NRW Carbon Positive Project

Greenhouse gas emissions and removals from woodlands on the NRW-managed estate

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Report No 277

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About this report

This report was commissioned by the NRW Carbon Positive Project to better understand the greenhouse gas emissions and removals associated with the woodlands on the estate that NRW owns and manages (the NRW-managed estate).

The information within this report has been used to inform the calculation of NRW's net carbon status and to support NRW's work on decarbonisation and carbon storage, including the Carbon Positive Enabling Plan and its supporting Action Plan.

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Natural Resources Wales Carbon Positive Project

Greenhouse gas emissions and removals from woodlands on the NRW-managed estate

Contents

Executive summary

Background to this work

Natural Resources Wales' purpose is to ensure that the environment and natural resources of Wales are sustainably maintained, enhanced and used, now and in the future. The Carbon Positive Project will evaluate NRW's net carbon status, accounting for both greenhouse gas (GHG) emissions and carbon sequestration across the whole of NRW's estate. NRW engaged Forest Research to provide the best available estimates of GHG emissions and carbon stocks/sequestration for the woodland habitats on the NRW-owned and managed estate, through the application of a state of the art forest sector carbon accounting model, CARBINE.

Purpose of this report and study

This report describes the modelling undertaken by Forest Research to construct baseline or "business as usual" projections of GHG emissions and carbon stocks/sequestration rates associated with woodlands on land owned or managed by Natural Resources Wales. The general purpose of this study has been to assess emissions and removals of carbon dioxide (CO_2) and emissions of other prominent GHGs, i.e. methane (CH_4) and nitrous oxide (N_2O), associated with woodlands on land owned or managed by Natural Resources Wales, including the impacts of management activities.

GHG emissions included in assessment

As far as possible, this study has aimed to assess all relevant carbon sequestration and GHG emissions. However, some non-CO_2 GHG emissions have been excluded. Specifically, the assessment includes contributions to GHG emissions and removals (carbon sequestration) due to:

- CO_2 emissions and removals due to carbon stock changes in the trees, litter and soil of NRW woodlands and harvested wood products (HWP)
- The main GHG emissions (CO_2, CH_4 and N_2O) arising from woodland operations (tree establishment, woodland management and harvesting).

The system boundary does *not* include contributions to GHG emissions due to:

- CH_4 and N_2O emissions from woodland soils (particularly organic soils)
- GHG emissions arising from timber transport from the woodland
- GHG emissions arising from the processing of harvested wood and the manufacture and installation of finished wood products

- GHG emissions potentially avoided from using wood products (including woodfuel) in place of alternative products (possibly supplied or manufactured using other types of materials or fuels, including fossil fuel sources).

The scope of CO_2 emissions and sequestration and non-CO_2 emissions covered in this study is consistent with current UK GHG inventories (see ensuing discussion of the system boundary adopted in this study).

System boundary for this study

A critical first step involves defining the goal and scope of the study, and in particular defining the object or system being studied, and the system's "function". Intimately associated with the definition of the system and its function, is the delineation of an appropriate "system boundary".

Spatial system boundary

The spatial system boundary encompasses a set of "pools" or "reservoirs" of carbon in the biomass of trees, in deadwood and litter and in soil associated with NRW woodlands. Essentially, the spatial system boundary encompasses carbon transfers and GHG emissions/removals occurring within woodlands, involving all activities from the "forest nursery" to "forest gate". Generally, processes and activities that occur outside woodlands after trees are harvested are not within the system boundary. Amongst the relevant excluded activities are timber transport and the processing and use of harvested wood and its subsequent disposal. However, the retention of carbon in harvested wood products after their extraction from woodlands is allowed for as part of the assessment.

The spatial system boundary is generally consistent with that adopted for the Land Use, Land-Use Change and Forestry (LULUCF) Sector referred to in national GHG inventories compiled and reported under the United Nations Framework Convention on Climate Change (UNFCCC). In a departure from UNFCCC conventions, GHG emissions from operations associated woodland management are also included as specified by NRW.

Temporal system boundary

The temporal system boundary for this assessment of GHG emissions and carbon stocks/sequestration rates was specified by NRW as from the year 2015 (effectively the base year for the assessment) to the year 2040 (the "time horizon" for this study).

Definition of baseline scenario

In order to model a projection of a baseline trajectory of GHG emissions associated with woodlands and their management, it is necessary to first define a "baseline scenario", which, in most circumstances is taken to be synonymous with a "business-as-usual" or "BAU" scenario.

In the context of this project, a BAU scenario for the development of woodlands owned or managed by NRW has been based on a number of important assumptions, as specified at a high level by NRW, specifically:

- The scenario modelled in this study is based on the composition of the NRW woodland estate as defined by data maintained in NRW's woodland management database
- The tree species composition and management prescriptions applied to NRW woodlands will be unchanged from the base year of 2015
- The scenario did not consider possible future activities such as land being taken out of commercial production for e.g. peatland restoration or renewable energy developments.

Whilst the above statement describes the broad assumptions made in the development of a BAU scenario for this study, considerable effort is required to translate these into detailed assumptions for the purposes of modelling. A significant assumption made in the modelling of the BAU scenario involved the adoption of a fixed NRW-scale annual target for wood volume production from NRW (commercial) woodlands over the period 2015 to 2040. Such a target is consistent with the current NRW Timber Marketing Plan of 850,000 m^3 per year. This NRW-scale annual target was disaggregated to provide consistent targets for annual wood volume production from five geographical operational regions within NRW woodlands (Northeast, Northwest, Mid, Southeast, Southwest).

Modelling approach

The modelling undertaken in this study has involved the application of the Forest Research CARBINE forest sector carbon accounting model. The projections for GHG emissions and carbon stocks/sequestration rates associated with NRW woodlands simulated the carbon dynamics of vegetation, litter, soil and harvested wood associated with woodland systems. The GHG emissions associated with relevant operations carried out in woodlands were also estimated.

The modelling approach involved a constrained non-linear optimisation procedure, which reconciled the available data on the composition and management of NRW woodlands with assumptions defining the BAU scenario to produce the inputs required for the CARBINE model.

Main results of study

Results for woodland carbon stocks

For the base year of this study of 2015, carbon stocks in the trees, deadwood/litter and soils of NRW woodlands and in wood products supplied from NRW woodlands are estimated at 26.2 MtC (million tonnes carbon).

About 50% of the carbon stocks are in woodland soils, 30% in trees, 15% in harvested wood products with the remaining 5% in deadwood and litter.

Under a business as usual scenario for woodland composition and management, as defined in this study, by the time horizon for this study of 2040, the total carbon stocks in NRW woodlands are predicted to increase to 29.5 MtC, an increase of 2.9 MtC compared with the base year of 2015.

About 64% of the projected increase in woodland carbon stocks is due to the accumulation of carbon stocks in trees, with about 28% contributed by accumulating soil carbon stocks, whilst deadwood/litter and harvested wood products contribute approximately 1% and 7% respectively.

Per-hectare results for total carbon stocks and total carbon stock changes in NRW woodlands, as predicted by this study, are consistent with estimates of carbon stocks as reported in a selection of scientific literature, either of relevance to Wales or the UK, or based on a meta-analysis of available results.

Different regions of NRW woodlands (commercial woodlands in the Northeast, Northwest, Mid, Southeast, Southwest operational regions and non-commercial woodlands) make variable contributions to total carbon stocks. Typically, these variations are simply related to differences in the total area of woodlands in each region. However, non-commercial woodlands make a disproportionately large contribution to total carbon stocks, compared with the contributions of commercial woodlands. This reflects higher per-hectare carbon stocks predicted for non-commercial woodlands, due to the assumptions that a large part of the non-commercial woodland area will be composed of mature trees, and that harvesting activities and natural disturbances in non-commercial woodlands have been, and will be, quite limited.

Results for GHG emissions and removals

When considering the results produced by this study for GHG emissions and removals associated with NRW woodlands, it should be noted that:

- Typically, results for GHG emissions/removals are expressed in units of CO_2-eq. (carbon dioxide equivalent)
- Negative results indicate net GHG removals (i.e. net carbon sequestration); positive results indicate net GHG emissions.

Under a business as usual scenario for woodland composition and management, the projected annualised total net GHG removals (carbon sequestration) for all NRW woodlands over the period 2015 to 2040 are predicted to be -409.5 ktCO_2-eq. yr^{-1} (thousand tonnes carbon dioxide equivalent per year; see Table 1). This is the net result of:

- A projected annualised total net carbon sink in NRW woodlands (trees, deadwood/litter and soils) of -394.2 $ktCO_2$-eq. yr^{-1}
- Projected net carbon sequestration in harvested wood products supplied from NRW woodlands of -28.0 $ktCO_2$-eq. yr^{-1}
- Projected GHG emissions due to woodland operations in NRW woodlands of +12.7 $ktCO_2$-eq. yr^{-1}.

Table 1 Summary of estimated annualised GHG emissions and removals in NRW woodlands for the period 2015-2040

Contribution	GHG emissions (+)/removals (-) ($ktCO_2$–eq. yr^{-1})
Soil	-119.7
Litter	-4.4
Trees	-270.1
Harvested wood products (HWP)	-28.0
Total (no HWP)	**-394.2**
Total (with HWP)	**-422.2**
Woodland operations GHG emissions	+12.7
Total (with woodland operations)	**-409.5**

Per-hectare results for total net GHG removals associated with trees in NRW woodlands, as predicted by this study, are consistent with previously published estimates for woodland trees in Great Britain.

The projected total net GHG removals predicted for NRW woodlands are reasonably stable between 2015 and 2040, increasing by only 5% over this period. However, the apparent stability of total net GHG removals between 2015 and 2040 masks some quite significant trends in the contributions made by individual carbon pools (see Figure 1).

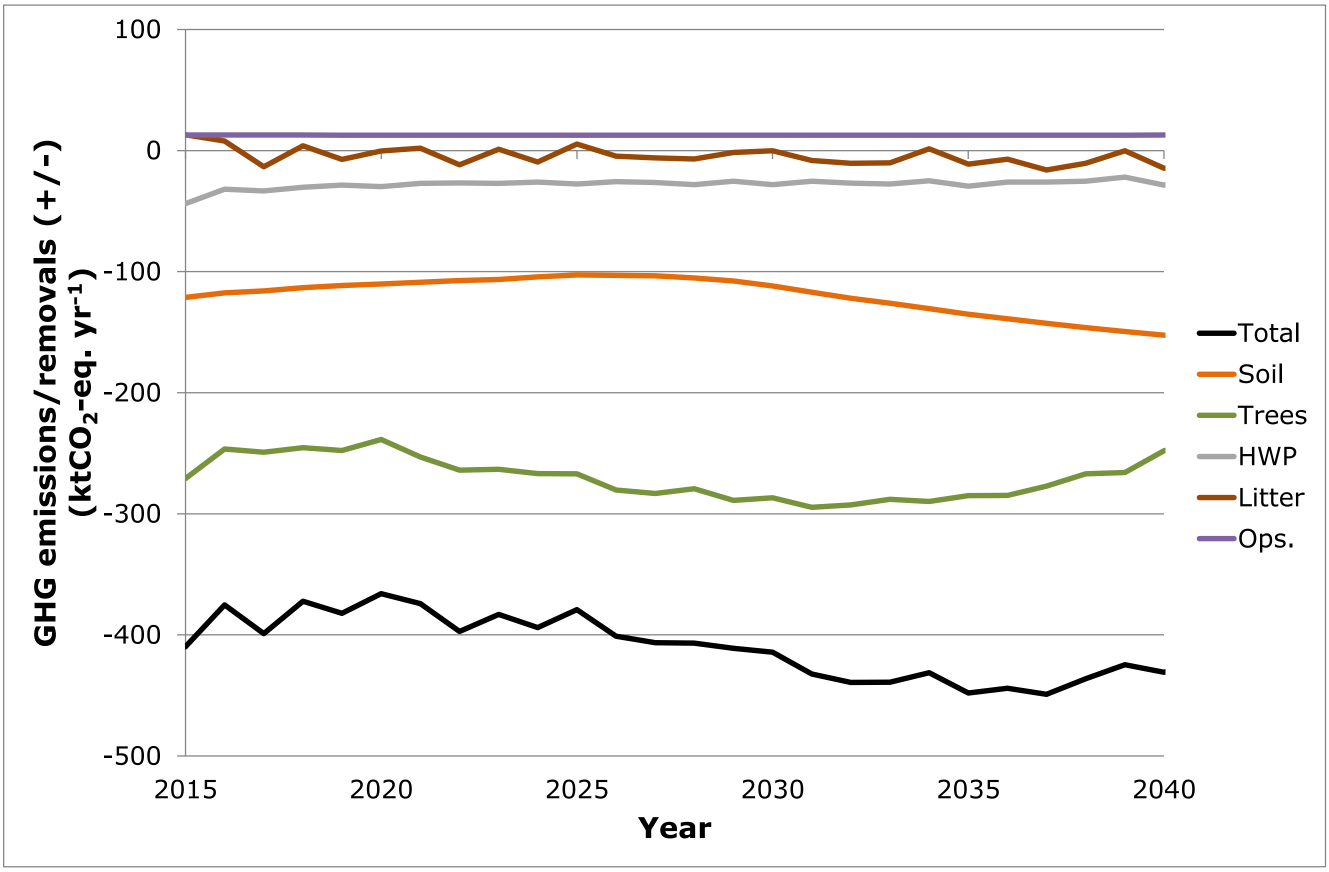

Figure 1. Projected development of net GHG emissions/removals for all NRW woodlands.

Regional variations in net GHG removals

Different regions of NRW woodlands (commercial woodlands in the Northeast, Northwest, Mid, Southeast, Southwest regions and non-commercial woodlands) make variable contributions to total net GHG removals between 2015 and 2040. Very broadly, these variations are simply related to differences in the total area of woodlands in each region. However, there is some complexity in the trends of relative contributions from regions:

- The rates of net GHG removals due to commercial woodlands in the Northeast, Northwest, Mid and Southeast regions are predicted to rise over the period from 2015 to 2040, being most marked for the Mid operational region
- In contrast to other regions, the rate of net GHG removals due to commercial woodlands in the Southwest region is predicted to decline progressively and significantly over the period from 2015 to 2040
- Projected net GHG removals are smallest for the non-commercial NRW woodlands and removals decrease gradually over the period from 2015 to 2040.

Causes of regional trends in woodland GHG removals

An investigation of the main causes of the trends exhibited in projections of net GHG removals for individual regions of NRW woodlands over the period 2015-2040 has identified, with reasonable confidence, a number of driving factors:

- The proportion of broadleaved woodland in the region (these woodlands are predicted to make a significant contribution to rate of net GHG removals but may decline over time)
- The proportions of coniferous and broadleaved woodland in the region composed of trees aged younger than 40 years (these woodlands are predicted to make a significant contribution to rate of net GHG removals that may rise over time)
- The proportion of coniferous woodland in the region either managed on the basis of "minimum intervention", not involving wood production, or managed based on long-term retention of the growing stock (these woodlands are predicted to make a significant contribution to rate of net GHG removals but declining gradually over time)
- The proportion of coniferous woodlands managed for wood production using either shelterwood or selection systems (these woodlands are predicted to make a moderate contribution to rate of net GHG removals, declining over time)
- The proportion of coniferous woodlands managed for wood production with clearfelling (these woodlands are predicted to make a significant contribution to rate of net GHG removals but declining significantly over time).

Possible options for management of NRW woodlands for climate change mitigation

For simplicity, the various woodland management activities can be classified into the three contrasting generic options of:

1. Woodland carbon reserve management – this option is characterised by minimal intervention in woodlands, with a gradual long-term but finite increase in carbon stocks
2. Substitution management – under this option, there is an emphasis on the production of good quality stemwood for use in product displacement along with the extraction of woody biomass for use as woodfuel.
3. Selective intervention carbon management – this option is similar to carbon reserve management but, in addition, there is low-level harvesting of certain trees to clearly defined specifications in order to supply high-value niche applications.

A possible approach to developing a strategy or policy for managing existing NRW woodlands to support the objective of climate change mitigation could involve assigning specific areas of NRW woodlands to be managed according to one of these three broad options. Detailed management of the classified woodland areas could then be determined as part of the woodland planning process, referring to appropriate possible more detailed measures.

As a general guide, selective intervention and carbon reserve management will usually result in higher long-term carbon stocks within a given woodland ecosystem but this will be a one-off increase in carbon stocks which takes place over a finite period. On the other hand, substitution management and, to a lesser extent, selective intervention carbon management have the potential to deliver long-term reductions in GHG emissions due to woodland management, through the long-term provision of additional supplies of timber and woodfuel.

It is possible to identify certain specific approaches and measures aimed at mitigating GHG emissions through woodland management that could be of particular relevance in the context of the management of the NRW estate:

- Increasing the area of broadleaves managed as woodland carbon reserves
- Identifying a mix of management approaches in coniferous woodland areas managed on low impact silvicultural systems (shelterwood and selection systems versus reserve/retention systems)
- Actively restocking clearfelled stands to achieve changes in the species composition of NRW woodlands to meet climate change mitigation objectives, notably restocking unimproved Sitka spruce with genetically improved Sitka spruce trees (i.e. Sitka spruce trees that have been bred selectively for high productivity)
- Ensuring full restocking of clearfelled woodlands occurs as quickly as possible and the establishment of successor woodlands is achieved consistently across the NRW estate
- Out of all the options, it is important not to forget the possibility of creating new woodland areas on the land owned or managed by NRW, where such opportunities may exist.

Main recommendations of this study

- The possibility could be explored of adopting a broad strategic approach to the management of NRW woodlands to support climate change mitigation.
- Further evaluation could be made of the specific approaches and measures identified for woodland management on the NRW estate to support climate change mitigation.

NRW could develop a series of scenarios involving changes to woodland management potentially contributing towards climate change mitigation goals. These scenarios could be evaluated through comparison with the baseline scenario developed in this project, through extension of the modelling approach developed in this study.

1. Background to this work

Natural Resources Wales' purpose is to ensure that the environment and natural resources of Wales are sustainably maintained, enhanced and used, now and in the future.

The Carbon Positive Project is evaluating NRW's net carbon status, accounting for both greenhouse gas (GHG) emissions and carbon sequestration across the whole of NRW's estate. The project has identified mitigation opportunities to reduce the carbon impact of the organisation and deliver projects to demonstrate these measures. The project will also put in place a plan for future implementation of mitigation measures, embedding carbon management across the organisation and facilitating NRW becoming an exemplar in carbon management. Through sharing our approach and experiences, the Carbon Positive Project will help disseminate best practice in carbon management across the Welsh public sector.

NRW engaged Forest Research to provide the best available estimates of GHG emissions and carbon stocks/sequestration for the woodland habitats on the NRW-owned and managed estate, through the application of a state of the art forest carbon accounting model, CARBINE. The work was to provide an accurate projection of the future development of the GHG emissions and carbon stocks/sequestration rates of habitats on the NRW estate, as part of the NRW net carbon status calculation conducted as part of the Carbon Positive Project.

2. Purpose of this report and study

This report describes the modelling undertaken by Forest Research to construct baseline or "business as usual" projections of GHG emissions and carbon stocks/sequestration rates associated with woodlands on land owned or managed by Natural Resources Wales.

The general purpose of this study has been to assess emissions and removals of carbon dioxide (CO_2) and emissions of other prominent GHGs, i.e. methane (CH_4) and nitrous oxide (N_2O), associated with woodlands on land owned or managed by Natural Resources Wales, including the impacts of management activities. However, certain contributions to GHG emissions have been excluded in this assessment, as indicated in the discussion in Section 3 of this report, in particular in Sections 3.1.1 to 3.1.6.

2.1. Combined impacts of different greenhouse gases

In this report, to enable comparison, and to permit an appreciation of the combined impact of different GHGs, emissions of CH_4 and N_2O are expressed in units of equivalent CO_2. This is achieved by referring to quoted values of global warming potentials (GWPs) for these GHGs. The values referred to in this report for the GWP for the key GHGs are taken as 1 for CO_2, 25 for CH_4 and 298 for N_2O, hence 1 tonne of CH_4 equals 25 tonnes CO_2-equivalent (25 tCO_2-eq.). These GWPs are based on modelling the relative warming potential of CO_2, CH_4 and N_2O over a 100-year time horizon, as reported in IPCC (2007). It should be noted that these GWP values are being adopted for use in the calculation of GHG inventories reported to the UNFCCC and under the Kyoto Protocol, replacing earlier GWP values reported in IPCC (1996). The IPCC has further updated the values for GWPs in its Fifth Assessment Report, but these have not yet been adopted for use in the calculation of GHG inventories. Other studies referred to in this report may use different values to those adopted here for the GWPs for CH_4 and N_2O.

The report makes frequent reference to stocks of carbon in vegetation, litter and soil, and to carbon sequestration. A stock of 1 tonne carbon in vegetation, litter and/or soil is equivalent to 44/12 = 3.67 tonnes of sequestered CO_2.

2.2. Structure of this report

The principles and methods adopted in the modelling for this study are described in Sections 3 to 6 of this report. First, Section 3 describes how a system boundary was defined for this study, and the significance of the system boundary for determining the scope of GHG emissions and carbon stocks/sequestration covered in this assessment. This is followed in Section 4 by an explanation of what is generally meant by a "baseline scenario" and the high-level assumptions made in developing such a scenario for the purposes of this study. Section 5 then provides an overview of the Forest Research CARBINE forest carbon accounting model, which is of central relevance to the modelling work undertaken for this study. The approach taken to applying the CARBINE model in this study, including the sources of data and qualitative information referred to in modelling the baseline scenario for this study, are discussed in Section 6.

Section 7 presents and interprets the main results of this study.

2.3. Relevant background information

The development of robust measures aimed at climate change mitigation rely on an understanding of the fundamental science of the role of woodlands in the carbon cycle and wider GHG emissions, and the potential impacts of interventions in woodland management. It should be noted that thorough background discussions of concepts relevant to these issues, including the assessment of scenarios involving actions to mitigate climate change, have been provided in the reports of Morison *et al*. (2012), Section 3 of Matthews *et al*. (2014a) and Sections 3 and 4 of Matthews *et al*. (2014b).

3. System boundary for this study

As explained in detail in Section 4 of Matthews *et al*. (2014a), a critical first step in an assessment such as undertaken here involves defining the goal and scope of the study, and in particular defining the object or system being studied, and the system's "function". Intimately associated with the definition of the system and its function, is the delineation of an appropriate "system boundary". The identity of a system can be established by a system boundary, which is an imaginary line drawn around all the activities that are relevant to the analysis being conducted. It should be noted that, whilst it is common for the system boundary to be considered a *spatial* concept, it also has a *temporal* dimension which is of equal importance. The specific spatial and temporal location of a system boundary is important because it subsequently defines what is included, and, therefore, what is excluded from the system and its analysis.

3.1. Spatial system boundary

Figure 3.1 illustrates what is effectively the spatial system boundary adopted for this particular study of GHG emissions and carbon stocks/sequestration rates associated with woodlands on land owned or managed by Natural Resources Wales.

As will be seen from the figure, principally, the system boundary encompasses a set "pools" or "reservoirs" of carbon in the biomass of trees, in deadwood and litter and in soil associated with NRW woodlands. In the context of this study, in general, the term "NRW woodlands" refers collectively to commercially-managed woodlands and non-commercial woodlands owned or managed by Natural Resources Wales. Commercial woodlands are those woodland areas owned or managed by Natural Resources Wales where timber production is a significant objective, whilst non-commercial woodlands consist of woodland areas primarily on protected sites. In addition to including the major pools of carbon physically in woodlands, the system boundary also encompasses carbon retained in the biomass of harvested wood products after their extraction from the woodlands.

Transfers of carbon between the pools of carbon included in the assessment of GHG the emissions/removals associated with NRW woodlands are shown as arrows crossing the system boundary. Essentially, the spatial system boundary encompasses carbon transfers and GHG emissions/removals occurring within woodlands, involving all activities from the "forest nursery" to "forest gate". As such, activities within the system boundary include:

- Plant production in nurseries in support of woodland regeneration
- Ground preparation for planting
- Weed control
- Tree protection
- Tree growth
- Tree harvesting and extraction

- Consequent carbon dynamics of other woodland carbon pools (deadwood, litter and soil).

Generally, processes and activities that occur outside woodlands after trees are harvested are not within the system boundary. Amongst the relevant excluded activities are timber transport and the processing and use of harvested wood and its subsequent disposal. However, as already noted above, the retention of carbon in harvested wood products after their extraction from woodlands is allowed for as part of the assessment (see Section 3.1.4).

The system boundary is generally consistent with that adopted for the Land Use, Land-Use Change and Forestry (LULUCF) Sector referred to in national GHG inventories compiled and reported under the United Nations Framework Convention on Climate Change (UNFCCC, 1992). In a departure from UNFCCC conventions, GHG emissions from operations associated woodland management are also included (see Section 3.1.5) as specified by NRW. However, as this assessment confirms, the contributions to GHG emissions from these activities is relatively small.

When interpreting results for GHG emissions and carbon stocks/sequestration rates as assessed in this study, it is important to note a number of detailed points relating to the spatial system boundary, as described below, several of which are related to the current scope of the CARBINE forest carbon accounting model (see subsequent discussion in Section 5).

3.1.1. Non-woodland vegetation

Inputs to soil carbon from non-woodland vegetation (e.g. existing prior to afforestation) are represented in the CARBINE model as these can be significant. However, biomass of non-woodland vegetation is not represented in the current version of CARBINE. Generally contributions from non-woodland biomass (e.g. grass) will be small compared with woodland biomass. Contributions from non-woodland biomass may be included by making supplementary calculations if required. Non-woodland vegetation is of limited relevance to the NRW woodland estate which has been established as woodland for some time. Hence, the impacts of transitions of land use from non-woodland to woodland, particularly with regard to non-woodland biomass, have occurred in the past.

3.1.2. Soil

Fluxes of methane (CH_4) and nitrous oxide (N_2O) related to woodland soils are not represented in the current version of CARBINE. This is also more generally the case in current UK national GHG inventories. This is an area for improvement of UK GHG inventories but currently is not identified as a high priority.

