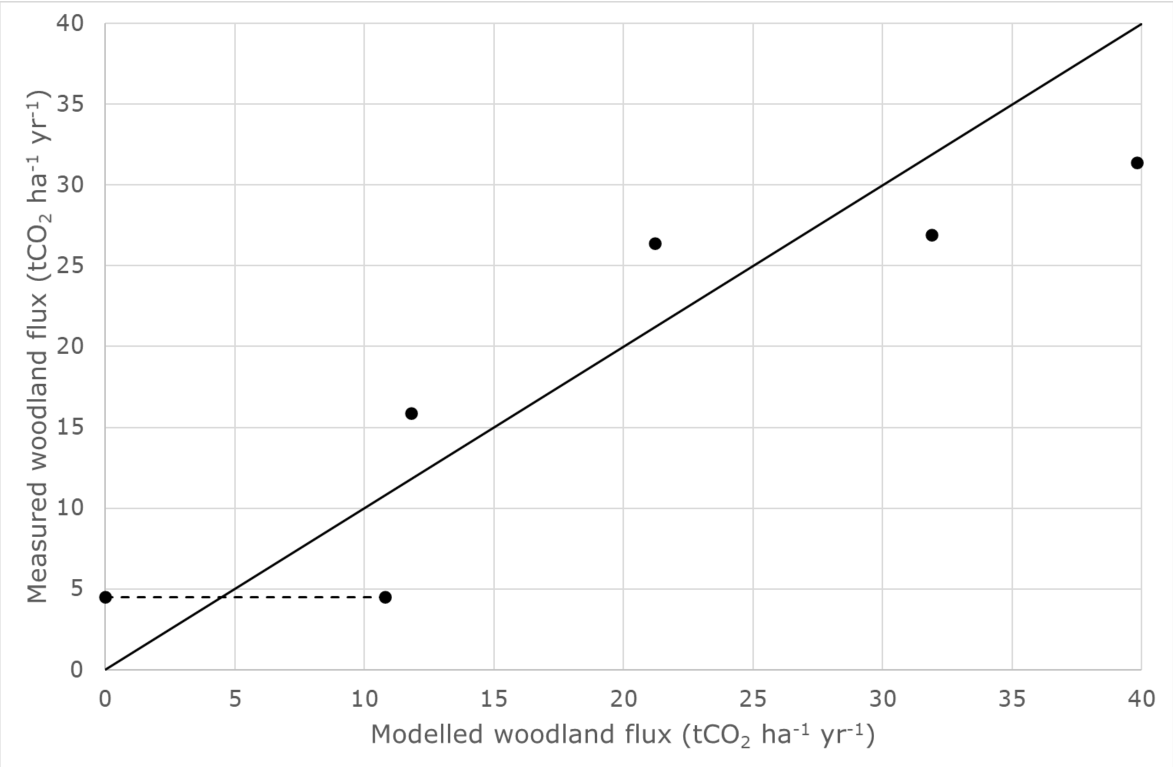

Figure 3.4. Comparison of direct measurements of CO_2 fluxes in woodlands with compatible estimates produced by the CARBINE model. Dashed line indicates uncertainty in modelled CO_2 flux for one site.

3.3 Recent assessments of woodland options

There are two main examples of recent published assessments of the GHG emissions mitigation potentials of different woodland options relevant to the UK, by Forster *et al.* (2021) and Bradfer-Lawrence *et al.* (2021a, b). These studies are briefly reviewed below, and their findings are compared with those produced in this current assessment. Further discussion of these studies is provided in the full Assessment Report.

3.3.1 Study of Forster *et al.*

The study of Forster *et al.* (2021) assessed the potential woodland carbon sequestration and GHG emissions avoided through creating four main woodland options:

1. Planting a mixture of (native) broad-leaved tree species (a mixture of birch, oak and rowan) and managing them minimally to allow maximum accumulation of carbon stocks in the woodlands
2. Planting a mixture of broad-leaved and coniferous tree species and managing them minimally to allow maximum accumulation of carbon stocks in the woodlands
3. Planting fast growing coniferous tree species (Sitka spruce) and managing them minimally to allow maximum accumulation of carbon stocks in the woodlands
4. Planting fast growing coniferous tree species (Sitka spruce) and managing them with thinning and clearfelling on a 'standard' rotation for the supply of wood products and wood fuel.

The detailed assessment methods were similar in many respects to those adopted for this current assessment.

The assessment included a quite extensive sensitivity analysis, which investigated how varying assumptions in calculations affected the estimates obtained for woodland carbon sequestration and GHG emissions avoided through wood product displacement effects. Key assumptions varied in the sensitivity analysis included:

- Yield class of woodlands
- Allocation of harvested wood to different products (primary and subsequent uses)
- Extent and type of product displacement
- Speed of decarbonisation of the wider economy, including deployment of carbon capture and storage (CCS) technologies.