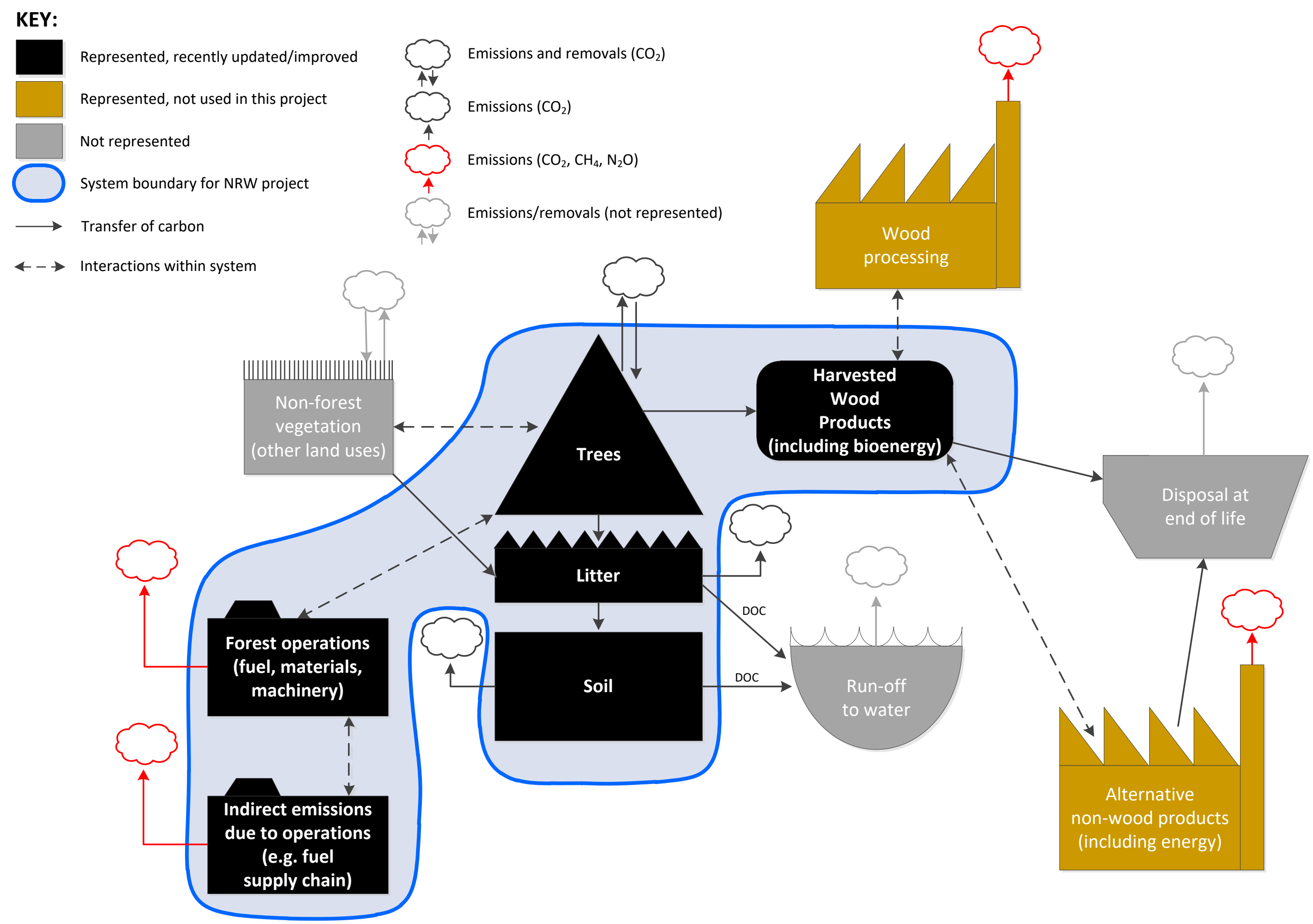

Figure 3.1. Illustration of system boundary adopted in this study.

3.1.3. Runoff to water

Transfers of dissolved organic carbon (DOC) from litter and soil to water are represented as a transfer of carbon across the system boundary, i.e. in effect as an emission of CO_2 from the system. Transfers of particulate organic carbon (POC) from litter and soil to water are not represented in the current version of CARBINE. Current IPCC Guidance suggests that fluxes due to POC are uncertain but likely to be negligible, although this is noted in IPCC Guidance as an area for methodological improvement.

3.1.4. Harvested wood products

Carbon stocks retained in harvested wood products are represented within the system boundary. Losses of carbon due to the disposal of finished wood products are represented as a transfer of carbon across the system boundary, i.e. in effect as an emission of carbon dioxide (CO_2) from the system. Possible subsequent sequestration of carbon in harvested wood products disposed to landfill and possible subsequent related GHG emissions are not represented.

3.1.5. Woodland operations and related GHG emissions

The GHG emissions associated with a wide range of woodland operations are included in the assessment, allowing for relevant emissions of CO_2, CH_4 and N_2O. Further details are provided in Appendix 1 to this report.

3.1.6. Wood processing and alternative non-wood products

GHG emissions related to the processing of wood into finished products, also the potential impacts on GHG emissions due to displacing non-wood products with wood products, are represented in the CARBINE model but relevant results have not been estimated for this project, which are outside the system boundary as defined in Figure 3.1. The relevant GHG emissions factors referred to in the CARBINE model are now old and require updating. Hence, the use of these results in this project was not recommended. Relevant GHG emissions and impacts may be estimated by making supplementary calculations based on more up to date information (see for example Section 5 of Matthews *et al*., 2015).

3.2. Temporal system boundary

The temporal system boundary for this assessment of GHG emissions and carbon stocks/sequestration rates was specified by NRW as from the year 2015 (effectively the base year for the assessment) to the year 2040 (the “time horizon” for this study).

The time horizon of the study was set at 2040 to ensure that the projections made could be based on realistic assumptions. In particular, it was considered by NRW specialists that likely levels of wood production (hence woodland management related to these production levels) could be predicted accurately for the next 5 to 10 years, and with reasonable confidence over a 25-year period. However, predicting likely levels of wood production becomes more difficult beyond this period. One key reason for this is that, after 25 years, a significant proportion of the existing growing stock of NRW woodlands will have been felled and restocked, and there is less certainty over the composition and management of the restocked growing stock.

4. Definition of baseline scenario

The potential contributions of possible climate change mitigation measures need to be assessed in terms of their "additionality" to a baseline scenario. Specifically, Matthews *et al*. (2014b; Appendix 1) explain that the term "additional" or "additionality" refers to the positive [or potentially negative] net benefits, in terms of climate change mitigation, directly attributable to a mitigation activity or project [or mitigation measure]. The concept generally refers to net GHG emissions reductions over and above that which would have occurred anyway in the absence of a given mitigation activity or project.

In order to estimate the benefits of a climate change mitigation measure in terms of "additional" greenhouse gas emissions reductions, it is necessary to compare the levels of GHG emissions and removals estimated for the mitigation activity with those estimated assuming the mitigation activity is not carried out. The reference estimate or trajectory referred to in such a comparison is known as a "baseline". Hence, in order to model a projection of a baseline trajectory of GHG emissions associated with woodlands and their management, it is necessary to first define a "baseline scenario", which, in most circumstances is taken to be synonymous with a "business-as-usual" or "BAU" scenario.

Matthews *et al*. (2014b; Appendix 1) define a BAU scenario as a scenario describing specified activities, services and processes, and associated flows, e.g. of energy and GHG emissions, intended to represent the current and future situation in the absence of policy interventions other than those already being implemented.

In the context of this project, a BAU scenario for the development of woodlands owned or managed by NRW has been based on a number of important assumptions, as specified at a high level by NRW, specifically:

- The scenario modelled in this study is based on the composition of the NRW woodland estate as defined in the sub-compartment database as of the 31st March 2015
- Projected future timber production, and associated carbon stocks, carbon stock changes and GHG emissions associated with woodlands reflect the broad assumptions that, in general, the tree species composition and management prescriptions applied to NRW woodlands will be unchanged from the base year of the temporal system boundary (i.e. 2015, see Section 3.2)

- The scenario did not consider possible future activities involving land being taken out of commercial production for e.g. peatland restoration or renewable energy developments.

Whilst the above statement describes the broad assumptions made in the development of a BAU scenario for this study, considerable effort is required to translate these into detailed assumptions for the purposes of modelling. In some cases, it was possible to refer to existing data sources as a basis for developing these assumptions, for example, information on the existing tree species composition of NRW woodlands could be obtained from databases. In other cases, it was necessary to obtain qualitative information from NRW specialists and determine assumptions in conjunction with the modelling undertaken for this study. In particular, it was very important to be clear what should be considered to be the "existing management prescriptions" applied to woodland areas, and exactly what leaving these prescriptions "unchanged" would entail.

Section 6 of this report discusses how the detailed assumptions underlying the definition of the BAU scenario were developed, and the sources of information referred to for this purpose. Particular note should be made of the caveats attached to the definition of the BAU scenario as adopted in this study (see Section 6.2.3).

5. The CARBINE model

The modelling undertaken in this study has involved the application of the Forest Research CARBINE forest sector carbon accounting model. The projections for GHG emissions and carbon stocks/sequestration rates associated with NRW woodlands simulated the carbon dynamics of vegetation, litter, soil and harvested wood associated with woodland systems. The GHG emissions associated with relevant operations carried out in woodlands were also estimated.

An outline description of the CARBINE model is provided below. As an aid to understanding how CARBINE works, example calculations are included in Appendix 2. Reference may also be made to examples included in Matthews *et al*. (2014ab).

The CARBINE model was first developed by the Research Division of the Forestry Commission (now Forest Research) in 1988 (Thompson and Matthews, 1989). Essentially it is an analytical model of the exchanges of carbon that take place between the atmosphere, woodland ecosystems (trees, deadwood, litter and soil) and the wider forestry sector (harvested wood products) as a result of tree growth, mortality and harvesting (Thompson and Matthews, 1989; Matthews, 1991; Morison *et al.*, 2012). Other land uses are represented in CARBINE "at the margin", i.e. to the extent necessary to represent land use transformations involving woodlands such as afforestation of cropland or grassland or conversion of woodland to other land uses (deforestation). CARBINE also represents other economic sectors "at the margin", notably the Energy and Construction sectors, in order to estimate the impacts of changes in patterns of timber harvesting and utilisation on consumption of fossil fuels and alternative materials, and consequent changes in GHG emissions (Matthews, 1994, 1996). However, this aspect of the functionality of the CARBINE model is in need of significant updating, to reflect improved information on GHG emissions factors available from recent research (e.g. Matthews *et al.*, 2015). Hence, the functionality of the CARBINE model addressing such cross-sectoral impacts on GHG emissions was not applied in this project.

CARBINE has common features of structure and functionality with other analytical forest sector and forest carbon accounting models, notably EFISCEN (Schelhaas *et al.*, 2007), C-Flow (Dewar, 1990, 1991; Cannell and Dewar, 1995), CO_2FIX (Mohren and Klein Goldewijk, 1990; Nabuurs, 1996; Mohren *et al.*, 1999), CBM-CFS3 (Kurz *et al.*, 2009), C-change (Beets *et al.*, 1999) and GORCAM (Marland and Schlamadinger, 1995, 1999; Schlamadinger and Marland, 1996). Studies comparing CARBINE and C-Flow (the other main forest carbon accounting model developed in the UK) revealed many similarities and consistencies in the functioning and results produced by the two models (Robertson *et al.*, 2003; Matthews *et al.*, 2014c).

Simulations produced by forest sector carbon accounting models such as CARBINE have an important role in evaluating the impact on carbon stocks and sequestration of different woodland management regimes involving harvesting. These models are also relevant to estimating carbon stocks in wood products for different geographical regions, and ultimately impacts due to the utilisation of woodfuel and wood products in place of fossil fuels and non-wood materials.

Initial versions of CARBINE produced per-hectare scale estimates of carbon exchanges associated with individual stands of trees (Thompson and Matthews, 1989; Matthews, 1994). Subsequently CARBINE was further developed into a national-scale scenario analysis tool and has been used to assess the impacts of current and alternative forestry practices on greenhouse gas balances in Great Britain and the United Kingdom (Matthews, 1991, 1996; Matthews and Broadmeadow, 2009). Recently CARBINE has been further developed for application to National GHG Inventory calculations for the UK LULUCF sector, taking over from the C-Flow model in 2013. The application of CARBINE has permitted a more complete and refined representation of Forest Land within the UK's LULUCF GHG Inventory. CARBINE has also been applied in an international context to provide forestry projections for many countries in support of discussions amongst parties to the UNFCCC.

In terms of documentation, the CARBINE model has been described and discussed in a number of papers (Thompson and Matthews, 1989; Matthews, 1991, 1994, 1996; Matthews and Broadmeadow, 2009; Morison *et al.*, 2012). The development and improvement of the model has been a significant exercise covering many years and the publication of a complete description of CARBINE is planned.

A schematic diagram of the structure of the CARBINE model is given in Figure 5.1.

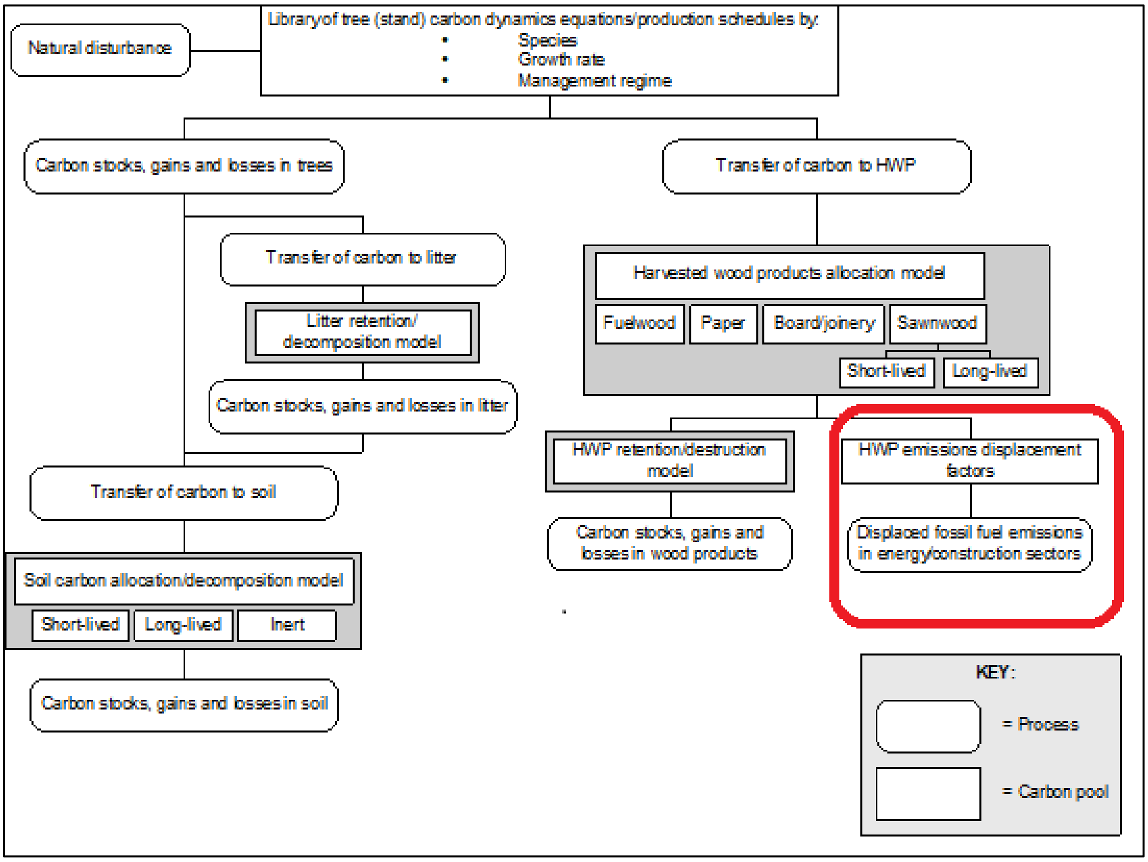

Figure 5.1. Diagram illustrating the scope, structure and function of the CARBINE model. Note that the functionality relevant to assessing GHG emissions due to wood processing and impacts in other economic sectors (highlighted by the red boundary in the diagram) was not applied in this project (see preceding discussion).

5.1. Tree growth, management and wood production

The main driving module of CARBINE consists of a set of computerised mathematical functions and algorithms describing the accumulation (and loss) of carbon in tree biomass of different woodland systems at the per-hectare scale. Different functions and algorithms are used to represent distinct woodland systems, defined in terms of:

- Tree species composition
- Tree growth rate (yield class)
- Management regime applied.

The tree species and growth rates represented are based on yield models originally produced by the British Forestry Commission (Edwards and Christie, 1981). The tree species covered include examples for coniferous species of spruces, pines, firs, larches, cedars, cypresses and all the major temperate and boreal broadleaf tree species. Growth rates in terms of mean annual increment of stem volume can be represented in the range from 2 m^3 ha^{-1} yr^{-1} up to 30 m^3 ha^{-1} yr^{-1}.

As already explained, the mathematical functions describing woodland development and levels of harvesting are based on standard models of forest growth and yield developed by the British Forestry Commission (Edwards and Christie, 1981). However, these are implemented in CARBINE as a dynamic yield model, known as M1 (Arcangeli and Matthews, unpublished model), which enables the representation of a wide range of management prescriptions (e.g. in terms of patterns of thinning and felling). Basic management regimes represented in the CARBINE model include:

- No thinning and no felling (i.e. effectively no management for production)
- No thinning with clearfelling on a specified rotation
- Thinning with clearfelling on a specified rotation
- "Continuous cover" silviculture (i.e. woodland management with harvesting based on thinning only, that also aims to always maintain tree cover on the land).

It is also possible to specify detailed rotations and levels of thinning, and changes in the management of woodland areas over time, involving transitions between the broad management regimes indicated above, and also adjustments to rotations and transitions in tree species and growth rates on restocking.

5.2. Tree biomass and carbon

In CARBINE, stem biomass is estimated by multiplying estimates of stem volume by a value for the basic density of wood for the relevant tree species, expressed as oven dry tonnes of mass per cubic metre of "green" timber volume (Lavers, 1983). Biomass estimates are converted to equivalent estimates of carbon by multiplying by a standard value for wood carbon content of 0.5 tC odt^{-1} (Matthews, 1993).

Carbon and biomass in tree roots, branches and foliage are estimated based on allometric relationships with stemwood (Matthews *et al.*, 2014c). These relationships are based on interpretation of summary estimates of root, branch, foliage and stem biomass using the Forestry Commission BSORT woodland stand biomass model (Matthews and Duckworth, 2005; Jenkins *et al.*, 2014).

5.3. Deadwood and litter carbon

CARBINE includes a sub-model for representing accumulation and loss of carbon in deadwood and litter. Inputs of carbon to deadwood and litter are related to the turnover rates of standing biomass of trees and also to rates of tree mortality.

Levels of tree mortality are represented implicitly in the standard Forestry Commission growth models, and explicit estimates are included in models for stands subject to no thinning, where mortality levels are high. Root and branch wood volume associated with dead trees is estimated in the same way as for living stemwood, by reference to allometric relationships.

The current representation of litter turnover and decomposition in the CARBINE model is based on the approach developed in the ForClim-D model (Perruchoud *et al.*, 1999; Liski *et al.*, 2002). The turnover of litter is assumed to produce fermenting organic material which is incorporated into the soil.

5.4. Soil carbon

The representation of soil carbon dynamics in the CARBINE model has been developed principally by adapting the essential functionality of the ECOSSE soil carbon model (Smith *et al.*, 2010, 2011). The soil carbon sub-model also incorporates features of the SPAW model (Saxton and Rawls, 2006; Saxton, 2009) to represent soil water characteristics relating to soil texture.

Inputs to soil carbon include:

- Direct organic material input to the soil (e.g. turnover of roots)
- Decomposing litter (fermenting organic material, see Section 5.3) transferred into the soil via mechanisms such as soil fauna activity
- Transfer of soluble organic carbon through drainage from one soil layer to the next
- Additional carbon input from the crop or trees in the form of root exudates.

These various inputs of carbon to the soil are represented through explicit linkages within CARBINE between the tree sub-model, deadwood and litter sub-model and the soil carbon sub-model.

As illustrated in Figure 5.2, the soil carbon sub-model represents a soil profile consisting of a number of fixed-depth soil layers. Within each soil layer, components of organic carbon are represented according to the system adopted in the RothC (Coleman and Jenkinson, 2008) and ECOSSE (Smith *et al.*, 2010, 2011) soil carbon models. These components consist of five sub-pools of organic matter:

- Resistant Plant Material (RPM)
- Decomposable Plant Material (DPM)
- Humus (HUM)
- Biological (BIO)
- Inert material.

Additional carbon in the form of Dissolved Organic Carbon (DOC) is also represented.

The soil carbon model represents exchanges of carbon between these sub-pools and the accumulation and loss of carbon from the soil. For the purposes of this study, results for soil carbon stocks were reported for a soil depth of 1 metre.

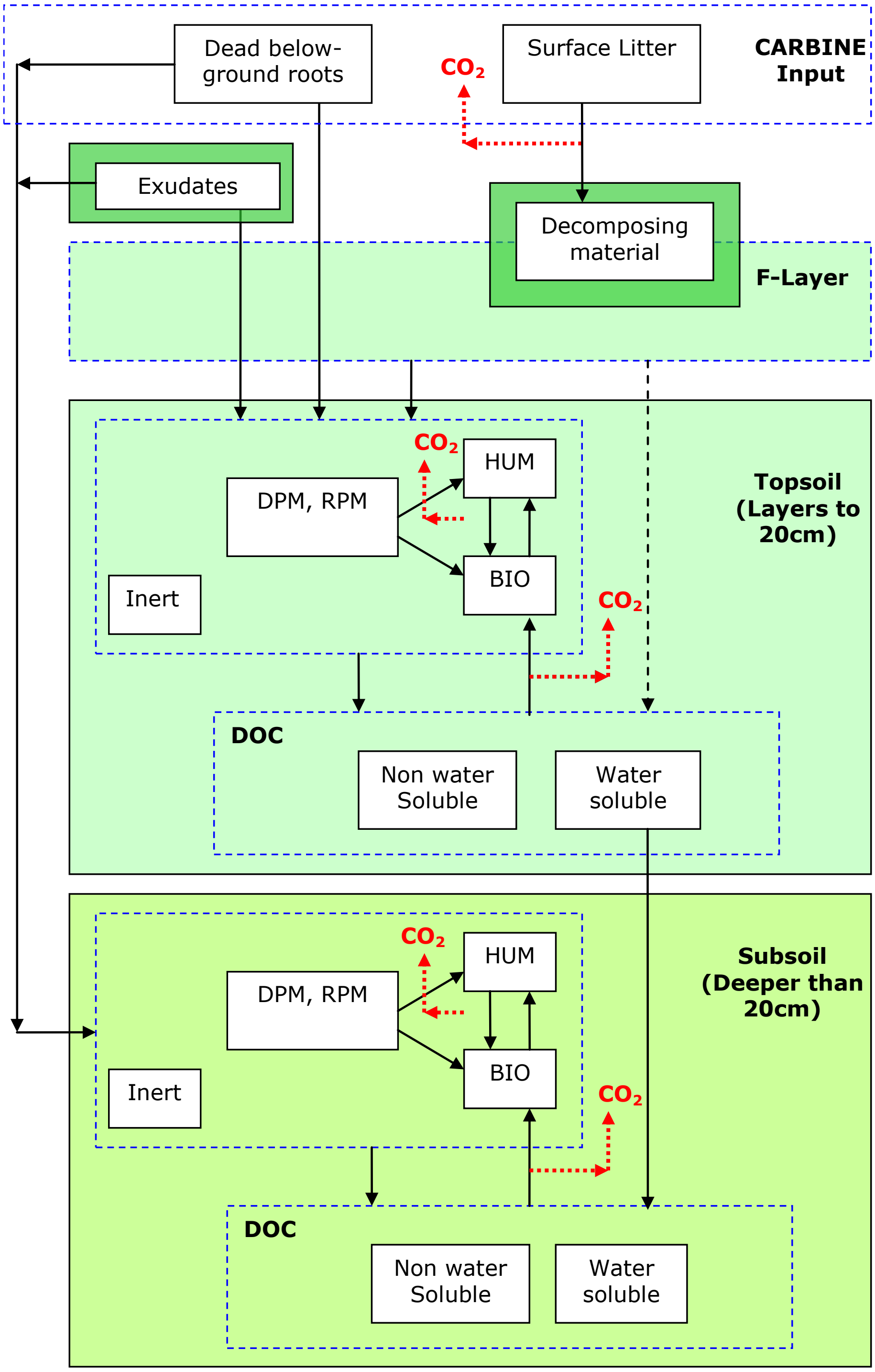

Figure 5.2. Representation of soil layers in soil carbon sub-model, illustrated by an example based on two soil layers.

5.5. Carbon in harvested wood products

The CARBINE model includes a sophisticated representation of the fate of woodland biomass and carbon following harvesting and conversion into useful wood products, including bioenergy. The general approach is illustrated by Figure 5.3, which shows the detailed allocation of harvested wood to litter in the woodland and to a range of different primary wood products.

The first step involves an initial allocation to harvesting residues left as litter in the woodland and to three "raw" stemwood categories of "bark", "small Roundwood" and "sawlogs". The proportion of stemwood allocated to litter is determined by an allocation coefficient, which is set to a standard value of 10% (see for example Forestry Commission, 2015. The allocation of the remaining stem material to bark, small roundwood and sawlogs (otherwise known as a product assortment) is also determined by allocation coefficients which depend on the size and shape of the harvested trees. In turn, tree size and shape depend on many factors but notably tree species, growth rate and how the trees have been managed (Matthews and Mackie, 2006). The specific definitions used for small roundwood and sawlogs also influence these allocations.

In the CARBINE model, coniferous (softwood) sawlogs are defined as (individually or collectively) taking up the maximum available length in stemwood (as opposed to taking a specified fixed length), up to a minimum top diameter of 18 cm over bark, but with a minimum length constraint of 1.3 m, excluding that portion of stemwood allocated to litter. Broadleaf (hardwood) sawlogs are defined as (individually or collectively) taking up the maximum available length in stemwood (as opposed to taking a specified fixed length), up to a minimum top diameter of 24 cm over bark, but with a minimum length constraint of 1.3 m, excluding that portion of stemwood allocated to litter. The more conservative specification of sawlogs adopted for broadleaves compared to conifers reflects differences in the utilisation of the two broad types of timber, but also allows for the occurrence of significant branching and forking of tree stems in broadleaves (generally higher up the stem and at smaller top diameters), which limit the suitability of such material for utilisation as sawlogs.

Small roundwood is defined as the remaining portion of stem material (excluding any portion allocated to litter) to a minimum top diameter of 7 cm over bark. By convention in the forest industry, sawlog volume (or biomass or carbon) is expressed as an under-bark quantity, whilst small roundwood is expressed as an over-bark quantity (i.e. including any associated bark). In CARBINE, quantities of harvested sawlogs and small roundwood are both calculated on an under-bark basis because this approach is more appropriate for the methodology used in the model for allocation of harvested carbon to raw and ultimately primary wood products. The calculation of the bark, small roundwood and sawlog allocation coefficients is based on tables given in Matthews and Mackie (2006) and Edwards and Christie (1981).

A further set of allocation coefficients is used to determine how branchwood, small roundwood, sawlogs and bark are used for different primary products, as shown in Figure 5.3. These allocation coefficients can be specified for different tree species and are user-definable, to enable patterns of wood use relevant for particular woodland types and scenarios to be represented. It is also possible to specify changes and trends in the allocation coefficients over time, for example to represent the progressive diversion of harvested wood from use for one type of product to another. A further refinement permits the setting of a threshold with respect to the mean size of harvested trees, which affects whether the trees are harvested as whole stems for use as bioenergy or converted to sawlogs and small roundwood and allocated to a range of primary products. Specifically, if the percentage of sawlog volume in stemwood of harvested trees falls below the threshold, then all stemwood and 90% of branchwood are allocated to use for bioenergy. If the percentage is above the threshold, then allocation to wood products follows the scheme in Figure 5.3. The setting of the threshold can be varied by tree species and over time, allowing this treatment of harvested trees to be represented dynamically. This facility has been included in CARBINE to allow the detailed representation of patterns in the use of harvested wood over the life cycle of a stand of trees (see Section 2.3 of Matthews *et al.*, 2014b). It also permits the representation of possible trends in the use of harvested wood, notably recent interest in the use of early thinnings primarily to supply bioenergy.

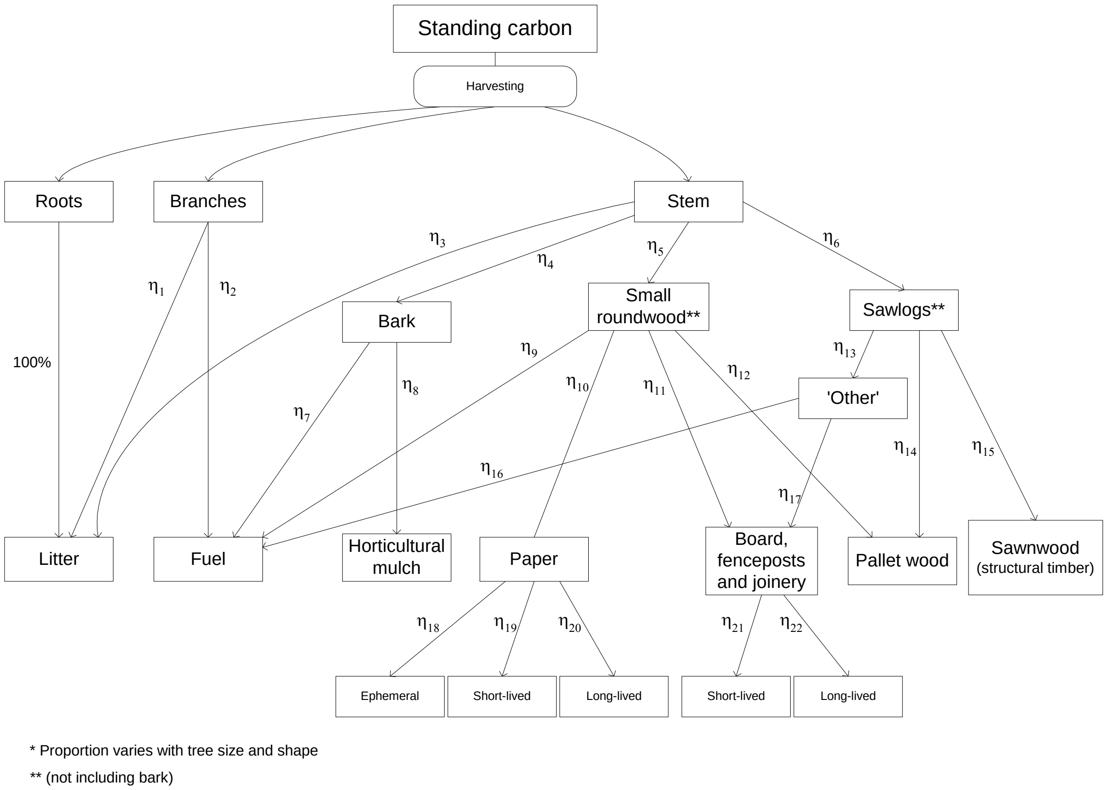

Figure 5.3. Schematic illustration of allocation of harvested wood material to primary wood products and litter as implemented in the standard version of CARBINE.

The CARBINE model also includes a sub-model to represent the retention of carbon in harvested wood products and the eventual release of carbon to the atmosphere when wood products are destroyed or decay. This is based on the methodology recommended in recent IPCC Good Practice Guidance (IPCC, 2006, 2014).

The IPCC Guidance identifies four general categories of semi-finished wood products:

1. Fuel
2. Paper
3. Wood-based panels (i.e. particleboard, medium density fibreboard, oriented strand board etc.)
4. Sawnwood (including fencing and pallets as well as structural wood).

If the annual levels of supply of these product categories are known, the carbon stocks in harvested wood products may be estimated by assuming the various products are disposed of or destroyed according to a first order process with an associated half-life for each product category. Fuel is considered to be oxidised instantaneously, whilst the half-lives recommended in IPCC Guidance for paper, wood-based panels and sawnwood are 2, 25 and 35 years respectively.

5.6. GHG emissions from woodland operations

The CARBINE model includes calculations for estimating the GHG emissions (CO_2, CH_4 and N_2O) resulting from a range of woodland operations such as growing of nursery stock, ground preparation, weed control and harvesting operations. Further details of the range of operations covered are provided in Appendix 1. The original calculation methodologies described in Morison *et al.* (2012) have been substantially revised and improved through reference to relevant life cycle assessment literature (see Appendix 1).

5.7. GHG emissions from processing wood and alternative materials

The CARBINE model includes simplistic calculations for estimating GHG emissions (in CO_2-equivalent units) arising from the processing of wood into finished products, and the GHG emissions potentially avoided through using wood products in place of products made from other materials. The current emissions factors referred to in these calculations (Morison *et al.*, 2012) are quite out of date and lack transparency. Consequently, GHG emissions from the processing of wood into finished products and the GHG emissions potentially avoided through using wood products in place of products made from other materials have not been included in this current assessment.

6. Modelling methodology

This section describes the modelling work undertaken in this study, to develop input datasets for the CARBINE model to enable the simulation of BAU projections of the GHG emissions and carbon stocks/sequestration rates of NRW woodlands. Section 6.1 explains the types of input data required to run a CARBINE simulation. The sources of data and information referred to in compiling the input data are then described in Section 6.2, whilst Section 6.3 describes the approach taken to developing the input data for the CARBINE model. The approach to running the CARBINE simulations is discussed in Section 6.4.

6.1. Input data required by CARBINE

To run the CARBINE model, it is necessary to provide input data on woodland areas broken into components consisting of:

- Area of woodland component (ha)
- Year in which the woodland component was originally planted or naturally regenerated
- Species composition of woodland component
- Potential productivity of woodland component (expressed as yield class)
- Soil type associated with the woodland component (essentially mineral or organic)
- Land use prior to planting or regeneration of woodland (essentially arable or grassland)
- Management prescription (details of any thinning, felling and rotation to be applied, including specifying how these details may change over time)
- Specification for how any harvested wood is used (vectors of allocation coefficients and thresholds).

6.2. Sources of data and information

Table 6.1 summarises the essential data and information sources that were referred to in order to develop simulations for NRW woodlands based on the application of the CARBINE model. Essentially, data on woodland composition and management came from three sources:

1. For woodland areas under commercial management, information was obtained from the Forester GIS database (as of 31st March 2015); these data are part of the basis of existing Forest Design Plans and future Forest Resource Plans.
2. Additionally for woodland areas under commercial management, supplementary quantitative and qualitative information was supplied by NRW (see Section 6.2.3)

3 For woodland areas identified for their scientific and conservation value and not under commercial management, supplementary qualitative information was supplied by NRW (see Appendix 3).

It is important to note that some assumptions about the management of woodland areas were refined as part of subsequent interpretation and modelling (see Sections 6.2.2 to 6.2.4).

Table 6.1 Summary of data sources referred to in developing inputs to the CARBINE model

<table>
<tr><th>Input data</th><th>Source</th></tr>
<tr><td>Area of woodland component(s)</td><td rowspan="4">For commercial woodlands, all four data items were obtained from Forester GIS database.

Business rules for handling missing values of yield class (including yield class values of zero) were provided by the NRW project team (see Section 6.2.2).

For non-commercial woodlands, the area was calculated by NRW based on all woodland areas reported in the National Forest Inventory falling within the boundaries of the NRW-managed estate, excluding areas of woodland represented in the Forester GIS database as at 31st March 2015. A qualitative description the composition of these woodlands was supplied by NRW reserve managers through the project team (see Appendix 3).</td></tr>
<tr><td>Year in which the woodland component was planted or naturally regenerated</td></tr>
<tr><td>Species composition of woodland component</td></tr>
<tr><td>Potential productivity (yield class) of woodland component</td></tr>
<tr><td>Soil type associated with the woodland component</td><td>Soils were classified as either mineral or organic (i.e. deep peats). The classification of woodland areas as on mineral or organic soils was based on a comparison of the National Forest Inventory 2015 woodland map (clipped to the area of NRW woodlands) with the Wales-wide Unified Peat Map, developed as part of the Welsh Government-funded GMEP (Glastir Monitoring and Evaluation Programme) project to quantify deep peat stocks in Wales (Evans et al., 2015). See Appendix 4.</td></tr>
<tr><td>Land use prior to planting or regeneration of woodland</td><td>For this project, this information is only relevant for recent afforestation activities. An assumption was made that all afforestation takes place on marginal land or grassland, rather than former arable land. This assumption leads to conservative estimates of potential sequestration of carbon in soils following afforestation. Generally, the effects of this assumption on the final results will be small.</td></tr>
</table>

Table 6.1 (continued) Summary of data sources referred to in developing inputs to the CARBINE model

Input data	Source
Management prescription	For commercial woodlands, prescriptions were obtained from records from Forester GIS database but substantially supplemented and modified by specifications provided by NRW specialists (see Sections 6.2.2 and 6.2.3). For non-commercial woodlands, prescriptions were based on qualitative description of woodland management supplied by NRW reserve managers through the project team (see Appendix 3). Modelling of rotations applied to areas managed on a clearfell regime was also required (see Sections 6.3.2 and 6.3.3).
Specification for how any harvested wood is used	Information was provided by NRW on the quantities of wood utilised for different categories of product (see Appendix 5).

6.2.1. Basic data on woodland areas

The main features of the basic woodland area data may be summarised in tables such as shown in Tables 6.2 to 6.4. These tables summarise the raw data on woodland areas for all land owned or managed by Natural Resources Wales, classified with respect to:

- Tree species and broad management prescription (Table 6.2)
- Tree species and yield class (Table 6.3)
- Tree species and planting/regeneration period (Table 6.4).

It should be noted that:

- The areas in Tables 6.2 to 6.4 are expressed on a gross basis, i.e. no reduction has been made for unmapped areas not stocked with trees, occupied by rocks, roads, rides, lakes etc.
- For commercial woodlands, broad management prescriptions were derived from the management coupe types assigned to woodland areas in the Forester GIS
- For non-commercial woodlands, information on woodland composition and management was provided by NRW specialists (see Appendix 3).

It is important to stress that the information in Tables 6.2 to 6.4 provides a summary of data on woodland composition and management as recorded in the Forester GIS database for NRW woodlands. Fundamentally, these data formed the basis of the inputs to the CARBINE model in representing the baseline scenario. However, sometimes it was necessary to interpret and modify the data as represented in the Forester GIS as part of subsequent modelling. Further explanation of the interpretation and processing of data on NRW woodlands is provided in Sections 6.2.2 to 6.2.4 and Section 6.3.

Table 6.2 Summary of basic data on NRW woodland areas by tree species (CARBINE species codes) and broad management types

Tree species	Woodland area by management type (ha)					
	Clearfell	Shelter-wood	Selection	Coppice	Reserve/ retention	Total
SS	39 104	2 982	5 177	38	3 227	50 529
NS	3 196	838	1 826	10	650	6 519
SP	868	448	767	3	217	2 304
CP	444	703	801	0	39	1 987
LP	2 086	170	315	1	245	2 817
EL	29	67	105	2	19	222
JL	4 194	1 574	4 135	10	693	10 606
DF	1 837	962	2 282	49	409	5 540
GF	192	86	174	0	27	478
NF	258	42	72	0	34	406
WH	596	122	124	1	29	871
WRC	178	62	127	6	30	404
OK	501	720	1 323	17	1 942	4 503
BE	107	384	1 352	3	405	2 250
SAB	3 700	2 771	4 213	42	3 096	13 769
PO	7	9	36	0	2	55
NO	4	67	24	0	1	96
					Felled area	6 544
					Total area	**109 952**

Key to tree species codes: SS = Sitka spruce, NS = Norway spruce, SP = Scots pine, CP = Corsican pine, LP = lodgepole pine, EL = European larch, JL = Japanese larch, DF = Douglas fir, GF = grand fir, NF = noble fir, WH = Western hemlock, WRC = Western red cedar, OK = oak, BE = beech, SAB = ash, birch and sycamore, PO = poplar, NO = nothofagus.

Table 6.3 Summary of basic data on NRW woodland areas by tree species (CARBINE species codes) and yield class

Tree species	Woodland area by yield class (ha)													
	2	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**>24**	**Total**
SS	1 186	458	765	1 584	3 699	11 448	11 228	8 204	4 877	3 039	1 847	2 190	4	50 529
NS	288	66	156	339	985	1416	1 164	933	617	319	229	7	0	6 519
SP	43	79	230	577	842	367	129	37	0	1	0	0	0	2 304
CP	45	11	92	203	418	586	328	238	47	19	0	0	0	1 987
LP	188	337	735	903	419	159	62	10	0	4	0	0	0	2 817
EL	4	15	35	75	45	42	3	2	0	0	0	0	0	222
JL	76	84	254	1 076	3 026	3 133	2 817	139	0	0	0	0	0	10 606
DF	33	2	5	29	191	832	1 016	1 469	851	579	249	284	0	5 540
GF	9	5	0	0	8	17	31	83	34	102	31	58	90	467
NF	3	6	23	7	37	67	83	72	40	29	36	1	0	406
WH	20	2	7	4	14	59	105	165	189	127	85	94	0	871
WRC	30	3	6	8	33	68	65	82	38	38	24	9	0	404
OK	1 202	2 183	757	290	60	6	4	0	0	1	0	0	0	4 503
BE	414	443	622	681	88	1	0	1	0	0	0	0	0	2 250
SAB	6 714	3 535	806	898	340	102	25	5	12	3	0	1	0	12 441
PO	11	22	9	5	9	1	0	0	0	0	0	0	0	57
NO	2	2	8	9	11	6	5	1	3	0	0	0	0	47
													Felled area	6 544
													Total area	**108 513**

Key to tree species codes: SS = Sitka spruce, NS = Norway spruce, SP = Scots pine, CP = Corsican pine, LP = lodgepole pine, EL = European larch, JL = Japanese larch, DF = Douglas fir, GF = grand fir, NF = noble fir, WH = Western hemlock, WRC = Western red cedar, OK = oak, BE = beech, SAB = ash, birch and sycamore, PO = poplar, NO = nothofagus.

Table 6.4 Summary of basic data NRW woodland areas by tree species (CARBINE species codes) and planting periods

Tree species	Woodland area by planting year period (ha)								
	2000+	1990-1999	1980-1989	1970-1979	1960-1969	1940-1959	1920-1939	<1920	Total
SS	10 034	10 087	9 550	7 898	7 173	5 363	421	3	50 529
NS	1 690	963	261	308	941	1 710	614	32	6 519
SP	406	194	17	23	337	902	410	15	2 304
CP	131	278	81	91	326	886	191	3	1 987
LP	62	72	86	446	1 352	761	38	0	2 817
EL	4	1	4	8	12	63	96	33	222
JL	1 688	1 700	1 175	1 282	1 322	2 964	473	1	10 606
DF	1 109	1 001	1 224	608	516	692	384	6	5 540
GF	23	4	14	183	147	85	11	0	467
NF	69	98	11	20	108	98	2	0	406
WH	32	64	68	69	417	203	17	1	871
WRC	70	5	6	43	107	154	19	0	404
OK	1 170	172	94	21	51	694	360	1 939	4 503
BE	59	27	36	18	114	1 227	309	460	2 250
SAB	4 983	2 083	1 138	454	515	1 696	632	939	12 441
PO	14	0	0	2	7	32	1	0	57
NO	1	6	25	10	2	3	0	0	47
All spp.	**21 546**	**16 756**	**13 793**	**11 485**	**13 447**	**17 533**	**3 978**	**3 433**	**101 970**
								Felled area	6 544
								Total area	**108 513**

Key to tree species codes: SS = Sitka spruce, NS = Norway spruce, SP = Scots pine, CP = Corsican pine, LP = lodgepole pine, EL = European larch, JL = Japanese larch, DF = Douglas fir, GF = grand fir, NF = noble fir, WH = Western hemlock, WRC = Western red cedar, OK = oak, BE = beech, SAB = ash, birch and sycamore, PO = poplar, NO = nothofagus.

The total area given in Table 6.2 (109,952 ha) is slightly larger than the total areas given in Tables 6.3 and 6.4 (108,513 ha). The main difference is due to an additional area of just over 1,000 ha of broadleaf woodland (ash, birch and sycamore), included in Table 6.2. This is very likely to represent marginal areas of broadleaved trees, essentially scrub, with no yield class or planting year assigned. This area has been excluded from the study, giving a total study area of 108,513 ha, as reported in Tables 6.3 and 6.4.

It is important to clarify that the tree species referred to in Tables 6.2 to 6.4 are "CARBINE model species", i.e. the tables show the woodland areas assigned to the specific tree species represented in the CARBINE model. For the majority of the woodland area, the CARBINE model species will be the same as the actual tree species recorded in the NRW sub-compartment database. However, for some small areas of relatively minor tree species, areas have been "mapped" to the closest tree species represented in CARBINE (see Appendix 1 of Matthews *et al.*, 2016). For example, any area of Serbian spruce is mapped to Norway spruce. It should be noted that areas of marginal and minor broadleaved species are generally mapped to the CARBINE model for ash, sycamore and birch, which is already a combined model for these tree species.

Table 6.2 shows the area of woodland owned or managed by NRW, classified according to tree species and the broad prescription of management applied. The categories of management prescription are:

- Clearfell – management as even-aged stands with periodic clearfelling on a specified rotation
- Shelterwood – management as uneven-aged, continuous cover woodland with a relatively simple structure (e.g. two storeys of trees, one or few tree species)
- Selection – management as uneven-aged, continuous cover woodland with a relatively complex structure (e.g. multiple storeys of trees, several tree species)
- Coppice – management involving coppicing of trees
- Reserve/retention – management based on "minimum intervention", which does not involve wood production, or long-term retention (i.e. no felling or deferred felling).

The data in Tables 6.2 to 6.4 are for the entire area of NRW woodlands. Data were also obtained separately for the area of non-commercial woodlands and for the five operational areas of commercial woodlands forming the NRW estate (Northwest, Northeast, Mid, Southwest and Southeast)[1]. Summary tables for these more detailed results are provided in MS Excel workbooks with the file names:

[1] NRW had five regions for operational purposes at the beginning of 2015, i.e. the baseline year for this study.

- "NRW woodland area by CARBINE species and coupe type v06.xlsx"
- "NRW woodland area by CARBINE species and yield class v05.xlsx"
- "NRW woodland area by CARBINE species and pyear v05.xlsx".

As stressed previously, the information in these Excel workbooks provides a summary of data on woodland composition and management as recorded in the Forester GIS database for NRW woodlands. Fundamentally, these data formed the basis of the inputs to the CARBINE model in representing the baseline scenario. However, sometimes it was necessary to interpret and modify the data as represented in the Forester GIS as part of subsequent modelling. Further explanation of the interpretation and processing of data on NRW woodlands is provided in 6.2.2 to 6.2.4 and Section 6.3.

6.2.2. Use of data on woodland management

For commercial woodlands, it is important to understand how data on woodland management available from the Forester GIS database were used for the purposes of this study. It is equally important to understand where these data were *not* used for the purposes of this study.

The Forester GIS database contains a number of datasets describing the management of commercial woodlands owned or managed by NRW, specifically:

- Codes describing broad management prescriptions assigned to all woodland areas (see Table 6.2)
- For the vast majority of woodland areas, more detailed records indicating whether or not woodlands have been thinned previously and whether or not they are to be thinned in the future; for many woodland areas, there are more detailed records indicating a schedule for the timings of thinning events and intended levels of production
- Rotations (felling years) assigned to all woodland areas prescribed with management involving clearfelling and restocking
- For some woodland areas, adjustment factors may be specified to allow for local variations in levels of volume production from woodlands when making forecasts of production.

Table 6.5 shows how these types of data were used (or not used) in developing input datasets for the CARBINE model to represent BAU management.

Table 6.5 Use of management data in this study

Data type	Use of data in this study
Broad management prescription	Used to assign a "basic management regime" as represented in the CARBINE model (see Section 6.1) to woodland areas. However, this exercise was also informed by the business rules supplied by NRW specialists (see Sections 6.2.3 and 6.3.2).
Thinning records	Used to assign woodland areas to management regimes involving either thinning or no thinning. However, this exercise was also informed by the business rules supplied by NRW specialists (see Sections 6.2.3 and 6.3.2).
Rotations (felling years)	Not used (see further discussion immediately after this table).
Adjustment factors	Not used. These factors are intended primarily to refine forecasting at local/small scales and are of limited relevance to large-scale scenario modelling such as undertaken in this study.

The decision not to use data on rotations/felling years assigned to woodland areas in the Forester GIS database requires further explanation. In fact, in the early stages of this project, initial CARBINE model simulations used these directly as input data to determine the timing of clearfelling activities. However, the results of the simulations were difficult to interpret, due to the presence of extremely large inter-annual variations in production levels and, consequently, very large fluctuations in the level of carbon loss or carbon sequestration in NRW woodlands as predicted by CARBINE.

A detailed inspection of the data on felling years revealed that the data exhibited certain limitations in the context of this study. To illustrate the issues, Figure 6.1 shows the annual area scheduled for clearfelling in NRW woodlands over the period from 2015 to 2040 (the temporal system boundary for this study). It is apparent from the figure that the woodland area scheduled for clearfelling varies very significantly from year to year, the largest area (in 2037) being more than 25 times greater than the smallest scheduled area (in 2038). In practice, such significant variations in area felled would not occur. This raises the question as to why big variations in felled area from year to year occur in the data.

It is important to recognise that, principally, the Forester GIS is a business management tool. The timing of harvesting in woodlands is often managed in five year periods. Sometimes, the felling year ascribed to a given woodland area will reflect the mid-point of a five year period in which felling is planned, rather than a precise year. Furthermore, most likely, some of the larger variations in the annual area assigned to felling can be explained by the assignment of notional or provisional felling years to woodland areas (perhaps based on standard felling ages recommended in Forestry Commission yield tables). The assignment of such provisional felling years would reflect current uncertainty about the actual planned time of felling for these woodlands, as this may fall outside the current time horizon for woodland design planning. It is likely that the prescribed time of felling for the relevant woodland areas would be updated as design planning evolves into the future.