Forster *et al.* reported per hectare estimates for cumulative carbon sequestration and avoided GHG emissions for each of the woodland options defined above, over a time horizon from 2020 to 2100, assuming trees were planted in 2020.

Relevant results produced for inclusion in the MS Excel software tool developed for this current assessment can be compared with the estimates reported by Forster *et al.*

The estimates from the assessment of Forster *et al.* and from the Excel software tool were found to be similar, with overlapping ranges when sensitivities to assumptions were allowed for. Forster *et al.*'s estimates for woodlands managed for production were relatively high. Analysis suggests that the main factors leading to differences in estimates are:

- Assumptions made in calculating potential GHG emissions avoided by wood products and wood fuel displacing non-wood products and fossil fuels
- Assumptions about the speed of general decarbonisation of the economy and deployment of CCS later in the century.

3.3.2 Study of Bradfer-Lawrence *et al.*

The study of Bradfer-Lawrence *et al.* (2021a, b) assessed the potential woodland carbon sequestration and GHG emissions avoided through creating woodlands in the UK. Part of this assessment was concerned with mapping land areas in the UK potentially suitable for woodland creation – this is not considered further here.

Another part of the assessment examined the carbon sequestration potential of one hectare of new broad-leaved and coniferous woodland over a 100 year time horizon. The initial assessment (Bradfer-Lawrence *et al.*, 2021b) compared the specific woodland options of:

- Sycamore, ash and birch, yield class 6, thinned but with no final clearfelling
- Sitka spruce, yield class 14, thinning with clearfelling on a rotation of 40 years.

A subsequent version of the assessment (Bradfer-Lawrence *et al.*, 2021a) was based on a very similar comparison but with the growth rate assumed for Sitka spruce changed to yield class 18.

The main source of estimates referred to by Bradfer-Lawrence *et al.* was the 'Woodland Carbon Code Carbon Calculation Spreadsheet', available as part of the guidance and tools produced in support of the UK Woodland Carbon Code (WCC, 2020). This calculator provides mean estimates of carbon sequestered in trees for 5 year periods from time of planting.

The WCC Carbon Calculation Spreadsheet was not developed for application to the type of research question considered here. However, this was partially addressed in the assessment of Bradfer-Lawrence *et al.* who made a number of supplementary calculations to estimate carbon stock changes in deadwood (originating from harvesting) and wood products (clearfelling only).

The estimates of carbon sequestration for the two woodland options presented by Bradfer-Lawrence *et al.* may be expressed as annualised changes in carbon stocks over a 100 year period from planting in units of tCO_2 ha^{-1} yr^{-1}. These estimates could be compared with relevant results produced for the MS Excel software tool developed for this current assessment.

The estimates of Bradfer-Lawrence *et al.* and from the Excel software tool for the broadleaf woodland option were found to have overlapping ranges when sensitivities to assumptions are allowed for. This was especially the case when comparing with estimates from the Excel software tool involving conservative assumptions about wood product displacement effects. However, it was apparent that Bradfer-Lawrence *et al.* estimate much lower rates of carbon sequestration for Sitka spruce woodlands managed for production. Detailed analysis suggests that this is the result of:

- Differences in modelled tree biomass allometry for Sitka spruce, as represented in the CARBINE model and in the WCC Carbon Calculation Spreadsheet (note that Forest Research is currently updating tree biomass allometry models for all tree species).
- Inclusion of substitution effects in the estimates derived for the Excel software tool
- More conservative contributions from carbon sequestration in soil in the estimates of Bradfer-Lawrence *et al.*
- The above factors are also present in the estimates for the broadleaf woodland but are less apparent.

3.4 Key conclusions from field-based studies and other published assessments

Estimates based on field measurements of woodland carbon stock changes and CO_2 fluxes show reasonable consistency with the modelled estimates which form the basis of the assessment in Section 2 of this report and the detailed assessments in the full Assessment Report.

When comparing modelled estimates with field estimates derived from long-term monitoring plots and chronosequence studies, uncertainties must be acknowledged in both field-based and model-based estimates of soil carbon stock changes in early years following woodland establishment and in carbon sequestration in trees following land abandonment to allow natural recolonisation. Given the very different methods used to produce direct measurements of CO_2 fluxes and model-based estimates of carbon stock changes, there is remarkable agreement between these two types of estimates.

There are limitations to comparing results from different assessment studies that have adopted different assumptions and calculation methodologies. Nevertheless, it is notable that the estimates of three separate assessments, i.e. those of Bradfer-Lawrence *et al.* (2021a, b) and Forster *et al.* (2021) and those from the Excel software tool produced for this assessment, are quite consistent. Differences in estimates reflect differences in underlying methodologies such as the inclusion or non-inclusion of specific carbon flows when calculating estimates of woodland carbon sequestration and GHG emissions mitigation.

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