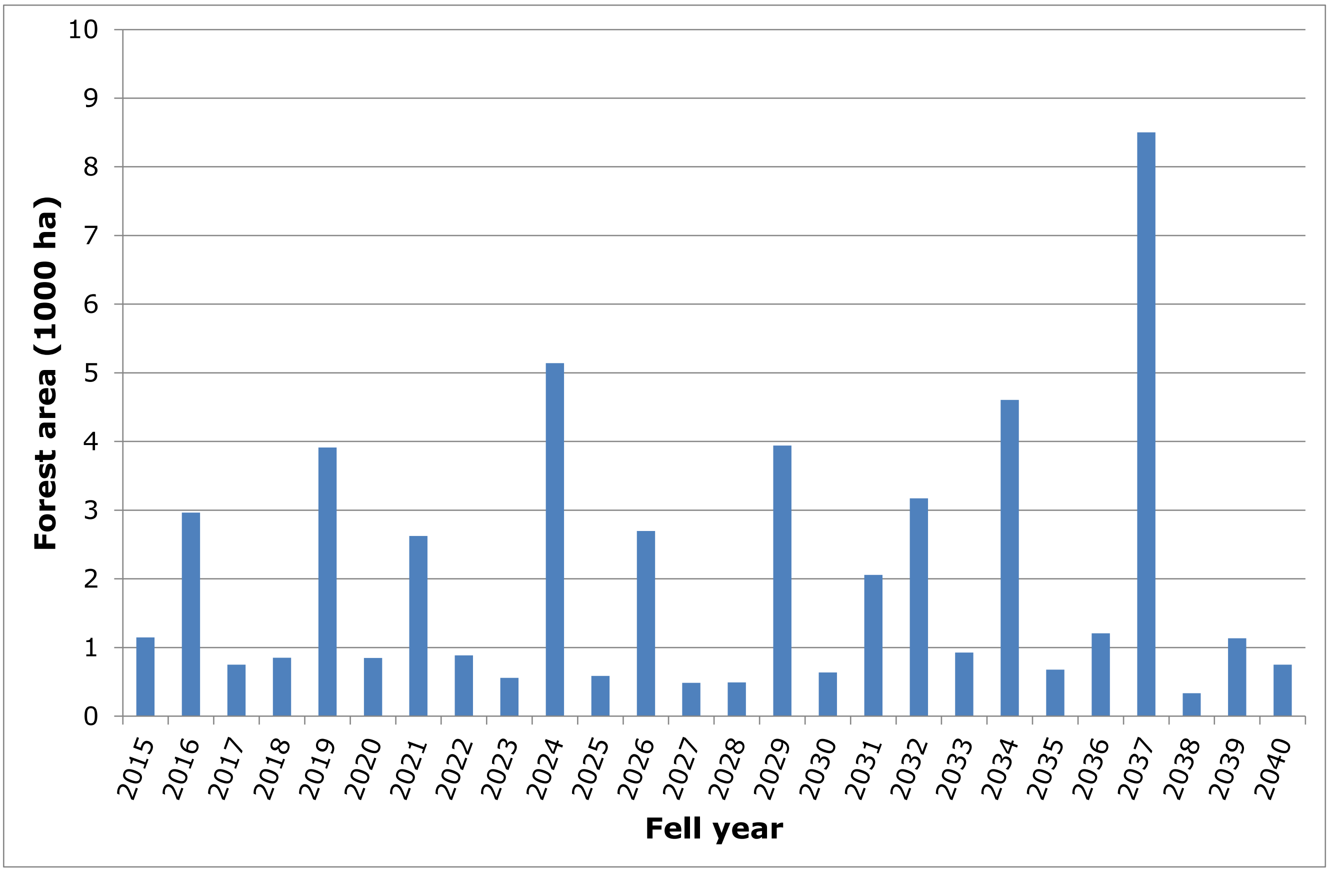

Figure 6.1. Area of woodland by felling year as represented in the Forester GIS database.

As an initial approach to addressing the issues with felling year data, as part of the data processing for this study, adjustments were made to some fell years, with the aim of smoothing the annual area of volume felled. However, this procedure still gave results that exhibited significant inter-annual variations, which made the results difficult to interpret.

As a consequence of the unsuitability for this study of available data on rotations/felling years applied to commercial woodland areas owned or managed by NRW, it was necessary to develop a more sophisticated approach to the modelling of felling in NRW woodlands, in order to generate a harvesting schedule that could be regarded as a reasonable representation of the business-as-usual management of the woodlands. This improved approach was founded on a set of assumptions and rules developed by NRW specialists.

6.2.3. Assumptions and rules provided by NRW

NRW specialists provided advice on a number of assumptions and rules to adopt in the modelling undertaken for the purposes of this study. Some of these assumptions and rules were concerned with how to handle missing or ambiguous data records but many specified parameters defining NRW's understanding of the detailed management of NRW woodlands under a baseline, i.e. a "business as usual", scenario. Effectively, these assumptions and rules provided the detailed specification supporting the broad assumptions stated originally with regard to the baseline or BAU scenario (see Section 4).

The key relevant assumptions and rules are described in Table 6.6. It is very important to note a number of caveats that should be attached to the BAU scenario that has been developed according to the rules specified in Table 6.6. Relevant caveats are discussed in Section 6.2.4.

Table 6.6 Key assumptions and rules adopted in modelling BAU projections for NRW woodlands

Description	Assumption or rule	Comments
Missing yield class record or yield class value of zero	Conifers: assume a yield class of 10 Broadleaves: assume a yield class of 2	NRW advised that there was no basis for assuming that a missing value of yield class for a conifer stand was either particularly low or high, hence the mean value of yield class should be assumed. The assumed yield class for broadleaved stands is conservative.
Woodland creation (afforestation)	Assume no creation of new woodland areas.	
Woodland loss (deforestation)	Assume no loss of existing woodland areas (however see *Felled woodland areas*)	
Felled woodland areas	Assume felled woodland areas are restocked with tree species, growth rates and management prescriptions reflecting the current growing stock of NRW woodlands. As an exception, assume that 300 ha in the Southwest operational region are *not* restocked.	NRW advised that approximately 300 ha of felled woodland in the Southwest operational region would not be restocked in order to meet habitat restoration objectives.

Table 6.6 (continued) Key assumptions and rules adopted in modelling BAU projections for NRW woodlands

Description	Assumption or rule	Comments
Restocking after felling of growing stock	Assume woodland areas felled in the future are restocked with trees of the same species and growth rate and managed in the same way as for the existing woodland areas.	
NRW-scale target for annual wood production from NRW commercial woodlands	Assume that total annual wood production of 850,000 m^3 over bark standing per year will apply as a maximum for the period 2016 to 2040, with a minimum of 700,000 m^3. Typically this will be composed of 100,000 to 180,000 m^3 from thinning, 270,000 m^3 from felling of larch stands and 330,000 to 400,000 m^3 from felling of stands of other species. Thinning of broadleaves is expected to contribute 5 000 m^3 per year.	Based on the NRW Timber Marketing Plan[2]. The felling commitments shown here apply for the foreseeable future. It should be noted that the felling commitments include a flexible element and NRW will be felling from a minimum of 700,000 m^3 up to a maximum of 850,000 m^3 per year broken down as shown. For the purposes of modelling the BAU scenario developed in this study, a "conservative" assumption was made that total annual wood production over the period 2016 to 2040 would be at the maximum level specified of 850,000 m^3. Since carbon sequestration in woodlands is influenced by intensity of harvesting, this assumption should result in somewhat conservative predictions of carbon sequestration in NRW woodlands.
Allocation of proportions of high-level target to NRW operational regions	Pro-rata, according to a preliminary forecast of potential volume production for each operational region for the period 2016 to 2050 (see Section 6.3.5)	Originally, NRW suggested that the high-level production target should be allocated to operational regions based on the woodland area of each region. However, subsequently, it was agreed that potential production from each region over a relevant time horizon would be a more robust approach.

[2] https://naturalresources.wales/media/681069/timber-marketing-plan 2017-22 final-for-publication english.pdf.

Table 6.6 (continued) Key assumptions and rules adopted in modelling BAU projections for NRW woodlands

Description	Assumption or rule	Comments
Target per-hectare levels of volume production	Thinnings: 60 m^3 ha^{-1} yr^{-1} Clearfelling of larch stands: 350 m^3 ha^{-1} yr^{-1} Clearfelling of other stands: 450 m^3 ha^{-1} yr^{-1}	Based on data for felling and thinning from records kept by Wales Harvesting and Marketing for the most recent 3 years. Volumes are over bark and per-hectare values are assumed to be based on net (i.e. stocked) area. It should be noted that, in practice, thinning volumes calculated by the CARBINE model are based on standard yield table prescriptions and simulated thinning volumes for individual woodland areas will vary from the specified target.
Special rule for broadleaved woodland areas	All areas assigned to wood production should be assumed to be managed according to continuous-cover silviculture	NRW advised that, for the purposes of this project, all broadleaved species under management for wood production should be managed by alternative silvicultural systems as described in NRW policies. However, it should be noted that levels of wood production from broadleaves were constrained by the target level of volume production.
Special rule for larch woodland areas	All areas should be assumed to be managed according to a clearfell management prescription	NRW advised that, due to the disease *P. ramorum* on larch there is a requirement to clearfell larch as part of the disease management strategy in Wales. Hence, for the purposes of this project, all larch should be managed under a clearfell management prescription.
Special rule for conifer woodland areas associated with a management prescription of "Coppice"	All areas should be assumed to be managed according to a shelterwood management prescription	NRW advised that all conifers that are designated coppice should be reassigned to shelterwood. It should be noted that there are very few species of conifer that coppice.
Management of NRW non-	Limited levels of harvesting.	For non-commercial woodlands, based on qualitative description of woodland management supplied by NRW reserve

commercial woodlands		managers through the project team (see Appendix 3).

6.2.4. Caveats attached to BAU scenario and assumptions and rules

It is important to recognise the very specific definition of a BAU scenario suggested by the discussion earlier in Section 6, and in particular based on the data and rules given in Tables 6.1 and 6.6. As already explained, in general, the scenario modelled in this study is based on the composition of woodlands owned or managed by NRW, as defined in the Forester GIS database as at 31st March 2015, but subject to certain assumptions and rules. Projected future woodland management (notably for wood production), and associated GHG emissions and woodland carbon stocks/sequestration rates reflect a BAU scenario, assuming that the essential composition and management of woodlands is unchanged from the base year of 2015 adopted for the study. Consequently, the impacts of a number of possible new activities or changes to activities (planned or potential) are not considered in the scenario, notably:

- Land-use changes – apart from the loss of 300 ha in the Southwest region, the modelled BAU scenario assumes zero woodland loss due to deforestation. Therefore, any potential future reductions in the extent of the woodland estate arising from certain activities are not allowed for, specifically, the restoration of upland planted ancient woodland sites (PAWS); the restoration of peatlands and other habitats; development of wind farms.

- Reduced and/or delayed restocking – the modelled BAU scenario assumes that restocking of felled woodland areas takes place immediately. However, in practice, restocking may not take place for 4 to 6 years after felling. There is a widening gap between felled and restocked woodland areas on the NRW estate due to a reduction in funding for restocking activities.

- Changes in tree species composition over time – the modelled BAU scenario assumes that felled woodland areas are restocked with the same tree species and growth rates as for the current growing stock of the felled NRW woodlands. Hence, potential activities aimed at diversifying the species composition of the NRW estate (or removal of species at severe risk of disease infestation) are not allowed for.

- Changes in clearfelling rotations – the modelled BAU scenario does not represent possible adjustments which may be made in the future to rotations applied to woodland areas managed according to a clearfell regime, e.g. because of improved understanding of the development of mean annual increment in woodland stands or the increasing deployment of genetically improved Sitka spruce (see for example Matthews *et al.*, 2017; Craig *et al.*, 2017).

- Adoption of alternative silvicultural systems – the modelled BAU scenario does not represent potential activities aimed at diversifying woodland management practices in the NRW estate, such as increased adoption of continuous cover management regimes.

6.3. Development of input data

The preparation of information for input to the CARBINE model required considerable processing of the available data, informed by the assumptions and rules defining the BAU scenario.

6.3.1. Basic data formatting and processing

The first stage in preparing information for input to the CARBINE model involved some essential processing of the available data:

- Woodland areas, classified by tree species, yield class, planting year and management prescription were processed into CARBINE input format.
- There was some limited processing of missing and ambiguous values, which involved the application of some of the assumptions and rules in Table 6.6, Section 6.2.3.

6.3.2. Woodland management prescriptions

The approach taken to the assignment of management prescriptions to woodland areas requires careful discussion, since this has been the principal basis for defining the baseline or "business as usual" projection of woodland carbon stocks/sequestration rates. The approach has relied upon a combination of:

- Records related to actual management of woodland area components as recorded in the Forester GIS (for which there is an explicit audit trail, see Sections 6.2.1 and 6.2.2)
- A set of assumptions and rules as already described in Section 6.2.3.

The CARBINE model can represent four broad management prescriptions:

1. Areas not subject to thinning or felling (effectively unmanaged in terms of wood production)
2. Areas subject to periodic clearfelling on a specified rotation with no thinning during the rotation
3. Areas subject to periodic clearfelling on a specified rotation with thinning according to standard yield tables during the rotation
4. Areas subject to periodic thinning but with no clearfelling, i.e. managed according to continuous cover.

Assigning management prescriptions to woodland areas involved two stages:

- Stage 1 – for each component of woodland area, the most appropriate broad management prescription was selected from amongst the four represented in the CARBINE model
- Stage 2 – for each woodland area component assigned a broad management prescription involving clearfelling, a rotation age (or sequence of rotation ages) was specified, setting the year(s) in which the woodland area component would be clearfelled.

The approaches taken to Stages 1 and 2 are illustrated, respectively, by the schematic diagrams in Figures 6.2 and 6.3.

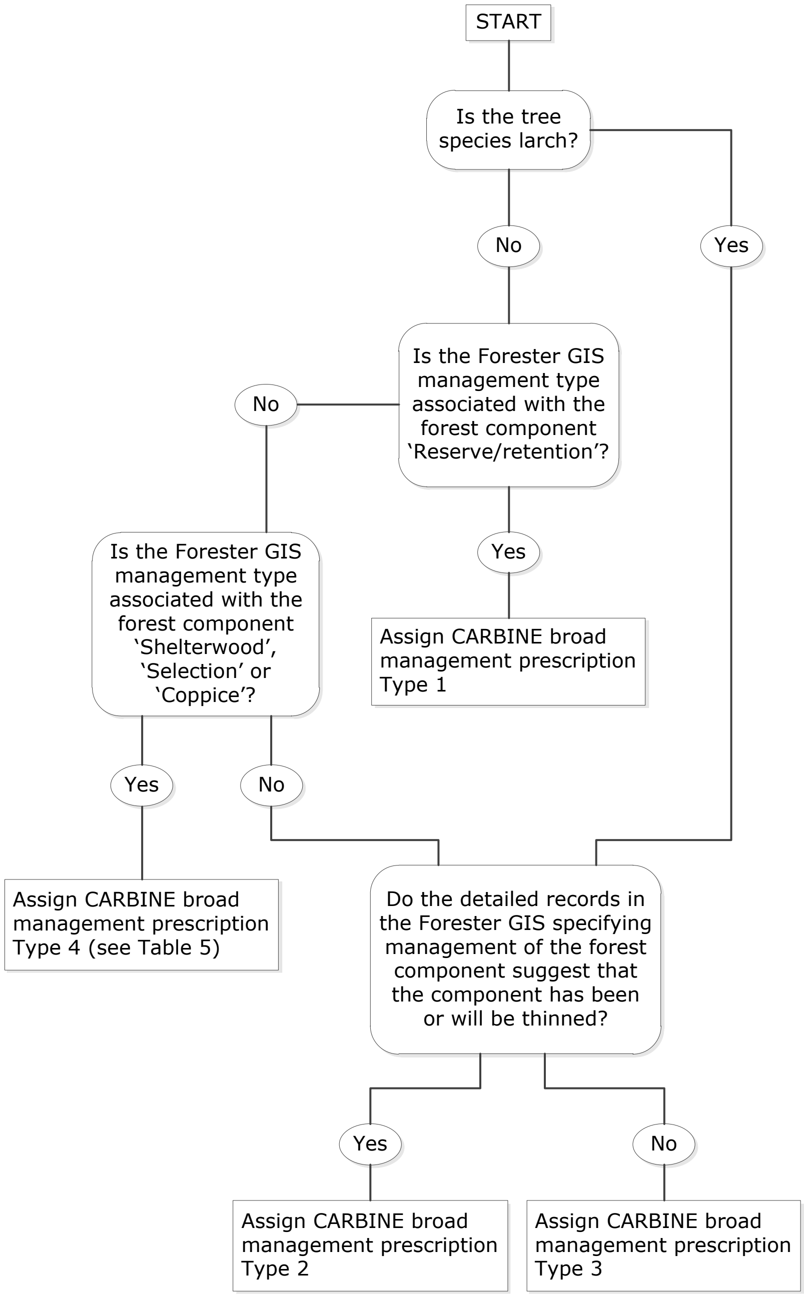

Figure 6.2. Data processing flow diagram to assign the most appropriate CARBINE broad management prescription to woodland components.

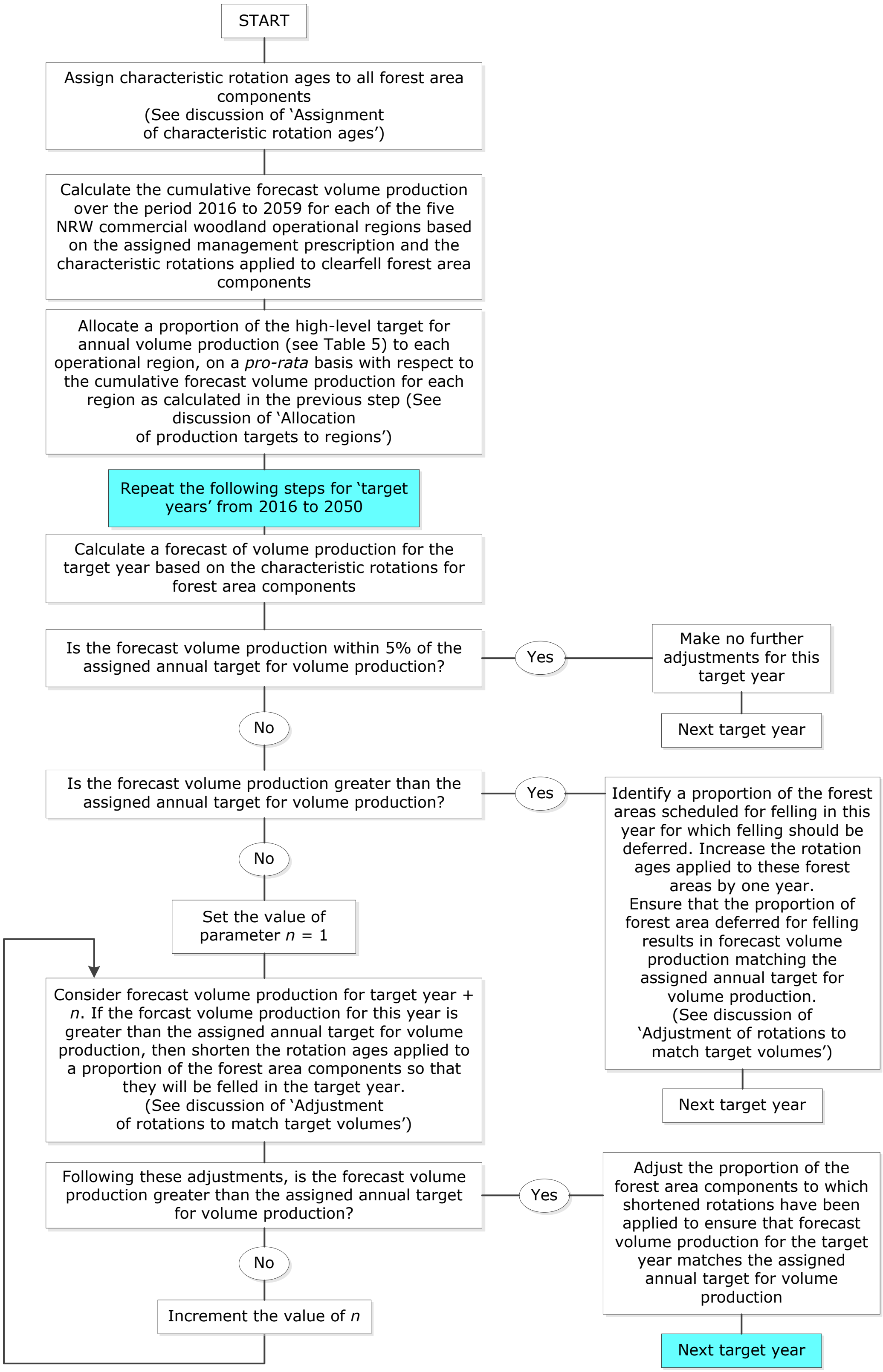

Figure 6.3. Data processing flow diagram to assign rotation ages to woodland components managed on a clearfelling regime.

6.3.3. Optimising rotations for target volume production

In essence, the approach in Stage 2 reconciles the rotations assigned to woodland areas to achieve consistency with the BAU scenario defined earlier in this report, by:

- Setting a top-down (NRW-scale) target for annual wood volume production (Table 6.6, Section 6.2.3).
- Making bottom-up adjustments to the rotations assigned to woodland areas (managed according to a clearfelling regime) so that the annual wood volume production forecast by the CARBINE model matches the top-down target.
- When adjusting rotations assigned to woodland areas, constraining the rotations to within a reasonable range to give clearfell volumes consistent with stand-scale targets for per-hectare felling volumes (Table 6.6, Section 6.2.3). In particular very extreme and unrealistic rotations (such as very short rotations) were avoided.

The constrained optimisation process in Stage 2 is quite complex and computationally intensive. However, such an approach was necessary because, as already explained in Section 6.2.2, it was not possible to develop a baseline or "business as usual" projection based more simply on the rotation ages (felling years) actually assigned to woodland area components, as recorded in the Forester GIS database. Furthermore, it was necessary to model the development of NRW woodlands in response to management assumptions that were a reasonable reflection of reality. In practice, as already noted in Table 6.6, in Section 6.2.3, there is an overall commitment to make volume available annually for supply from NRW woodlands, as stated in the NRW Timber Marketing Plan. The level of volume production committed is based on forecasts of potential for wood supply from NRW woodlands. However, the management of NRW woodlands follows the principles of sustainable forest management, including the principle of *sustainable yield*. Hence, a key aim of woodland management is for volume production from woodland areas to not exceed the maximum potential for production. The commitment to produce volume reflects this aim. Moreover, in any given year, not all of the potential production from NRW woodlands is harvested and the remaining volume is rolled over to meet supply volumes in future years. The optimisation process of Stage 2 aimed to reflect this general approach to the management of NRW woodlands to supply timber volume.

6.3.4. Assignment of characteristic rotation ages

As apparent in the schematic diagram in Figure 6.3, a first step in the setting of rotation ages applied to woodland areas managed according to a clearfell regime involved assigning a "characteristic rotation age" to all relevant woodland areas. In the context of this project, the characteristic rotation age of a woodland area component was based on the tree species and yield class of the woodland component, and the broad management prescription (i.e. involving thinning or not involving thinning). Given these details, yield models could be referred to in order to establish the age at which a woodland area would produce the target per-hectare felling volume specified in Table 6.6 (Section 6.2.3). In practice, this was achieved by running individual forecasts for each woodland area component to infer the associated characteristic rotation age. The target values in Table 6.6 were assumed to be reported on a net area basis, hence, volumes forecast by yield models for successive stand ages were reduced by applying a standard gross:net area factor of 85%[3]. The characteristic rotation age was thus identified as the youngest stand age at which 85% of the standing volume predicted by the relevant yield model met or exceeded the relevant felling volume target in Table 6.6.

In some situations, the characteristic rotation age obtained for a woodland area component might imply that it should have already been felled. For example, suppose a woodland area component had a planting year of 1950 and the characteristic rotation was calculated to be 55 years. This would imply that the component should have been felled in 2005, whereas it evidently still exists according to the Forester GIS database. In these situations, relevant components were labelled with a "warning flag" and assigned a rotation age equivalent to a felling year of 2016. In practice, this leads to a relatively large woodland area being assigned for felling in the year 2016, which is unrealistic. However, this issue was handled in later modelling steps as described in Figure 6.3 and below.

6.3.5. Allocation of production targets to regions

As described in Table 6.6 (Section 6.2.3) and Figure 6.3 (Section 6.3.2), the NRW-scale target specified for volume production from NRW woodlands was allocated to the five NRW operational regions (Mid, Northeast, Northwest, Southeast, Southwest) on a pro-rata basis, according to initial forecast estimates of potential volume production in each operational region accumulated for the period 2016 to 2050. The initial forecast estimates were obtained by running the CARBINE model for each operational region, applying initial assumptions about the management of woodland areas:

- Woodland areas assigned to CARBINE broad management prescription Type 1 did not contribute to volume production
- Woodland areas assigned to CARBINE broad management prescription Type 2 contributed to volume production from felling, assuming the application of characteristic rotations to woodland area components (see above)
- Woodland areas assigned to CARBINE broad management prescription Type 3 contributed to volume production from felling, assuming the application of characteristic rotations to woodland area components (see above); these areas also

[3] This 85% reduction factor has been a standard assumption in British forestry for many years. As part of the introduction to their Production Forecast Tables, Bradley, Christie and Johnston (1966) explain that a standard reduction of 15% (i.e. a multiplying factor of 85%) has been made to all the volumes in the tables, partly to allow for unproductive land areas (such as roads, rides etc.) and partly as a general allowance for variations in stocking.

contributed to volume production from thinning, which were fixed to follow standard yield model Forestry Commission thinning prescriptions (Matthews *et al*., 2016).

- Woodland areas assigned to CARBINE broad management prescription Type 4 contributed to volume production from thinning, which followed a fixed production pattern representative of continuous cover silvicultural practice, based on fixed underlying thinning intensities related to standard yield model Forestry Commission thinning prescriptions.

The results of this analysis, and consequent allocation of volume production targets to NRW operational regions, are summarised in Table 6.7, for the maximum assigned level annual volume production indicated in Table 6.6 (Section 6.2.3) of 850,000 m^3 per year. Note that a minimum target of 700,000 m^3 per year was also specified.

It is important to clarify that the annual timber volume production targets allocated to the five NRW operational regions were applied over the period represented by the temporal system boundary for this study. In other words, for example, the annual target for volume production from the Northwest operational region was set at 103,400 m^3 (Table 6.7, shown in thousands of m^3) for each year from 2015 to 2040. In practice, the relative contributions to annual volume production from the five operational regions will vary significantly from year to year. The volume production targets were also applied to the five operational regions beyond 2040, up to the year 2050, to ensure the stability of simulations immediately beyond the time horizon of the system boundary for this study of 2040.

Table 6.7 Initial forecast of potential volume production from NRW operational regions accumulated over the period 2016 to 2050 and allocation of annual targets

NRW operational region	Initial forecast (000's m^3)	Percentage allocation	Allocated annual target (000's m^3)
Northwest	3 840	12.2	103.4
Northeast	2 783	8.8	74.9
Mid	7 976	25.3	214.7
Southwest	9 311	29.5	250.6
Southeast	7 670	24.3	206.4
Total	**31 580**	**100**	**850**

Note to Table 6.7: Forecast volumes are over bark standing with no adjustment for net (stocked) area; target volumes are over bark standing.

6.3.6. Adjustment of rotations to match target volumes

As described in Figure 6.3 (in particular Section 6.3.3), the rotation ages applied to woodland areas managed on a clearfelling regime were adjusted to arrive at a forecast of volume production for each of the operational regions that matched the assigned target (see Table 6.7) over the period 2016 to 2050.

In broad terms, this procedure involved:

- Starting with the initial volume forecast based on characteristic rotations (see discussion in previous section)
- Where the forecast volume for a particular year exceeded the assigned target, deferring the felling of a proportion of woodland areas (i.e. by extending the rotations applied to them), to ensure the target was matched in the year being considered
- Where the forecast volume for a particular year was insufficient to meet the assigned target, identifying later years in which production exceeded the target, and bringing forward some of the production from those years (by shortening the rotations applied to a proportion of the relevant woodland areas), to ensure the target was matched in the year being considered.

In situations where some of the volume production in a particular year needed to be deferred, the extending of rotations was weighted towards those woodland area components which were already beyond the scheduled time of clearfelling (i.e. already being managed on extended rotations), as suggested by the characteristic rotations for the components. In other words, priority was given to producing volume from components that were identified as due for felling, as suggested by their characteristic rotation ages, rather than accumulating an ever larger proportion of woodland area on extended rotations.

In situations where it was necessary to bring some production forward, by shortening the rotations applied to some woodland areas, constraints were applied to ensure that adjusted rotations applied to woodland areas were not implausibly short.

6.3.7. Windblown and currently unstocked areas

As part of the modelling for this study, a number of assumptions were made about windblown and currently unstocked woodland areas in modelling the NRW woodland areas for a BAU simulation:

- Areas classified as windblown were assumed to have been cleared and restocked in 2015, similarly to the treatment of felled areas (see Table 6.6, Section 6.2.3)
- Areas classified as failed or burnt were assumed to have become unstocked in the period 2006 to 2015 and to be subsequently replanted, similarly to the treatment of felled areas.
- Where possible, the timing of the felling and restocking of felled, windblown, failed or burnt woodland area components was set so that simulated levels of volume production during the period 2006 to 2015 were reasonably consistent with the intended future levels as set in the targets for operational regions (see Section 6.3.5). This was to ensure the stability of simulations immediately prior to the base year of the system boundary for this study of 2015.

6.3.8. Existence of woodland areas before current rotation

It was also necessary to make assumptions about how long woodland areas had existed. If a woodland area had a recent planting year assigned, the chances were that in fact the area had been planted much earlier, then clearfelled and restocked. This is important for model simulations made with the CARBINE model, because results for litter and soil carbon dynamics depend strongly on the time since a woodland area first comes into existence.

For stocked areas of woodland assigned a management prescription of 2, 3 or 4 as described above, the assumption was made that most of these areas were in their second or third rotation. The details depended on the planting year assigned in the sub-compartment database and how recent this was. However, it was also assumed that the majority of the coniferous woodland area was created after 1920. For areas in their second or third rotation, the rotation currently applied was assumed to apply in the previous rotations, except in the case of woodland areas assigned a management prescription of 4, in which case it was assumed that management in previous rotations had involved clearfelling with a rotation that gave maximum volume production for the tree species and yield class. Stocked areas assigned a prescription of 1 as described above were assumed not to have been felled previously, hence the planting year assigned in the sub-compartment database was applied for these areas without adjustment.

It was assumed that all woodland areas assigned a prescription of 2 or 3 were restocked immediately following felling, i.e. in the same year. Woodland areas assigned a prescription of 4 were assumed regenerate an understorey during a period of the last 30 years over which a preceding overstorey was gradually removed.

6.3.9. Soil carbon

In principle, the modelling of soil carbon dynamics in relation to woodland management could be undertaken for each individual forest component forming the NRW estate. This is possible because information on both individual woodland components comprising the NRW estate and information on soil types are represented spatially. However, the datasets on woodland components and soils are maintained separately and a bespoke analysis to fuse these datasets would have been required if modelling of soil carbon were to be attempted at this level of detail. Moreover, such an approach would have involved running the CARBINE model for many thousands of data components (perhaps into the millions). The computational effort required was considered excessive and unlikely to result in a significant refinement of the results ultimately produced by the CARBINE model. Hence, the approach adopted for this project involved a number of simplifications as described below.

For the modelling of soil carbon stocks and stock changes, the CARBINE model represents a number of possible soil types. Currently, in national GHG inventories for the

UK and Devolved Administrations, reporting distinguishes two very broad soil types – “mineral” and “organic”. The same approach was adopted in this study for consistency with methods adopted in GHG inventories.

To produce the final results for soil carbon (see Section 6.4.3), it was necessary to know the relative areas of woodlands on mineral and organic soils for defined major woodland types. These estimates were derived from information provided by NRW specialists (see Table 6.1, Section 6.2). Further details of the data provided, the calculation approach and the estimates of relative areas of woodland on mineral and organic soils are given in Appendix 4.

6.3.10. Harvested wood products

The simulation of the carbon stock dynamics of harvested wood products (HWP) by the CARBINE model is based on assumptions about how any harvested wood is utilised for the manufacture of semi-finished and finished wood products (see Section 5.5). The CARBINE model includes default values for the relevant parameters controlling the allocation of harvested wood to semi-finished and finished products. However, for the purposes of this study, bespoke allocation parameters were developed, based on information provided by NRW specialists about the typical uses of wood harvested from NRW woodlands (see Appendix 5). This ensured that the predictions of detailed wood supply and utilisation produced by the CARBINE model were very consistent with the pattern of wood use suggested by NRW (see Section 7.1).

6.4. CARBINE simulations

6.4.1. Representation of regions and woodland types

The CARBINE model was applied separately for the area of non-commercial NRW woodlands and each of the five operational areas of commercial woodlands in the NRW estate (Northwest, Northeast, Mid, Southwest and Southeast). For each of these regions, separate simulations were made for three major woodland types:

1. Broadleaved woodlands (managed as reserves or according to continuous cover management prescriptions, Table 6.6, Section 6.2.3)
2. Coniferous woodlands managed as reserves or according to continuous cover management prescriptions
3. Coniferous woodlands managed according to clearfelling management prescriptions.

This required a total of 5 × 3 = 15 CARBINE simulations for each of the woodland components representing the commercial woodlands and a further component representing the non-commercial woodlands (which are composed entirely of broadleaved woodlands, see Appendix 3), giving 16 simulations in total.

Results for these regions and woodland types were then combined to give the overall results for all commercial woodlands, and for all the woodland areas forming the NRW estate.

6.4.2. Outputs

For the purposes of this study, CARBINE was used to produce annual outputs over the temporal system boundary for the study (2015 to 2040) for a relevant set of results:

- Wood production
- Carbon stocks in trees (before and after thinning)
- Carbon stocks in woodland litter (before and after thinning)
- Carbon stocks in woodland soils to a soil depth of 1 metre (before and after thinning, separately based on the alternative assumptions of mineral soils and organic soils – see earlier and below)
- Carbon stocks in harvested wood products (before and after losses due to decay or disposal)
- GHG emissions associated with a range of operations related to woodland management (see Appendix 1).

6.4.3. Processing of soil carbon results

As explained in Section 6.4.1, separate CARBINE simulations were made for each of the five operational regions for woodlands under commercial management in the NRW estate, and for the area of non-commercial woodlands as a whole. For each of these regions, results were further disaggregated for three major woodland types (broadleaved woodlands, coniferous woodlands managed as reserves or according to continuous cover prescriptions and coniferous woodlands managed according to clearfelling prescriptions).

For each of the 16 woodland components (see Section 6.4.1), the CARBINE model was applied to produce two sets of outputs for soil carbon stocks and stock changes, one set based on the assumption that all NRW woodlands are on mineral soils and a second set based on the assumption that all NRW woodlands are on organic soils. The reported results for soil carbon for each woodland component were then calculated as a weighted mean of the results for mineral soils and organic soils over the simulation period 2015 to 2040. The weighted mean was based on the estimated relative areas of woodlands forming the component under mineral and organic soils. For example, suppose that, for broadleaved woodlands in the Southeast operational region, 95% of the area is estimated to be on mineral soils and 5% is estimated to be on organic soils. In addition suppose that, in the year 2018, the CARBINE model projected a carbon stock for mineral soils of 6,000,000 tC and a carbon stock for organic soils of 11,500,000 tC. Then, the carbon stock in soils under broadleaved woodlands in the Southeast operational region in 2018 was calculated as

$$95\% \times 6{,}000{,}000 + 5\% \times 11{,}500{,}000 = 6{,}275{,}000 \text{ tC.}$$

Further details of the data underlying the calculations of relative areas of woodland on mineral and organic soils are given in Appendix 4.

6.4.4. Calculation of carbon stock changes

Results for carbon sequestration (conventionally referred to in GHG inventories as "CO_2 removals") and carbon emissions due to woodland areas, also allowing for carbon in harvested wood products, are based on the calculation of *changes* in carbon stocks. It is very important to understand the basis on which carbon stock changes (hence carbon sequestration and emissions) are calculated, and how this differs from the conventions for reporting woodland growth or "forest increment" and "wood harvesting" (also, confusingly, conventionally referred to as "wood removals") as part of forestry statistics.

Forest increment and harvesting

Forestry statistics routinely include results for forest increment and harvesting. Usually, forest increment represents the growth of the stem volume of trees in woodlands over a year or over a period of several years. However, it is equally valid to calculate forest increment based on total tree carbon stocks or on total woodland carbon stocks (i.e. in trees, litter and soil). There are two internationally-recognised measures of forest increment (normally based on stem volume, but here based on woodland carbon stocks):

Gross (carbon) increment	=	[	Carbon stock in woodlands at end of period *plus* any carbon losses (e.g. due to tree harvesting, tree mortality, litter and soil decay)	–	Carbon stock in woodlands at start of period after losses including harvesting	] /	Time period

Depending on the context of the assessment, the term "carbon stock in woodlands", and hence the results for gross carbon increment referred to above, can refer to all relevant carbon stocks, i.e. carbon in trees, litter and soil, or carbon in specific components of woodland carbon stocks, e.g. just the carbon stocks in the trees.

Net (carbon) increment	=	[	Carbon stock in woodlands at end of period *plus* any carbon stocks in trees removed in harvesting *but not including* any carbon losses (e.g. due to tree harvesting, tree mortality, litter and soil decay)	–	Carbon stock in woodlands at start of period after losses including harvesting	] /	Time period

As previously, net carbon increment can be calculated for all woodland carbon stocks (trees, litter, soil etc.) or for specific components, e.g. just carbon stocks in trees, depending on the context of the assessment being made.

These calculations give results for gross and net increment expressed in units of tC per year (tonnes carbon per year) or multiples thereof (e.g. ktC per year, or thousand tonnes carbon per year).

Net increment is usually regarded as more relevant than gross increment, when assessing sustainable forest management. It is important to recognise that net increment represents the "growth" of woodland carbon stocks before allowing for any carbon losses from the woodland due to harvesting. Effectively, drawing an analogy with a banking- or accounting-balance sheet, net increment represents the "income" (of carbon) due to woodland growth, before subtracting any "expenditure" due to forest harvesting.

Forest harvesting, as reported in forestry statistics, usually involves reporting the annualised standing stem volume of any trees felled in the woodland in harvesting activities over a specified period. As with increment, it is equally valid to calculate forest harvesting based on total tree carbon stocks or total woodland carbon stocks, expressed in units of tC per year or multiples thereof. Continuing the analogy with a banking- or accounting-balance sheet as already observed, results for forest harvesting represent the "expenditure" associated with harvesting in woodlands.

Woodland carbon stock changes

Statistics for woodland carbon sequestration or emissions, as reported for example for Forest Land in national GHG emissions inventories, are calculated as

Woodland carbon stock change	=	[	Carbon stock in woodlands at end of period after harvesting, i.e. not including carbon harvested from woodlands	–	Carbon stock in woodlands at start of period after harvesting	]	/	Time period

This calculation can also be expressed as

Woodland carbon stock change	=	[	Net forest (carbon) increment	–	Carbon harvested and extracted from woodland	]	/	Time period

Carbon stock changes can also be calculated for components of woodland carbon stocks (e.g. just based on carbon stocks in trees), depending on the context of the assessment. When calculating total carbon stock changes (for trees, litter, soil and perhaps harvested wood products), it is important to note that carbon in parts of harvested trees that are left as waste in the woodland are not included as part of the carbon harvested and extracted from the woodland. Rather, this carbon is added as "income" to "accounts" for woodland deadwood/litter carbon stocks, with losses from these accounts due to decay being allowed for in subsequent years.

As with forest increment and harvesting considered earlier, these calculations give results expressed in units of tC per year (tonnes carbon per year) or multiples thereof (e.g. ktC per year, or thousand tonnes carbon per year).

In banking or accounting terms, these measures of carbon stock changes are analogous to the "balance" between woodland carbon "income" (increment) and "expenditure" (carbon losses from the woodland due to harvesting). Hence, importantly:

- Results for woodland carbon stock changes are not the same as results for forest carbon increment, and the two types of measure should not be confused or compared with one another
- Whilst, under normal circumstances, results for carbon increment would be expected to be always positive (i.e. reflecting woodland growth over a period), results for carbon stock changes in different periods can be either positive or negative, depending on the balance between levels of growth and harvesting during the period.
- A negative net woodland carbon stock change implies a net reduction or loss of woodland carbon stocks, with implied net emissions to the atmosphere. When expressed in units of CO_2, this value is given a positive sign. For example, a net carbon stock change of -1 tC is reported as a CO_2 emission of +3.67 tCO_2 (allowing for the conversion of carbon emitted as CO_2 to units of tonnes CO_2). A positive net woodland carbon stock change implies a net increase or gain of woodland carbon stocks, with an implied sequestration of carbon from the atmosphere. When expressed in units of CO_2, this value is given a negative sign. For example, a net carbon stock change of +1 tC is reported as CO_2 sequestration (sometimes referred to as a "removal") of -3.67 tCO_2 (allowing for the conversion of carbon emitted as CO_2 to units of tonnes CO_2).

Woodland carbon stock changes including HWP

When calculating sequestration or emissions of carbon due to woodlands, it is important to recognise that any wood harvested and extracted from woodlands will not all decay and release the sequestered carbon back to the atmosphere at once. Rather, a significant fraction of this harvested wood will be used to make material wood products, and the carbon stocks will be retained in these products. However, eventually wood products will decay or be destroyed and it is necessary to allow for the consequent losses of carbon due to these processes.

The calculation of woodland carbon stock changes can be elaborated to allow for the contributions due to harvested wood products:

Woodland & HWP carbon stock change	=	[	Woodland carbon stock change	+	Additions of HWP carbon over period	-	Losses of HWP carbon over period	] /	Time period

This calculation can also be expressed as

Woodland & HWP carbon stock change	=	[	Woodland carbon stock change	–	Net carbon stock change in harvested wood products	] /	Time period

It is important to recognise that the net change in HWP carbon stocks over a given period involves the balance between additions of carbon from newly-harvested wood products and losses from decaying or destroyed wood products harvested in earlier years. This means that some of the contributions to carbon losses from harvested wood products will be due to the decay or destruction of wood products that were harvested in the years prior to the reporting period actually being considered. For example, considering the IPCC category of sawnwood products, which are assumed to be the most long-lived, and applying the decay rate suggested in IPCC Good Practice Guidance (IPCC, 2006, 2014; see Section 5.5 of this report), the decay of products will still be making a contribution to emissions (although very small) after 100 years since the time of manufacture. For the purposes of this study, historical wood production was estimated using the CARBINE model by "spinning the model up" for a number of decades prior to the base year adopted for the study.

7. Results

This section presents, assesses and interprets the main results of this study. In Section 7.1, results for projected wood production are checked for consistency with the scenario for "business as usual" (BAU) management earlier in this report. The key results for woodland carbon stocks are presented in Section 7.2, whilst results for GHG emissions and removals are presented in Section 7.3.

7.1. Wood production

7.1.1. Total and regional wood production

As explained earlier in this report (see in particular Sections 6.2.3 and 6.3.3), the construction of projections of the development of woodland carbon stocks for a baseline or BAU scenario involved an assumption of a fixed NRW-scale annual target for wood volume production from NRW (commercial) woodlands over the period 2015 to 2040 (extended to 2050 for the purposes of modelling). The NRW-scale annual target was disaggregated, to provide consistent targets for annual wood volume production from each of the five NRW operational regions (see Section 6.3.5, in particular Table 6.7).

Figure 7.1 shows the projected total level of wood production from NRW commercial woodlands, as simulated by the CARBINE model, over the period 2015 to 2040 (the temporal spatial boundary for this study). The individual contributions to production made by woodlands in the five NRW operational regions are also shown in the figure. The results for wood production are expressed in units of thousands of cubic metres over bark standing. Projected total wood production is slightly higher than but very close to the NRW-scale target set of 850,000 m^3 per year (see Table 6.6, Section 6.2.3). The projected total volume production is consistently within 1.5% of this target. Projections of wood production from individual NRW operational regions are also consistently very close to the allocated target contribution towards the NRW-scale target.

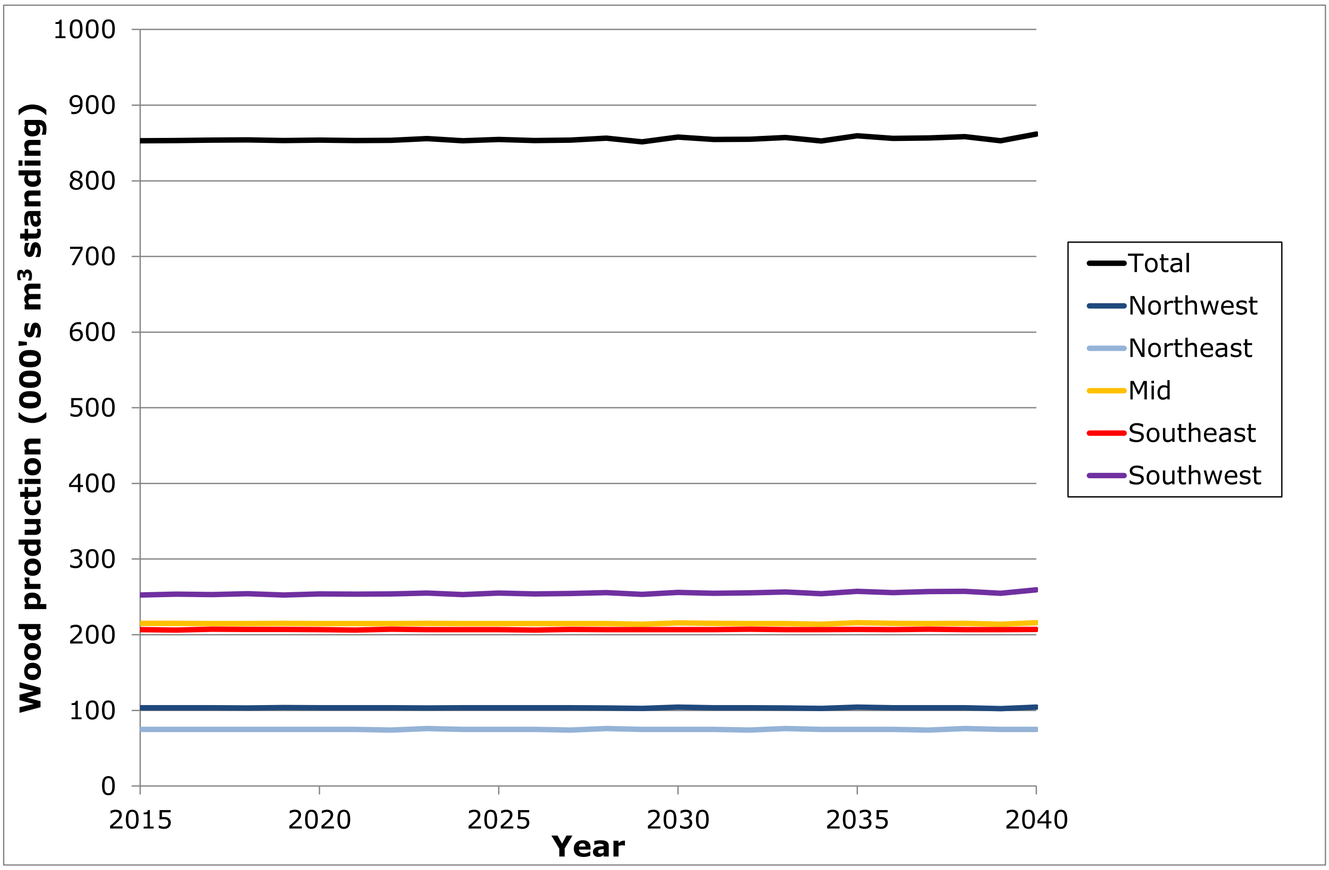

Figure 7.1. Projected levels of wood production from NRW commercial woodlands.

7.1.2. Wood production by major woodland types

Figure 7.2 shows the contributions to the projected total level of wood production from NRW commercial woodlands, as made by the three major woodland types defined in Section 6.4.1 (broadleaved woodlands, coniferous woodlands managed as reserves or according to continuous cover management prescriptions and coniferous woodlands managed according to clearfelling management prescriptions). The majority of simulated wood production is contributed by coniferous woodlands managed according to clearfelling management prescriptions (about 700,000 m^3 per year). However, it should be noted that production from areas managed on a clearfelling regime will include a variable element of production from thinning. Coniferous woodlands managed as reserves are assumed not to contribute towards wood production but coniferous woodlands managed according to continuous cover management prescriptions will contribute towards wood production through thinning operations. The projected contribution made by such thinning in continuous-cover coniferous woodlands is about 150,000 m^3 per year. All of the wood production from broadleaved woodlands is assumed to be from thinning operations (Table 6.6, Section 6.2.3). The contribution to total wood production from the thinning of broadleaves is small, typically about 4,700 m^3 per year. These results exhibit reasonable consistency with the information provided by NRW specialists on likely future volume production (Table 6.6, Section 6.2.3).

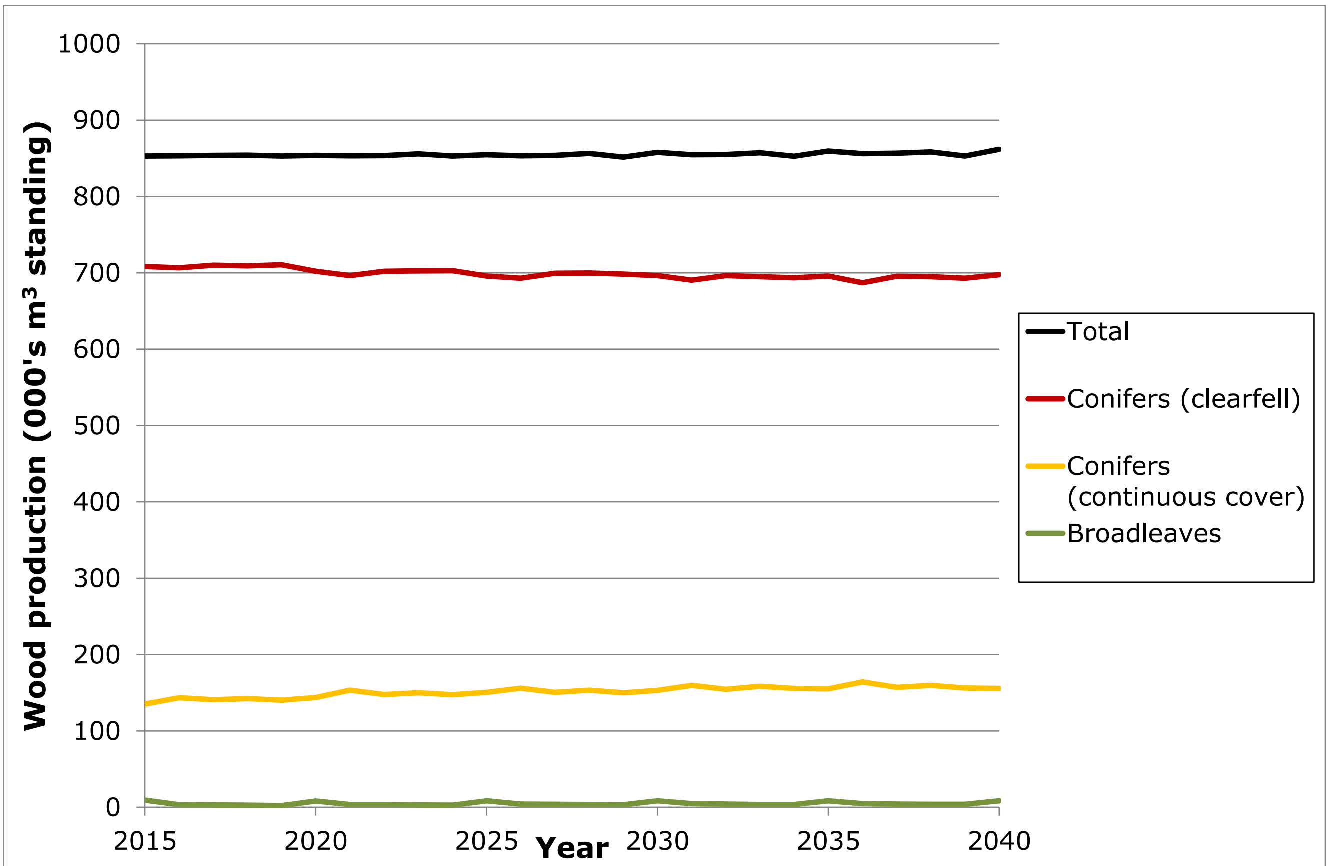

Figure 7.2. Contributions made by major woodland types to projected levels of wood production from NRW commercial woodlands.

7.1.3. Wood production by major woodland types within regions

As discussed in Section 7.1.1, projected levels of total wood production for each of the five NRW operational regions are reasonably stable over the period 2015 to 2040. Results for projected total wood production for each of the major woodland types are also reasonably stable when considered at the scale of all NRW commercial woodlands (see Section 7.1.2). However, results for projected levels of wood supply contributed by each of the major woodland types, within an individual NRW operational region, exhibit variability over time. This is illustrated in Figure 7.3, which shows the relevant results for the example of the Northeast operational region.

Figure 7.3 shows that projected total wood production in the Northeast operational region is reasonably stable over time at a level that is consistent with the target level of production set for this region as part of the definition of the BAU scenario (74,900 m^3, see Section 6.3.5). The bulk of the production in this region is from coniferous woodlands. However, the total production is made up of variable contributions over time from coniferous woodlands managed according to continuous cover management prescriptions and coniferous woodlands managed according to clearfelling management prescriptions. The main reason for the variability in these two contributions is due to the approach taken to modelling wood production in this study. Specifically, in the growth model underlying the CARBINE model, the scheduling of thinning from woodlands managed on continuous cover prescriptions is simulated according to when the individual modelled woodland areas are identified as having sufficient growing stock. Hence, the timing of thinnings in these types of woodlands depends on a number of factors, such as tree species, yield class and, notably, stand/tree age. The somewhat cyclical level of wood production from these woodlands as exhibited in Figure 7.3 is a reflection of the uneven age distribution of woodland areas managed according to continuous cover prescriptions. In the modelling of the BAU scenario for each region (see in particular Sections 6.3.2 and 6.3.6), production from coniferous woodlands managed according to clearfelling management prescriptions was scheduled to compensate for the variability in projected wood production from continuous-cover woodlands (both broadleaved and coniferous), so as to give reasonably stable projected wood production over time, consistent with the regional targets that were set.

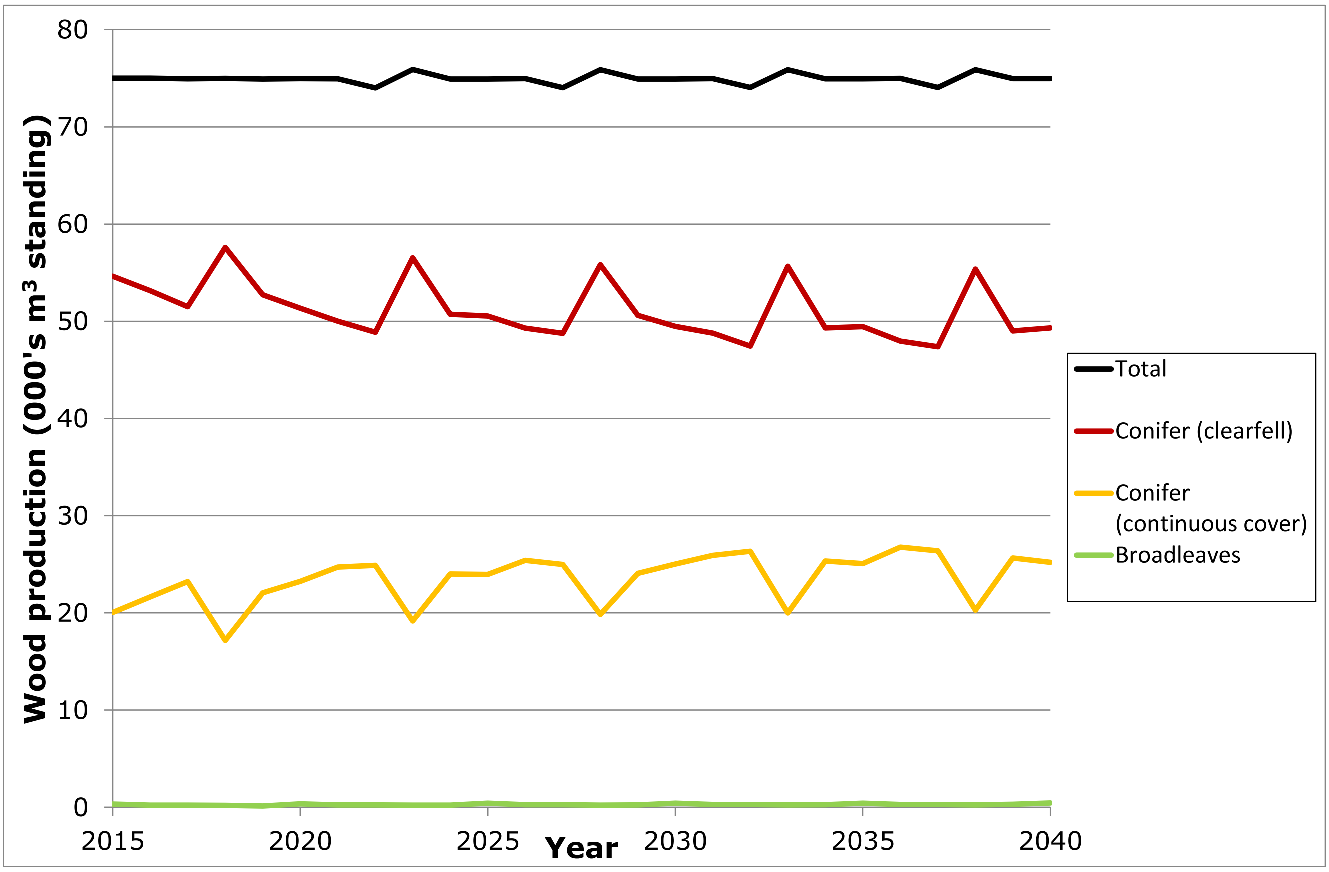

Figure 7.3. Contributions made by major woodland types to projected levels of wood production from commercial woodlands in the Northeast NRW operational region.

Whilst the variability in levels of wood production from the two coniferous major woodland types is clearly apparent in Figure 7.3, the inter-annual variation in wood production from the continuous-cover woodlands is typically within 10% of the average level over the period 2015 to 2040.

7.1.4. Wood production by product category

Figure 7.4 shows the percentage shares of projected wood production used for the manufacture of different categories of semi-finished wood products, as defined by the IPCC (2006, 2014, see also Appendix 5 of this report), specifically:

- Fuel
- Paper
- Wood-based panels
- Sawnwood.

The calculation of the percentage shares in Figure 7.4 allows for the conversion of standing volume into harvested and extracted wood products.

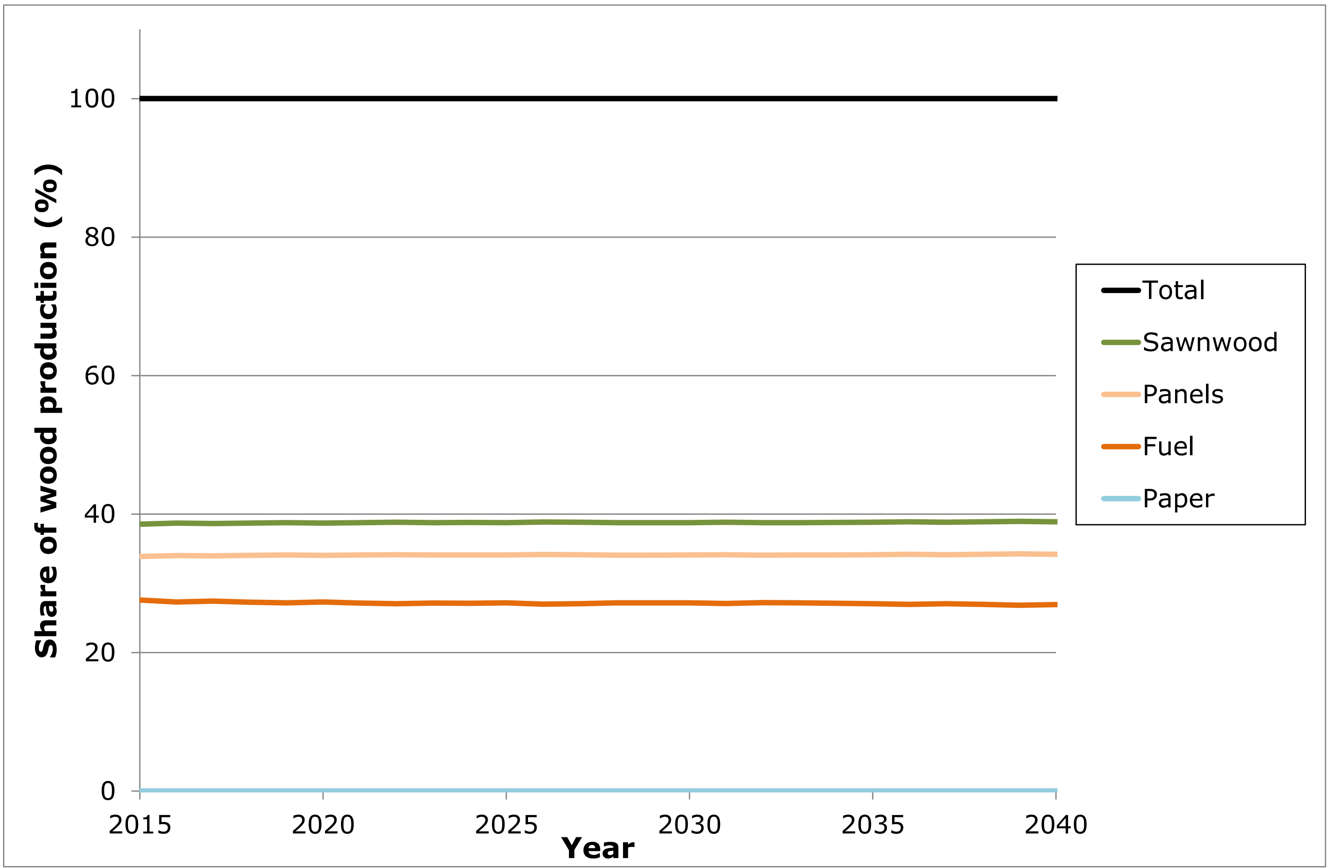

Figure 7.4. Percentage share of wood production used for the manufacture of different semi-finished wood product categories.

The relative quantities of harvested wood used for the different categories of semi-finished wood products are very stable and the shares are very consistent with those suggested by information provided by NRW specialists (see Appendix 5).

7.2. Woodland carbon stocks

7.2.1. Total carbon stocks in woodland carbon pools

Figure 7.5 shows the projected development of total woodland carbon stocks in all NRW woodlands, as simulated by the CARBINE model for the period 2015 to 2040 (the temporal system boundary for this study). The individual contributions made by different carbon pools associated with woodland (trees, litter, soil and harvested wood products) are also shown in the figure.

It should be noted that the results for carbon stocks produced by the CARBINE model have been adjusted by a factor of 85% to allow for unproductive land areas (such as roads, rides etc.) and as a general allowance for variations in stocking. This adjustment is based on a standard factor that is applied generally in British forestry to woodland forecast estimates (see for example Bradley, Christie and Johnston, 1966).

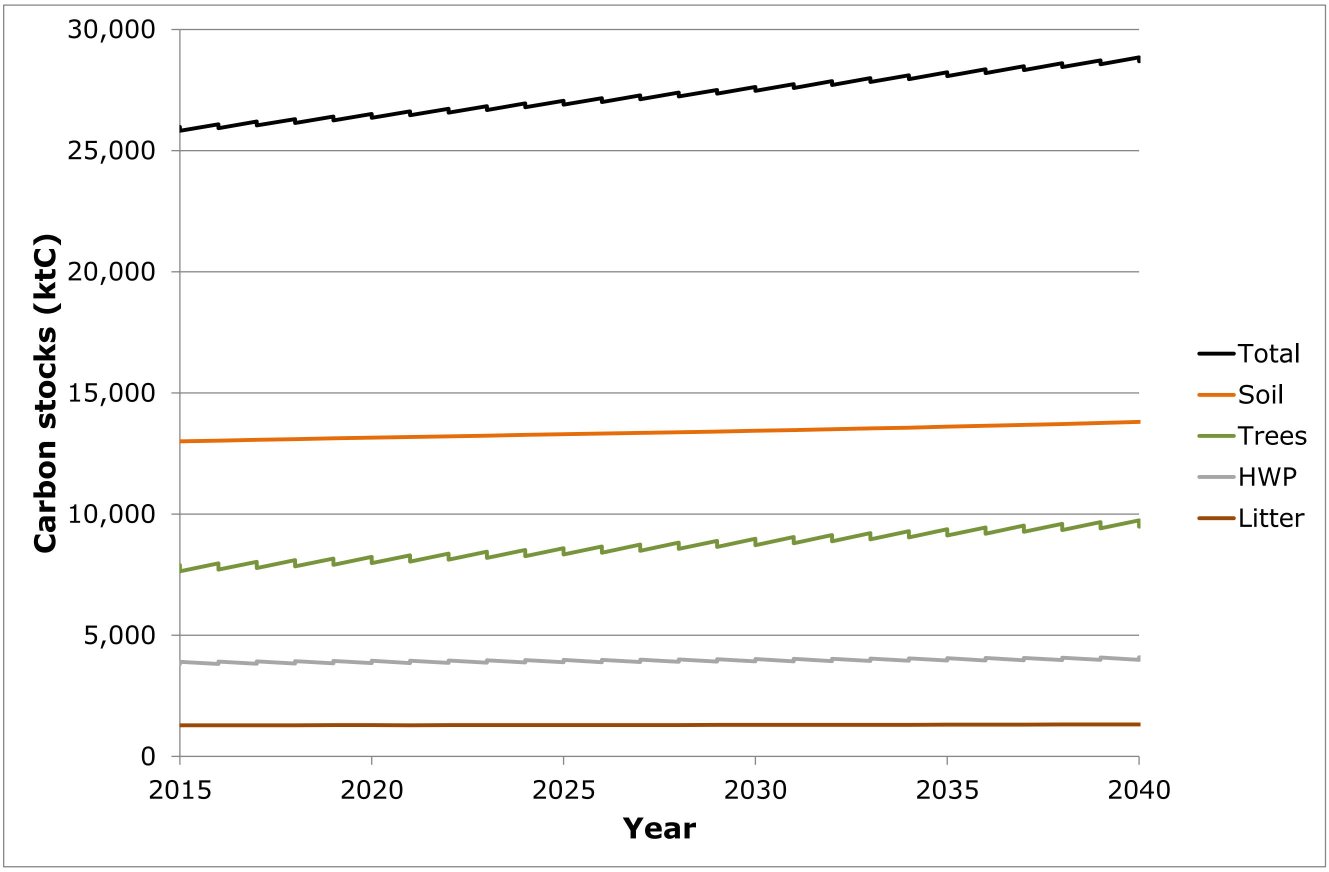

Figure 7.5. Projected development of total woodland carbon stocks for all NRW woodlands.

The total carbon stocks in NRW woodlands in the base year of 2015 are estimated at 26.6 MtC. About 50% of the carbon stocks are in woodland soils, 30% in trees, 15% in harvested wood products with the remaining 5% in woodland deadwood and litter.

By the time horizon for this study of 2040, the total carbon stocks are projected to have risen to 29.5 MtC, an increase of 2.9 MtC compared with the base year of 2015. About 64% of this increase is due to the accumulation of carbon stocks in trees, with about 28% contributed by accumulating soil carbon stocks, whilst litter and harvested wood products (HWP) contribute approximately 1% and 7% respectively to the total increase in carbon stocks.

The increase in carbon stocks relative to the carbon stocks in the base year in soil, litter, trees and HWP are, respectively, about 6%, 3%, 24% and 5%.

The above results for total carbon stocks and total carbon stock changes (over the period 2015 to 2040) in NRW woodlands are reasonably consistent with existing scientific evidence. For example, results and analysis reported by Morison *et al*. (2012) suggest that soil carbon stocks make the largest contributions to total woodland carbon stocks, followed by carbon stocks in trees. However, in general, carbon stocks in soil are relatively stable, hence carbon stock changes in soil tend to be smaller relative to the magnitude of the stock, when compared with other carbon pools, notably trees.

7.2.2. Per-hectare carbon stocks in woodland carbon pools

Figure 7.6 shows the projected development of per-hectare total woodland carbon stocks in all NRW woodlands, as simulated by the CARBINE model for the period 2015 to 2040. The individual contributions made by different carbon pools associated with woodland (trees, litter, soil and harvested wood products) are also shown in the figure.

It should be noted that the results for per-hectare carbon stocks are based on the assumed stocked area of woodland. Hence, both the carbon stock estimates and the area have been adjusted by a factor of 85% to allow for unproductive land areas (such as roads, rides etc.) and as a general allowance for variations in stocking. This adjustment is based on a standard factor that is applied generally in British forestry to woodland forecast estimates (see for example Bradley, Christie and Johnston, 1966). Note that the adjustment effectively cancels out since it is made to both the stocks and the area. The gross area referred to (for all NRW commercial woodlands and non-commercial woodlands) was 108,113 ha. This value is slightly lower than the area quoted in Tables 6.3 and 6.4 (see Section 6.2.1) of 108,513 ha, mainly due to the exclusion of 300 ha of felled woodland in the Southwest operational region (see Table 6.6, Section 6.2.2), but also partly as a result of small rounding errors in model calculations.

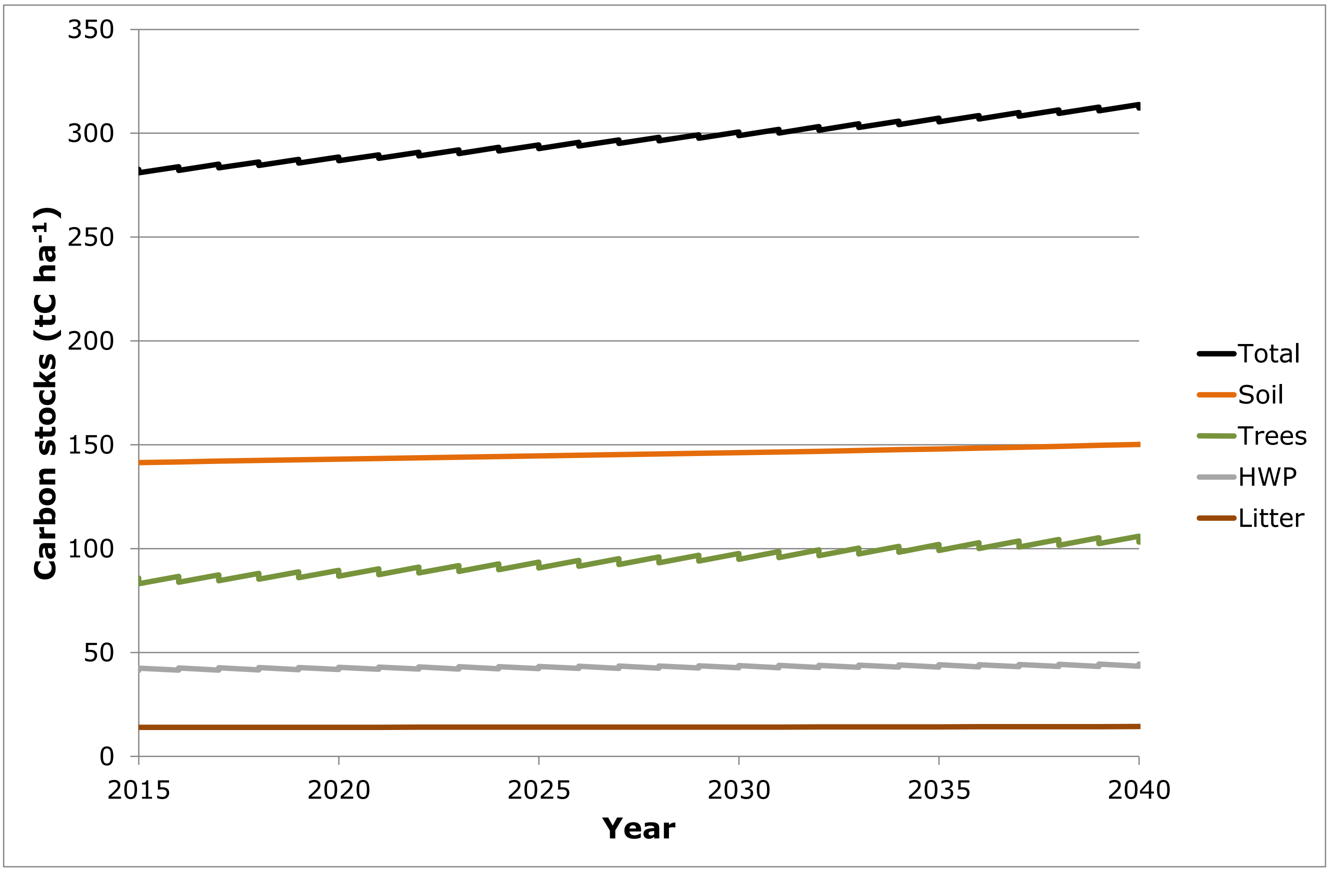

Figure 7.6. Projected development of per-hectare woodland carbon stocks for all NRW woodlands.

The per-hectare carbon stocks in different woodland carbon pools estimated in this study for the base year of 2015 are summarised in Table 7.1. The table also gives a range of estimates of carbon stocks as reported in a selection of scientific literature, either of relevance to Wales or the UK, or based on meta-analysis of available research results.

The modelled results exhibit quite strong consistency with the various estimates given in Table 7.1 although, as might be expected, results reported by different studies and reviews are variable. The results for soil carbon stocks show the greatest variability; this is due to a number of factors, including differences in the soil depth for which results apply and also different conventions adopted in defining the organic matter of soils (e.g. whether or not litter and/or fermenting litter are included as part of soil carbon).

Table 7.1 Estimated carbon stocks per hectare in NRW woodlands in 2015 compared with selected estimates from scientific literature

Source	Carbon stocks (tC ha^{-1})				
	Soil	Litter	Trees	HWP	Total
This study	150	14	83	42	289
Broadmeadow and Matthews (2003)	228[1]	-	70[2]	~50[3]	
Bradley *et al.* (2005)	200[4]	-	-	-	
Matthews (1991)	-	-	-	35[5]	
Morison *et al.* (2012)	133-155[6]	15-17[7]	57[8]	~25[9]	
IPCC (2006)	63-115[10]	13-26[11]	104[12]	-	

Notes to Table 7.1:

1 Average soil carbon stocks (soil depth 1 m) for all land classified as woodland in Wales, based upon information provided by the National Soil Resources Institute, the James Hutton Institute and Queen's University Belfast (Milne, 2001).

2 Estimate quoted for woodlands managed for wood production in the UK.

3 Based on interpretation of model simulations relevant to European forests reported by Nabuurs (1996), repeated in Figure 10 of Broadmeadow and Matthews (2003).

4 Average soil carbon stocks (soil depth 1 m) for all land classified as woodland in Wales.

5 Based on interpretation of Figures 3 and 7 in Matthews (1991), which present results for UK woodland stands.

6 Range quoted in Executive Summary of Morison *et al*. (2012) for GB mineral soils (1 m soil depth).

7 Average carbon stocks in litter for coniferous and broadleaved woodlands in the UK as quoted in Executive Summary of Morison *et al*. (2012).

8 Average carbon stocks in trees in GB woodlands as quoted in Executive Summary of Morison *et al*. (2012).

9 Based on interpretation of model results for GB woodlands given in Appendix 8 of Morison *et al.* (2012).

10 Reference estimates for soil carbon stocks (soil depth 30 cm) under native woodland vegetation ("cold/warm temperate, moist" climate).

11 Estimates are for "cold/warm temperate, moist" climate.

12 Estimates are for "temperate oceanic forest".

7.2.3. Total carbon stocks in woodland by region

Figure 7.7 shows the projected development of total woodland carbon stocks (in trees, litter, soil and harvested wood products) in all NRW woodlands, as simulated by the CARBINE model for the period 2015 to 2040. The figure also shows the individual contributions made by carbon stocks in commercial woodlands in the different operational regions and by non-commercial woodlands. As previously, it should be noted that the results for carbon stocks produced by the CARBINE model have been adjusted by a factor of 85% to allow for unproductive land areas (such as roads, rides etc.) and as a general allowance for variations in stocking.

It should be noted that the results for the Mid and Southwest operational regions are almost coincident in Figure 7.7, to the extent that the yellow projection for the Mid region is barely visible.

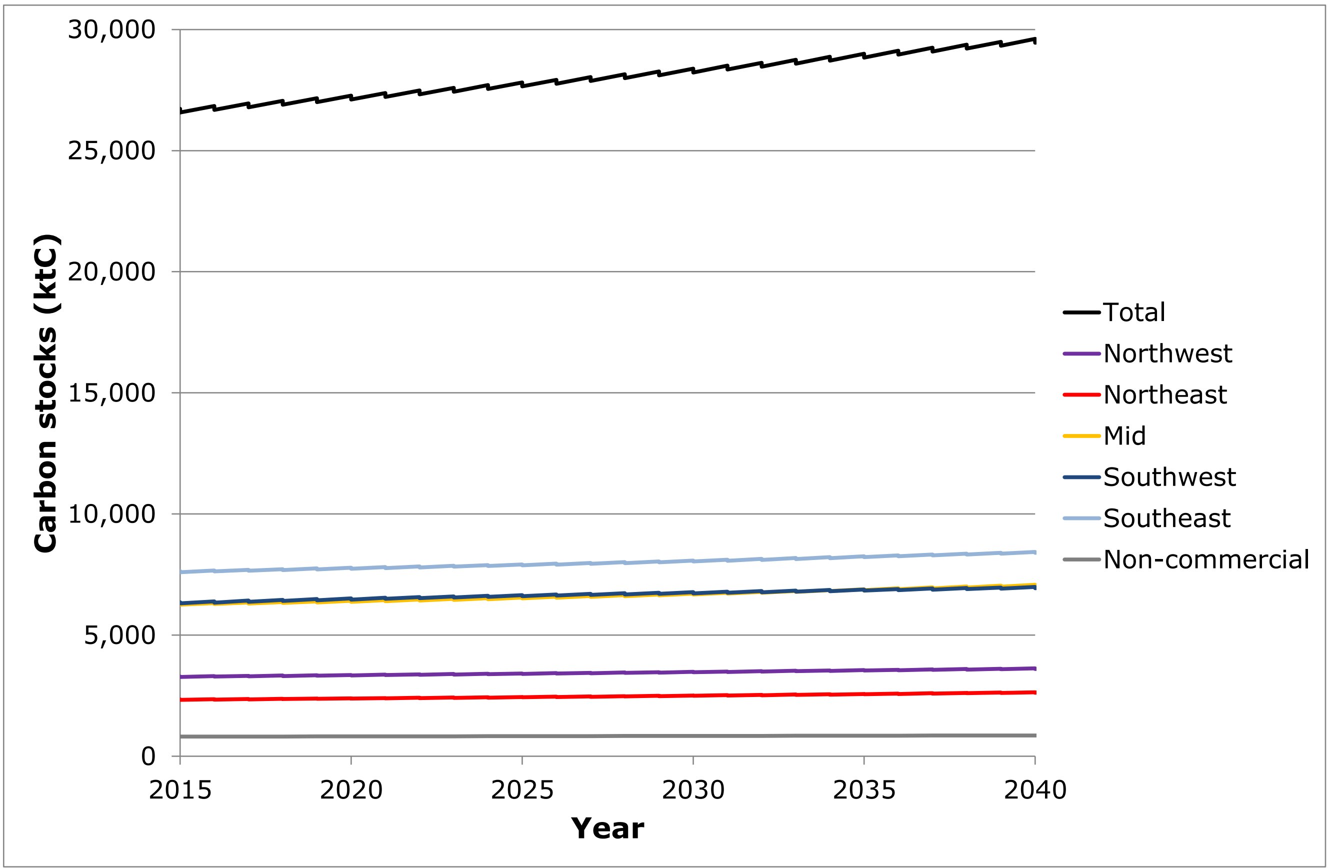

Figure 7.7. Projected development of total woodland carbon stocks for each NRW operational region and for non-commercial woodlands.

In general, the variable contributions to total carbon stocks from woodlands in different regions are simply related to differences in the total area of woodlands in each region. The biggest areas of woodland are in the Southeast, Southwest and Mid operational regions, the areas in the three regions being quite similar, at around 23,000 to 24,500 ha (net area). The net area of woodlands is smaller in the Northwest region (about 11,000 ha) and the Northeast region (about 8,500 ha), and smallest for non-commercial woodlands (about 1,400 ha net area). There are secondary effects on the relative contributions to total carbon stocks due to variations in the per-hectare woodland carbon stocks in individual regions (between 265 and 315 tC ha^{-1} for commercial woodlands in 2015), but these variations and their effects appear to be quite small. An exception is the area of non-commercial woodlands, which makes a disproportionately large contribution to total carbon stocks, compared with the contributions of commercial woodlands. This reflects the greater estimated per-hectare carbon stocks in these woodlands, at 583 tC ha^{-1} in the base year of 2015, which in turn reflects assumptions made in modelling that:

- A large part of the non-commercial woodland area will be composed of mature trees
- Harvesting activities and natural disturbances in non-commercial woodlands have been, and will be, quite limited.

7.2.4. Change in total carbon stocks in woodland by region

Table 7.2 shows results for the projected change in total woodland carbon stocks (in trees, litter, soil and harvested wood products) in all NRW woodlands, as simulated by the CARBINE model for the period 2015 to 2040. The table also shows the individual contributions made by carbon stocks in commercial woodlands in the different operational regions and by non-commercial woodlands. As previously, it should be noted that the results for carbon stocks produced by the CARBINE model have been adjusted by a factor of 85% to allow for unproductive land areas (such as roads, rides etc.) and as a general allowance for variations in stocking.

Table 7.2 Changes in total carbon stocks in NRW woodlands between 2015 and 2040

	North-west	North-east	Mid	South-west	South-east	Non-comm.	Total
Carbon stock in 2015 (ktC)	3 274	2 328	6 260	6 306	7 598	807	26 573
Carbon stock in 2040 (ktC)	3 604	2 624	7 035	6 938	8 395	856	29 452
Carbon stock change over period (ktC)	330	296	773	632	797	50	2 878
Relative change compared with base year (%)	10.1	12.7	12.4	10.0	10.5	6.2	10.8
Annualised carbon stock change (tC ha^{-1} yr^{-1})	1.2	1.4	1.4	1.1	1.3	1.4	1.3

Carbon stocks are projected to increase over the period 2015 to 2040 in all NRW regions (i.e. taken as a whole, NRW woodlands are acting as a net carbon sink over this period). The contributions made by individual regions to the total increase in carbon stocks are closely related to the magnitude of the total carbon stocks in each region in the base year of 2015. In turn, these base-year carbon stocks are simply related to the different areas of woodland in each region (see Section 7.2.3).

The percentage increase in carbon stocks relative to the total carbon stocks in the base year is quite consistent across the five operational regions of NRW commercial woodlands (between 10% and 13%). The equivalent percentage increase in non-commercial woodlands is lower, at about 6%, reflecting the relatively older age of these woodlands and the age-related decline in growth rates with tree age.

Results for the annualised per-hectare total carbon stock change over the period from 2015 to 2040 are remarkably similar (a net increase, or carbon sink, of between 1.1 and 1.4 tC ha^{-1} yr^{-1}). However, it should be noted that the lowest rate of per-hectare total carbon stock change is estimated for woodlands in the Southwest operational region (at 1.1 tC ha^{-1} yr^{-1}). This result is pertinent to subsequent analysis of results for GHG emissions and removals (see in particular Sections 7.3.1, 7.3.2, 7.3.4 and 7.3.6).

The results for non-commercial woodlands in Table 7.2 for the percentage relative increase in carbon stocks and for the annualised per-hectare carbon stock changes may appear to be contradictory, in that the result for the percentage relative increase is notably lower than results estimated for the commercial woodlands, whereas the result for the annualised per-hectare stock change is one of the highest. When interpreting the results for NRW commercial woodlands and non-commercial woodlands, it is important to recognise that the composition and management of non-commercial woodland areas are very different to the composition and management of commercial woodland areas. Most importantly, the non-commercial woodlands (as modelled in this study) are composed entirely of mature broadleaved tree species and coppice, and are not under any significant management for wood production. In contrast, the commercial woodlands are composed mainly of generally younger coniferous tree species and are under extensive management for wood production. As a consequence, the non-commercial woodlands have higher per-hectare carbon stocks when compared with the commercial woodlands forming the NRW estate.

The results in Table 7.2 for per-hectare carbon stock changes in NRW woodlands may be compared with estimates available from other studies for Great Britain, Europe, the Russian Federation and the World (see Table 7.3). When comparing the results of this study with the other estimates in Table 7.3, it is important to note that the results as calculated in this study include a (relatively small) contribution due to carbon sequestration in harvested wood products (see for example Table 7.1, Section 7.2.2), whereas the results quoted in other scientific studies generally do not include this contribution. Also, the results in Table 7.3 for Great Britain reported by Morison *et al*. (2012) are for trees only.

From Table 7.3 it may be seen that, for all regions, the estimated carbon stock change is positive, i.e. carbon stocks are increasing and the woodlands or forests are acting as a net carbon sink. The carbon sink estimated for the World's forests is lower than for Europe and the Russian Federation. This reflects variability in the composition and management of global forests. At the scale of the World's forests:

- There are significant areas of "natural" or "old-growth" forest; the rate of tree growth in these forest areas, hence the rate of carbon sequestration, may be expected to have declined compared with peak rates.
- Significant areas of forest are subject to major natural disturbances (storms, fires and disease infestations).
- Significant loss of forest areas is occurring as a result of deforestation activities.

In Europe and the Russian Federation, the rate of per-hectare carbon sequestration in forests is higher than for the World's forests taken as a whole. It is likely that this reflects a number of factors, but not least the impacts of programmes of woodland expansion and restoration undertaken during the previous century in a number of countries across Europe and the Russian Federation, which has significantly increased the area of relatively young (hence relatively fast growing) woodland areas. The past management of woodlands has also contributed to European forests having a relatively large proportion of younger woodland areas (Vilén *et al*., 2012). Currently, the carbon stocks of these young forests are increasing. The effects of historical efforts to expand and restore areas of woodland are certainly present in the results for GB and NRW woodlands.

Table 7.3 Comparison of estimates of net carbon stock changes

Region	Net carbon stock change (tC ha^{-1} yr^{-1})
NRW woodlands (this study)	1.1 to 1.4
Great Britain (mean rate, trees only)	0.9 to 1.4[1]
Great Britain (peak rates, trees only)	1.4 to 5.5[2]
Europe and Russian Federation	0.7[3]
World	0.3[3]

Notes to Table 7.3:

1 Estimates presented in the Executive Summary of Morison *et al*. (2012) for mean rate of carbon sequestration in trees in GB woodlands.

2 Estimates presented in the Executive Summary of Morison *et al*. (2012) for range in peak rates of carbon sequestration in trees (i.e. around the time of fastest tree growth) that may be observed in GB woodlands.

3 Based on estimates presented by Pan *et al*. (2011) and assuming forest areas based on FAO statistics (FAO, 2010). See Table 2.2 in Section 2.4.1 and Table 3.1 in Section 3.3 of Matthews *et al*. (2015).

The relatively high magnitude of the projected carbon sink to 2040, as estimated in this study for NRW woodlands, also reflects certain important assumptions made in defining the BAU scenario (see Sections 4, 6.2.3 and 6.2.4 of this report). One very important assumption concerns the level of harvesting assumed to take place over the period to 2040, which is estimated to be more than compensated for by the growth of trees in woodlands over the same period, with the consequence that, overall in NRW woodlands, tree carbon stocks increase between 2015 and 2040, even after allowing for harvesting.

A more detailed assessment of the projected net carbon sink of NRW woodlands, for example trends over time and the contribution of carbon stock changes to total GHG emissions or removals, is presented in Section 7.3.

7.2.5. More detailed results for woodland carbon stocks

Separate results for woodland carbon stocks such as described above for all NRW woodlands in Figures 7.5 (Section 7.2.1) and 7.6 (Section 7.2.2), have been produced for:

- Each operational region of NRW commercial woodlands (Northwest, Northeast, Mid, Southwest, Southeast), and for the area of NRW non-commercial woodlands
- Each of the three major woodland types (broadleaved woodlands, coniferous woodlands managed according to continuous cover management prescriptions and coniferous woodlands managed according to a clearfelling management prescription).

These results may be found in the MS Excel workbooks:

- "NRW_NW_summary_v13.xlsx"
- "NRW_NE_summary_v13.xlsx"
- "NRW_MID_summary_v13.xlsx"
- "NRW_SW_summary_v13.xlsx"
- "NRW_SE_summary_v13.xlsx"
- "NRW_NC_summary_v13.xlsx".

The results for all NRW woodlands may be found in the MS Excel workbook "NRW_ALL_summary_v17.xlsx" (see in particular worksheets with red and yellow coloured tabs).

7.3. Woodland GHG emissions and removals

This section presents the main results for projected GHG emissions and removals associated with NRW woodlands over the period 2015 to 2040. It is important to recall the spatial system boundary for this study, which encompasses all woodlands owned or managed by Natural Resources Wales and includes contributions to GHG emissions due to:

- CO_2 emissions and removals due to carbon stock changes in the trees, litter and soil of NRW woodlands and harvested wood products

- The main GHG emissions (CO_2, CH_4 and N_2O) arising from woodland operations (tree establishment, woodland management and harvesting).

The system boundary does not include contributions to GHG emissions due to:

- CH_4 and N_2O emissions from woodland soils (particularly organic soils)
- GHG emissions arising from timber transport from the woodland
- GHG emissions arising from the processing of harvested wood and the manufacture and installation of finished wood products
- GHG emissions potentially avoided from using wood products (including woodfuel) in place of alternative products (possibly supplied or manufactured using other types of materials or fuels, including fossil fuel sources).

Note also that:

- Results for GHG emissions/removals are expressed in units of CO_2-eq. (with units of C-eq. being used occasionally to permit comparison between some of the results in this section and those for carbon stock changes reported in Section 7.2)
- Negative results indicate net GHG removals; positive results indicate net GHG emissions.

7.3.1. Total woodland GHG emissions/removals

Figure 7.8 shows the projected development of net GHG emissions and removals due to NRW woodlands, as simulated by the CARBINE model for the period 2015 to 2040. The individual contributions made by different carbon pools associated with woodland (trees, litter, soil and harvested wood products), and by woodland operations, are also shown in the figure.

As previously (see Section 7.2.1), it should be noted that the results for GHG emissions and removals produced by the CARBINE model have been adjusted by a factor of 85% to allow for unproductive land areas (such as roads, rides etc.) and as a general allowance for variations in stocking.

The projected results in Figure 7.8 indicate that there are net GHG removals associated with NRW woodlands over the period 2015 to 2040, equal to about 410 $ktCO_2$-eq. yr^{-1} (0.4 $MtCO_2$-eq. yr^{-1}) in total. The main contribution to removals is from trees (about two thirds of total removals over the period from 2015 to 2040). Woodland soils contribute about 30% to total removals, with HWP contributing around 7%. The contribution to removals due to woodland litter is almost negligible. GHG emissions from woodland operations offset the total GHG removals by about 13 $ktCO_2$-eq. yr^{-1} (3%).

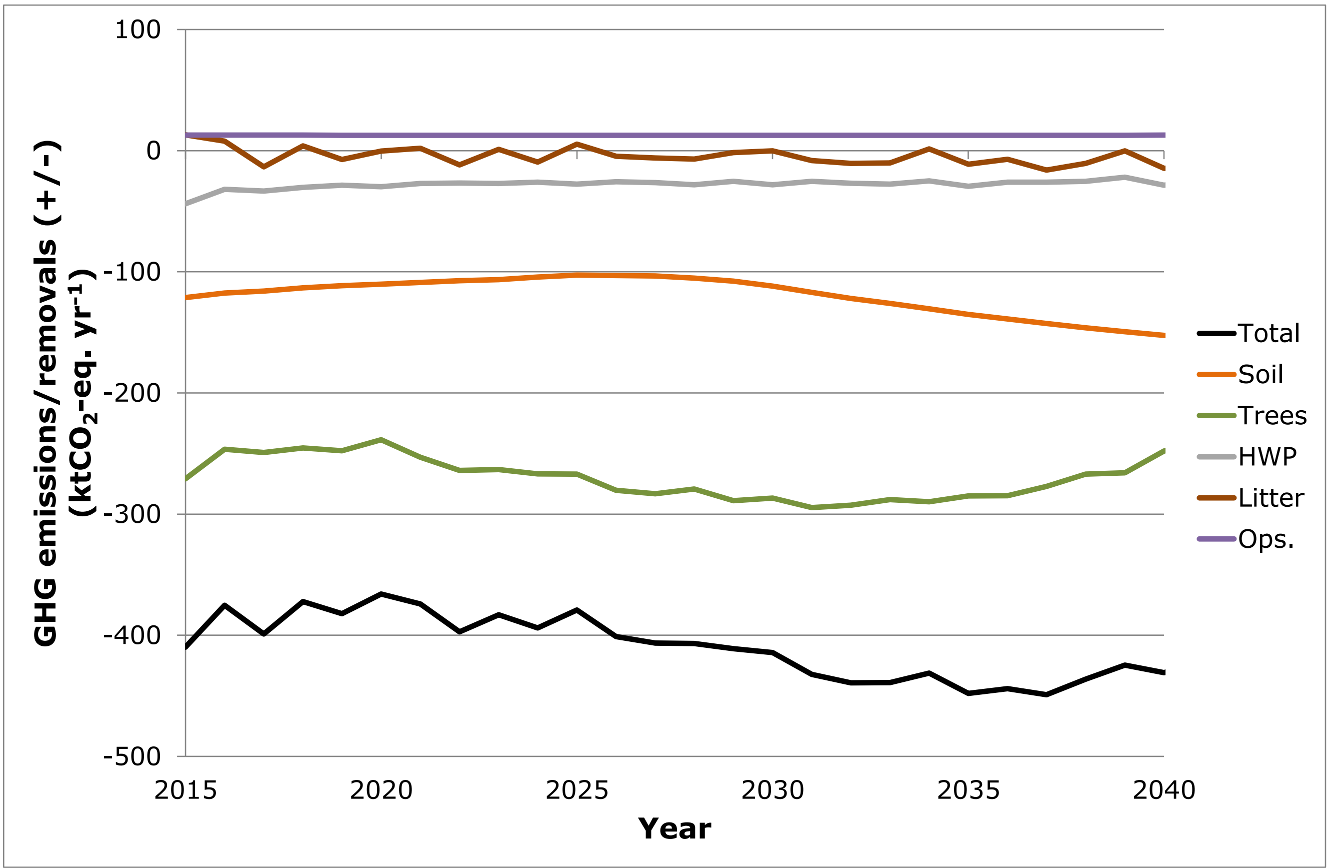

Figure 7.8. Projected development of net GHG emissions/removals for all NRW woodlands.

7.3.2. Key causes of trends and fluctuations in contributions made by woodland carbon pools and operations to GHG emissions/removals

The projected total net GHG removals are reasonably stable between 2015 and 2040, increasing by just 5% over this period. However, the apparent stability of total net GHG removals masks some quite significant trends and fluctuations in the contributions made by individual carbon pools and by woodland operations.

The main features in the projections for these contributions are summarised in the ensuing discussion, with a brief explanation of the most likely causes of the various features exhibited.

Woodland trees

Woodland trees are predicted to make a significant and fairly stable contribution to net GHG removals but with some evidence of a cyclical variation in magnitude over time and a possible progressive decline in removals after about 2030.

The causes of the pattern observed are related to the composition of the woodland growing stock in NRW woodlands and impacts of tree harvesting to meet the target(s) set for wood production. The details are quite complex and are the subject of further analysis and discussion in Sections 7.3.4 and 7.3.6.

There are also small inter-annual fluctuations in the magnitude of GHG net removals contributed by woodland trees.

These fluctuations are related to the types of woodland harvested each year to meet the target(s) for wood production. Although the annual level of wood production is held constant over the period, the modelled mix of tree species and relative levels of thinning and felling vary from year to year. This leads to variable impacts of woodland carbon stocks each year due to harvesting, resulting in turn in fluctuations in projected GHG removals associated with woodland trees.

The fluctuations in the modelled projection of GHG removals due to woodland trees (and indeed for total GHG removals) are relatively small. However, it is important to note that, in reality, the actual trajectory of GHG removals or emissions associated with NRW woodlands is likely to exhibit significant inter-annual variability. Notable major likely causes of this variability will be:

- Differences between the actual level of wood production from NRW woodlands and the assumed constant target each year, for example as influenced by timber markets; it should be noted that the business as usual scenario includes an assumption that annual wood production may vary between a minimum of 700,000 m^3 over bark standing and a maximum of 850,000 m^3 over bark standing (see Table 6.6, Section 6.2.3). Whilst the modelling of the scenario is based on the assumption of maximum planned wood production, in reality annual production could vary between 700,000 m^3 and 850,000 m^3.
- Natural disturbance events (due to, for example, storms, fires and disease infestations) that occur in NRW woodlands in particular years or over periods of years over the period 2015 to 2040.

Woodland litter

Woodland litter is predicted to make an almost negligible contribution to net GHG removals in NRW woodlands.

The very small GHG removals typically predicted for woodland litter reflect the fact that, generally, losses of carbon due to the decomposition of litter balance the inputs of carbon to the litter pool (from tree biomass turnover and harvesting). Note also that fermenting organic matter in litter is reported as part of the soil carbon pool by the CARBINE model, rather than as part of the litter pool. Hence, the accumulation of carbon in fermenting litter is reported as part of woodland soil carbon, rather than litter carbon.

There are also some inter-annual fluctuations between net removals and net emissions exhibited in the projected contributions from woodland litter.

As already explained in the discussion of woodland trees above, although the annual level of wood production is held constant over the period, the modelled mix of tree species and relative levels of thinning and felling vary from year to year. This leads to variable levels of inputs to litter each year from harvesting, resulting in turn in short-term fluctuations in projected GHG emissions or removals associated with litter.

Woodland soils

In general, woodland soils are predicted to make a moderately significant contribution to net GHG removals over the period 2015 to 2040. However, the magnitude of this contribution declines slightly between 2015 and 2025, followed by a pronounced progressive rise in the contribution to removals up to 2040.

The pattern observed in projected GHG removals due to woodland soils arises from an interplay in dynamic responses of soils carbon to the woodlands growing on them, and in particular how those woodlands are being managed:

- On the one hand, there are net losses of carbon from soil associated with wood harvesting activities (particularly clearfelling), due to soil disturbance during harvesting and reduced carbon inputs from growing trees, but the rate of loss declines and stabilises later on in the period.
- On the other hand, there are net gains in soil carbon in woodlands managed as natural reserves and in woodlands managed according to continuous cover prescriptions. This reflects the relatively high growing stock of these woodland types (hence relatively high carbon inputs to the soil). The accumulation of soil carbon associated with these types of woodland is the main effect later on in the period.

Harvested wood products

Carbon stock changes in HWP are predicted to make a small contribution to net GHG removals, which declines gradually over the period from 2015 to 2040.

The net GHG removals due to HWP reflect the accumulation of carbon in HWP, in response to increased production from NRW woodlands, in turn arising from past woodland expansion and restoration activities. However, the projected annual level of wood production is held constant over the period 2015 to 2040. As a consequence, as more and more HWP accumulate in use, losses of carbon from decaying and disposed HWP will eventually come into balance with the inputs of carbon to the HWP pool, leading to zero net removals associated with HWP. Hence, net removals due to HWP are very gradually declining towards zero.

Woodland operations

A very small contribution is predicted for GHG emissions arising from woodland operations. The magnitude of these GHG emissions is predicted to be stable between 2015 and 2040.

Harvesting and road maintenance activities make the biggest contributions. The projected annual level of wood production is held constant over the period, involving fairly similar woodland operations (particularly harvesting and road maintenance) each year.

7.3.3. Per-hectare woodland GHG emissions/removals

Figure 7.9 shows the projected development of per-hectare net GHG emissions and removals due to NRW woodlands, as simulated by the CARBINE model for the period 2015 to 2040. The individual contributions made by different carbon pools associated with woodland (trees, litter, soil and harvested wood products), and by woodland operations, are also shown in the figure. As previously, it should be noted that the results for GHG emissions and removals produced by the CARBINE model have been adjusted by a factor of 85% to allow for unproductive land areas (such as roads, rides etc.) and as a general allowance for variations in stocking. Note that the adjustment effectively cancels out since it is made to both the GHG emissions/removals and the area. The gross area referred to (for all NRW commercial woodlands and non-commercial woodlands) was 108,113 ha. This value is slightly lower than the area quoted in Tables 6.3 and 6.4 (see Section 6.2.1) of 108,513 ha, mainly due to the exclusion of 300 ha of felled woodland in the Southwest operational region (see Table 6.6, Section 6.2.2), but also partly as a result of small rounding errors in model calculations.

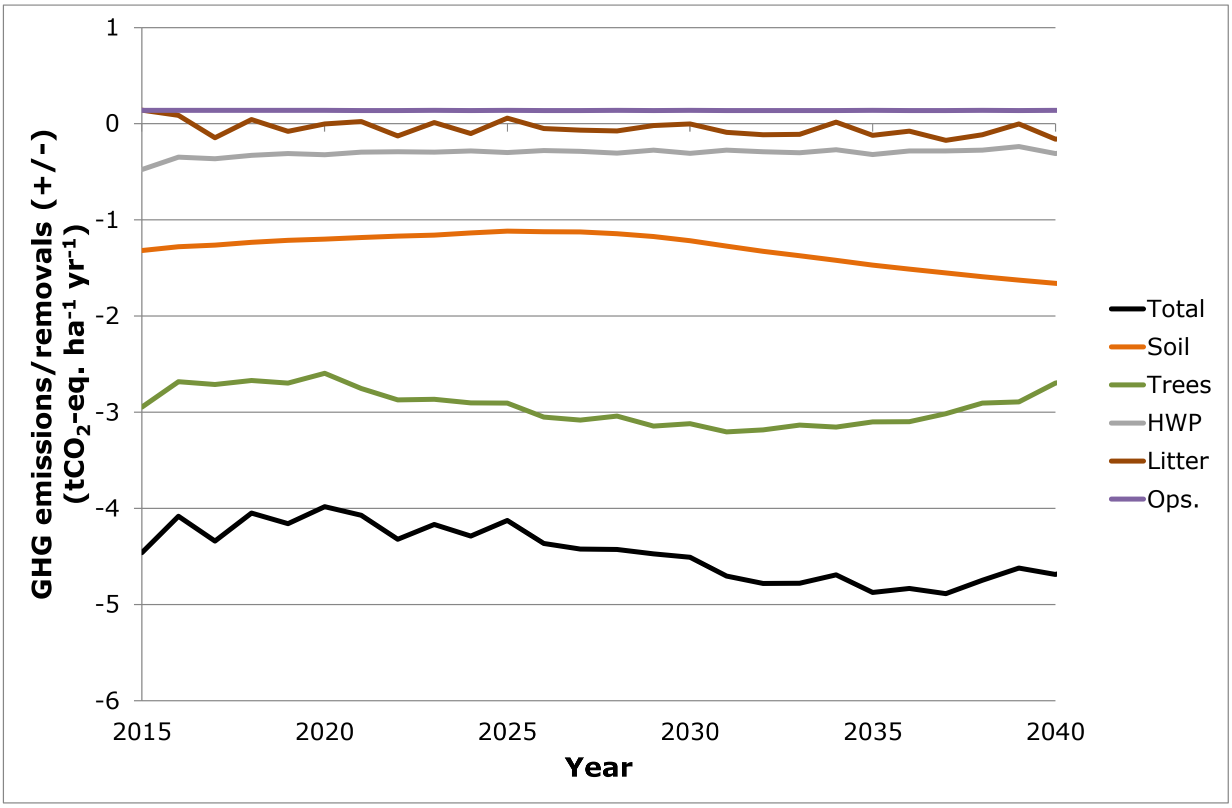

Figure 7.9. Projected development of per-hectare net GHG emissions/removals for all NRW woodlands.

As would be expected, the results for per-hectare net GHG emissions and removals in Figure 7.9 are very similar to the results for total net GHG emissions as already considered in Section 7.3.1.

Table 7.4 shows results for projected net GHG emissions and removals associated with NRW woodlands, annualised over the period 2015 to 2040. The results in Table 7.4 are expressed in units of both tCO_2-eq. ha^{-1} yr^{-1} and tC-eq. ha^{-1} yr^{-1}. Results are given in the table for the total net GHG and removals and contributions due to individual woodland carbon pools (trees, litter, soil and harvested wood products) and GHG emissions due to woodland operations.

Table 7.4 Projected annualised GHG emissions/removals associated with NRW woodlands over the period 2015 to 2040

Category	GHG emissions/removals (+/-)	
	tCO_2-eq. ha^{-1} yr^{-1}	tC-eq. ha^{-1} yr^{-1}
Woodland trees	-2.9	-0.8
Woodland litter	0.0	0.0
Woodland soils	-1.3	-0.4
Harvested wood products	-0.3	-0.1
Woodland operations	0.1	0.0
Total	**-4.4**	**-1.2**

Note to Table 7.4: The result for woodland operations expressed in tonnes carbon equivalent is small and positive, but appears as zero to one decimal place.

The result in Table 7.4 for total annualised net GHG removals expressed in units of tC-eq. ha^{-1} yr^{-1} are consistent with the results for annualised woodland carbon stock changes reported earlier in Tables 7.2 and 7.3 in Section 7.2.4. Similarly, the result in Table 7.4 for GHG removals contributed by woodland trees may be compared with the estimates given in Table 7.3 (Section 7.2.4) for woodland trees in Great Britain, originally reported by Morison *et al*. (2012). The estimate for NRW woodlands is reasonably consistent the estimates for mean carbon stock changes in GB woodlands.

7.3.4. Total woodland GHG removals by region

Figure 7.10 shows the projected development of total net GHG emissions and removals due to NRW woodlands, as simulated by the CARBINE model for the period 2015 to 2040. The figure also shows the individual contributions made by GHG emissions and removals due to commercial woodlands in the different operational regions and due to non-commercial woodlands. As previously, it should be noted that the results for GHG emissions and removals produced by the CARBINE model have been adjusted by a factor of 85% to allow for unproductive land areas (such as roads, rides etc.) and as a general allowance for variations in stocking.

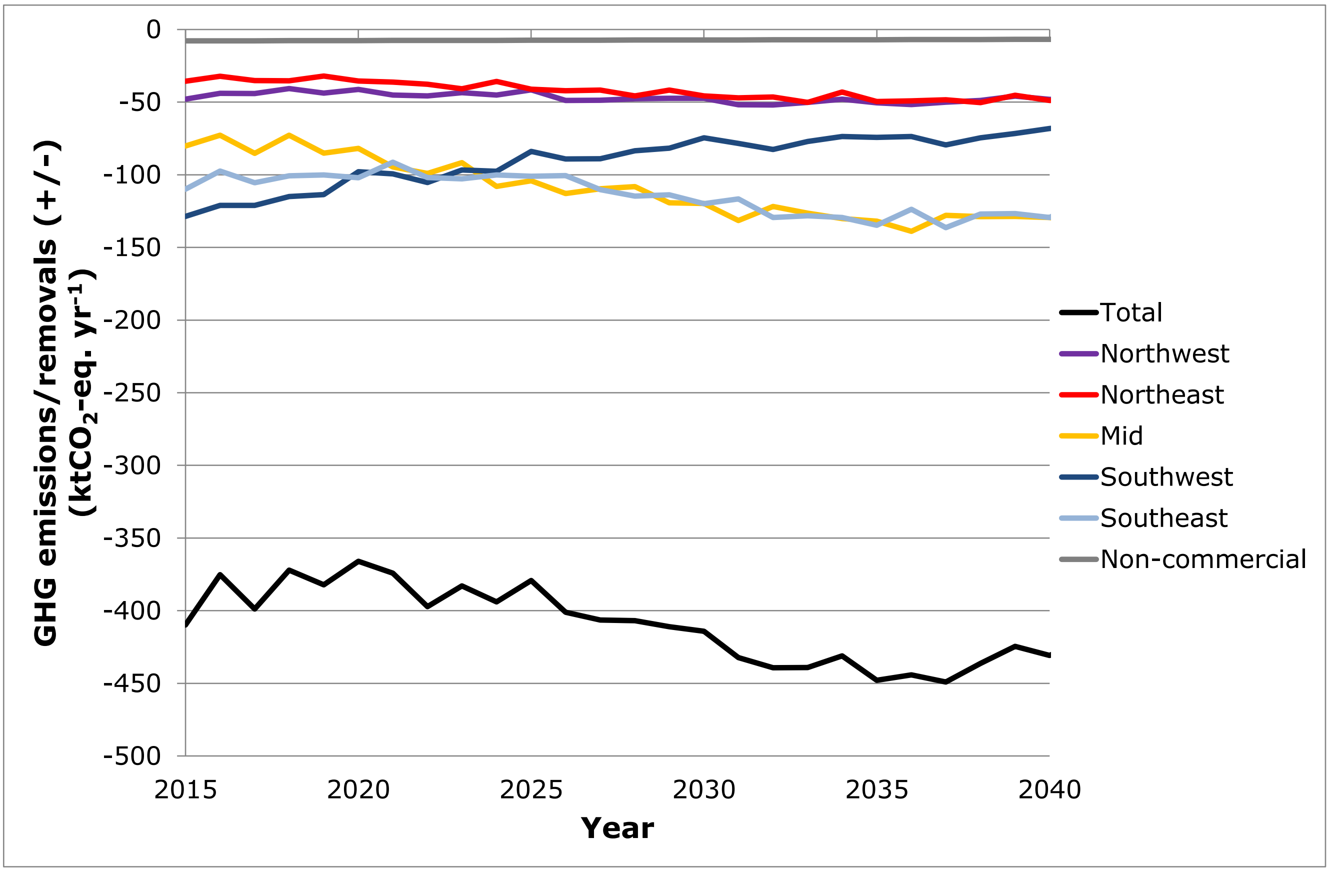

Figure 7.10. Projected development of total net GHG emissions/removals for each NRW operational region and for non-commercial woodlands.

In very broad terms, the variable contributions to total net GHG removals due to woodlands in different regions are simply related to differences in the total area of woodlands in each region, as was the case for woodland carbon stocks (see Section 7.2.3). However, it is clear that there is more complexity in the relative contributions from regions, particularly over time. The trends in the contributions are more apparent in Figure 7.11, which is similar to Figure 7.10 but omits the projection for total net GHG removals and consequently has an expanded y axis scale.

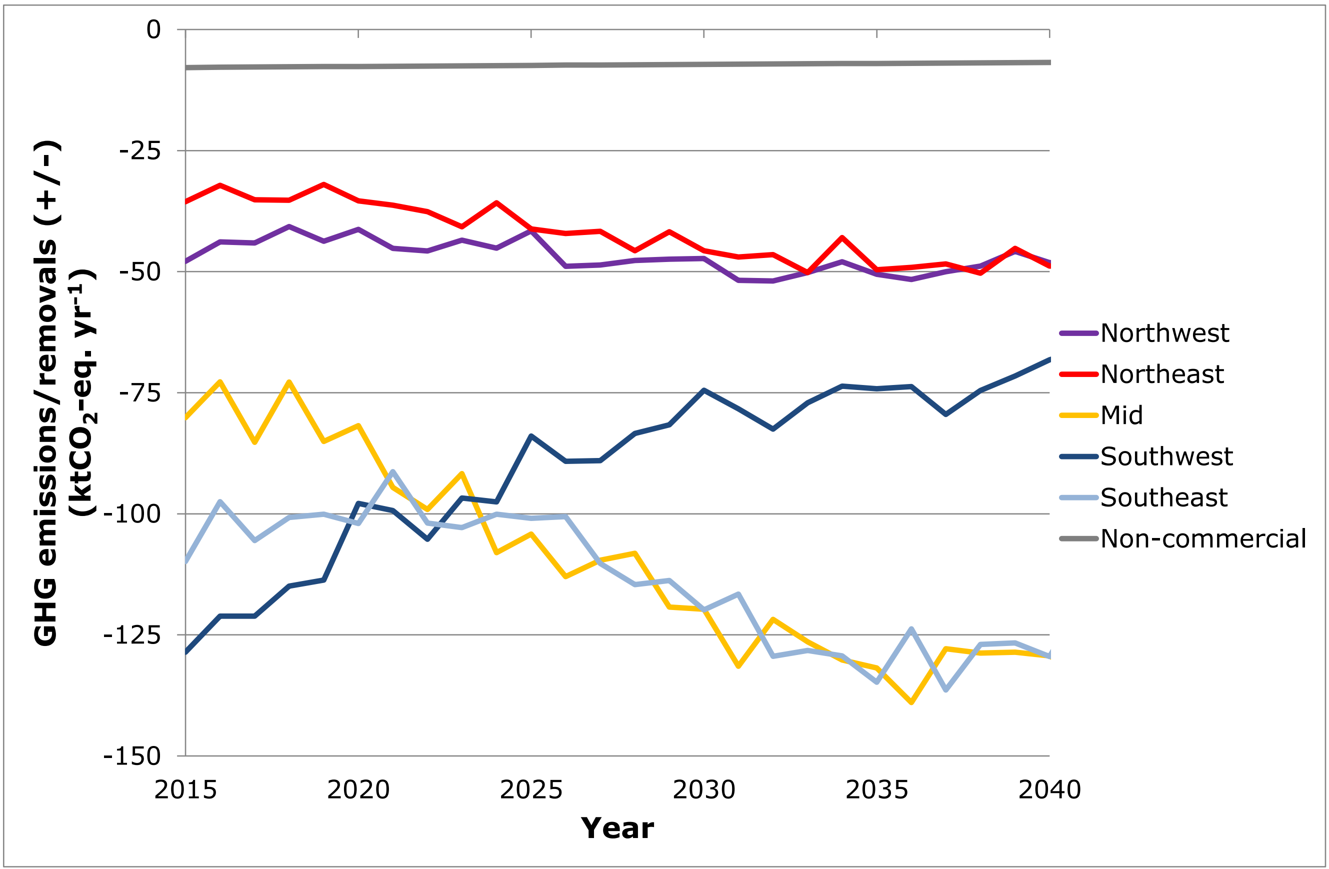

Figure 7.11. Details of projected development of net GHG emissions/removals for individual NRW operational regions and for non-commercial woodlands.

A number of features are apparent in the projections in Figure 7.11:

- All five operational regions of NRW commercial woodlands and the non-commercial woodlands are projected to contribute net GHG removals over the period 2015 to 2040
- There are relatively small inter-annual fluctuations in the projections of net GHG removals for commercial woodland areas (see Section 7.3.2, particularly the discussion of fluctuations in results for woodland trees and litter)
- The relative magnitudes of net GHG removals due to commercial woodlands in the Northwest, Northeast, Mid and Southeast operational regions broadly reflect the differing areas of woodlands in these regions; the net GHG removals in these regions are projected to rise over the period from 2015 to 2040
- The increase in net GHG removals over the period from 2015 to 2040 is most pronounced for woodlands in the Mid operational region, rising from about -80 $ktCO_2$-eq. yr^{-1} in 2015 to about -130 $ktCO_2$-eq. yr^{-1} in 2040

- In contrast to other operational regions, the projected net GHG removals due to commercial woodlands in the Southwest operational region decline progressively and significantly over the period from 2015 to 2040, falling from about -130 ktCO_2-eq. yr^{-1} in 2015 to about -70 ktCO_2-eq. yr^{-1} in 2040
- In 2015, the magnitude of net GHG removals is greatest in the Southwest operational region of commercial woodlands but by 2020 the net GHG removals are comparable to those for the Mid and Southeast operational regions and by 2030 the net GHG removals in the Southwest region are closer to those for the Northeast and Northwest operational regions
- Projected net GHG removals are smallest for the non-commercial NRW woodlands and removals decrease gradually over the period from 2015 to 2040 (see discussion of development of carbon stocks in non-commercial woodlands in Section 7.2.4).

Establishing the causes of the most important trends identified above has required very detailed investigation of the CARBINE model results and their relationship to the input data and assumptions made in this study. This subject is discussed further in Section 7.3.6.

7.3.5. Per-hectare woodland GHG removals by region

Figure 7.12 shows the projected development of per-hectare net GHG emissions and removals due to NRW woodlands, as simulated by the CARBINE model for the period 2015 to 2040. The figure also shows the individual contributions made by GHG emissions and removals due to commercial woodlands in the different operational regions and due to non-commercial woodlands. As previously, it should be noted that the results for carbon stocks produced by the CARBINE model have been adjusted by a factor of 85% to allow for unproductive land areas (such as roads, rides etc.) and as a general allowance for variations in stocking.

The results in Figure 7.12 indicate that the magnitudes of the projected rates of net GHG removals are broadly similar, ranging from between -3 tCO_2-eq. ha^{-1} yr^{-1} (-0.8 tC-eq. ha^{-1} yr^{-1}) and -6 tCO_2-eq. ha^{-1} yr^{-1} (-1.6 tC-eq. ha^{-1} yr^{-1}). The range indicated expressed in units of tC-eq. ha^{-1} yr^{-1} (allowing for change of sign) suggests that the rates of net carbon sequestration for woodlands in all ranges bear comparison with the rates reported in previously published studies (see Table 7.3 in Section 7.2.4).

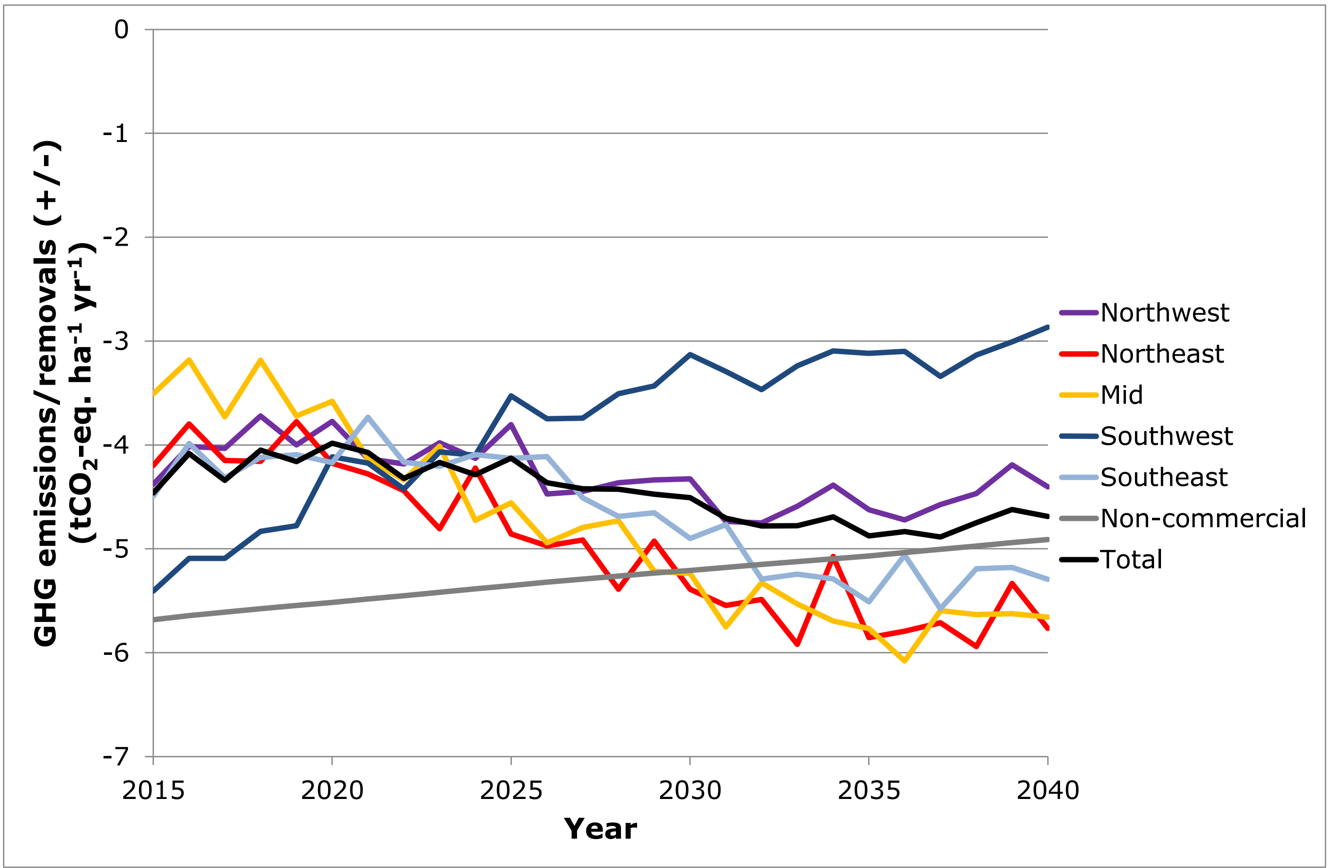

Figure 7.12. Details of projected development of net GHG emissions/removals for individual NRW operational regions and for non-commercial woodlands.

Whilst the general magnitudes of the per-hectare net GHG removals in Figure 7.12 seem reasonable for all operational regions of NRW commercial woodlands and for the non-commercial woodlands, there are significant differences in trends in per-hectare net GHG removals for individual regions over the period 2015 to 2040. In particular:

- There is a progressive increase in projected per-hectare net GHG removals in commercial woodlands in the Northeast, Mid and Southeast operational regions of commercial woodlands; the increase in removals is greatest for the Mid operational region
- Projected per-hectare net GHG removals in the Northwest operational region of commercial woodlands exhibit variations in magnitude over the period from 2015 to 2040 but, overall, the magnitude of removals is broadly stable over the period
- There is a progressive and significant decline in per-hectare net GHG removals in commercial woodlands in the Southwest operational region
- There is a gradual but progressive decline in the magnitude of per-hectare net GHG removals in the non-commercial woodlands.

Table 7.5 summarises the magnitudes of the per-hectare net GHG removals for the various NRW regions and the changes in magnitude of pre-hectare removals over the period 2015 to 2040. The most significant projected changes in per-hectare net GHG removals occur in the Northeast, Mid and Southwest operational regions of NRW commercial woodlands (the relevant results are highlighted in bold text in Table 7.5).

Table 7.5 Magnitudes of projected net per-hectare GHG removals in individual NRW regions and changes over the period 2015 to 2040

Region	Net GHG removals (tCO_2-eq. ha^{-1} yr^{-1})		
	Year 2015	**Year 2040**	**Increase/decrease in removals**
Northwest	-4.4	-4.4	0.0
Northeast	-4.2	-5.8	**1.6 increase**
Mid	-3.5	-5.7	**2.1 increase**
Southwest	-5.4	-2.9	**2.5 decrease**
Southeast	-4.5	-5.3	0.8 increase
Non-commercial	-5.7	-4.9	0.8 decrease
Total	**-4.5**	**-4.7**	**0.2 increase**

Establishing the causes of the most important trends observed in Figure 7.12, Table 7.5 and the associated discussion has required very detailed investigation of the CARBINE model results and their relationship to the input data given to the model. This subject is discussed further in Section 7.3.6.

7.3.6. Key causes of trends in woodland GHG removals by region

An investigation was made to establish the main causes of the trends exhibited in projections of net GHG removals for individual operational regions of NRW woodlands over the period 2015 to 2040. The analysis focussed on the commercial woodland areas, since the drivers of the magnitude and trend of total net GHG removals in non-commercial woodland were fairly straightforward to identify (see relevant discussions in Sections 7.2.3 and 7.2.4).

The analysis considered the overall increase or decrease in total net GHG removals as exhibited in each operational region of NRW commercial woodlands over the period 2015 to 2040, based on the projections for total net GHG removals as presented and discussed in Section 7.3.4. The increase or decrease for each operational region was traced back to underlying features of the composition of woodlands and aspects of woodland management in each region.

The approach to the analysis consisted of three steps:

1. Characterising the contributions to trends in GHG removals made by key categories of woodland comprising the NRW estate (e.g. young woodlands, broadleaved woodlands, woodlands managed as reserves or involving clearfelling etc.)
2. Characterising the composition of NRW commercial woodlands in each operational region, in terms of the proportions of woodland area occupied by the different woodland categories identified in Step 1
3. Assessing relationships between the trends in total GHG removals and the composition of woodland areas as characterised in Steps 1 and 2.

Step 1: Characterisation of contributions made by categories of woodland

For the purpose of this analysis, a set of woodland categories was defined. The categories were designed to be relevant to this study and the data referred to, and also designed to capture certain key aspects of woodland carbon dynamics. Categories were defined with the following names:

- Total broadleaves
- Young broadleaves
- Young conifers
- Conifer reserves
- Conifer CCF
- Clearfell conifer.

It should be apparent that the categories are related to the broader three major woodland types defined in Section 6.4.1 (broadleaved woodlands, coniferous woodlands managed as reserves or according to continuous cover prescriptions and coniferous woodlands managed according to clearfelling prescriptions).

In addition to the categories listed above, certain other possible woodland categories were investigated as part of this analysis (examples include larch woodlands, because of the special business rules specified for their management, as described in Table 6.6, Section 6.6, and young Sitka spruce woodlands, because of the high growth rates likely to be associated specifically with young Sitka spruce stands). However, these other categories were subsequently discounted because it was not possible to identify refinements in relationships between trends in woodland carbon sequestration in regions and these categories, over and above what could be inferred from analysis based on the categories listed above.

The following discussion describes each of the woodland categories and their relevance to woodland carbon dynamics. It will be apparent that there are overlaps in the areas of woodland represented by the various categories. However, this is not important from the perspective of the analysis undertaken here.

Total broadleaves

This category represents the total area of broadleaved woodland in a given operational region of NRW commercial woodlands. As explained in Section 6.2.3 (see Table 6.6), all broadleaved woodland areas were assigned to "alternative silvicultural systems". These consisted of:

- Either management of woodlands as "reserves" (management based on "minimum intervention" with no or very limited wood harvesting)
- Or management based on "continuous cover" (management as uneven-aged, continuous cover woodland, involving thinning but avoiding clearfelling).

As part of the modelling of the BAU scenario developed in this study, a significant proportion of broadleaved woodland was assigned to management as "reserves", in order to achieve a reasonable match with the NRW-scale target set for wood production from broadleaves (see Section 6.2.3, Table 6.6).

As a consequence of the relatively limited extent of harvesting activities, broadleaved woodland areas generally accumulate carbon stocks over time (i.e. sequester carbon), particularly in trees and soils over the period of the temporal system boundary of this study (2015 to 2040). Hence, generally, broadleaved woodlands contribute towards net GHG removals due to woodlands. However, the magnitude of this contribution will depend on the age of the trees making up the broadleaved woodlands; areas composed of older trees will exhibit an age-related decline in the rate of carbon sequestration.

Young broadleaves

This category represents the total area of broadleaved woodland in a given operational region of NRW commercial woodlands with a planting year more recent than 1979[4]. Young broadleaves were assigned similar management prescriptions to older broadleaved woodlands (see preceding description of "Total broadleaves" category). However, in addition, due to their relatively young age, the rate of carbon sequestration of young broadleaves is likely to increase over the temporal system boundary of this study. Hence, generally, young broadleaved woodlands will make an increasing contribution towards net GHG removals due to woodlands over the period 2015 to 2040.

[4] This year was selected based on the planting year classes in Table 6.4, Section 6.2.1. In effect, it selects the three most recent planting year classes in Table 6.4 as representing young trees. Woodland areas in these classes consist of stands of trees with ages 0 to 38 years. Typically, carbon sequestration in woodland stands is highest prior to the culmination of mean annual volume increment, which occurs roughly around age 40 to 70 years in typical woodland stands growing in UK conditions.

Young conifers

This category represents the total area of coniferous woodland in a given operational region of NRW commercial woodlands with a planting year more recent than 1979[4]. Regardless of the management prescription applied to young coniferous woodlands, due to their relatively young age, the rate of carbon sequestration of young conifers is likely to increase over the temporal system boundary of this study. Hence, generally, young coniferous woodlands will make an increasing contribution towards net GHG removals due to woodlands over the period 2015 to 2040.

Conifer reserves

This category represents the total area of coniferous woodland in a given operational region of NRW commercial woodlands assigned to management as "reserves" (management based on "minimum intervention" with no or very limited wood harvesting). As such, this category represents a sub-set of the major woodland type defined in Section 6.4.1 of coniferous woodlands managed as reserves or according to continuous cover prescriptions, in that continuous-cover woodland areas are not included.

As a consequence of the extremely limited extent of harvesting activities, conifer reserve areas generally accumulate carbon stocks over time (i.e. sequester carbon), particularly in trees and soils over the period of the temporal system boundary of this study. Hence, generally, conifer reserves contribute towards net GHG removals due to woodlands over the period 2015 to 2040. However, the magnitude of this contribution will depend on the age of the trees making up the conifer reserve woodlands; areas composed of older trees will exhibit an age-related decline in the rate of carbon sequestration.

Conifer CCF

This category represents the total area of coniferous woodland in a given operational region of NRW commercial woodlands assigned to management based on "continuous cover" (management as uneven-aged, continuous cover woodland, involving thinning but avoiding clearfelling). As such, this category represents a sub-set of the major woodland type defined in Section 6.4.1 of coniferous woodlands managed as reserves or according to continuous cover prescriptions, in that reserve areas are not included.

The carbon dynamics of this woodland category are complex but can be broadly summarised as follows:

- The avoidance of clearfelling activities reduces some of the impacts on woodland carbon stocks due to wood harvesting (see subsequent description of "Conifer clearfell" category)
- However, over the temporal system boundary of this project, sustained wood production through progressive thinning of relatively mature coniferous woodlands

leads to reductions in carbon sequestration by woodland trees and eventually net carbon stock losses (net emissions)

- The balance between avoidance of clearfelling, whilst enhancing additions to woodland litter as a result of thinning, leads to increased inputs of carbon to the soil and potentially increased carbon sequestration in soil.

As a consequence of these various impacts, conifer CCF woodlands can make a variable contribution to net GHG removals. Detailed inspection of the results of the CARBINE simulations for this study indicates that, on balance, conifer CCF woodlands frequently are associated with moderate net reductions to total net GHG removals over the period 2015 to 2040.

Conifer clearfell

This category represents the total area of coniferous woodland in a given operational region of NRW commercial woodlands managed according to clearfelling management prescriptions.

Generally speaking, the age distribution of coniferous woodlands in the NRW estate reflects past efforts to expand and restore productive woodland areas. As a consequence, there are substantial areas of coniferous woodlands that are now mature and of an age suitable for clearfelling, with the result that clearfelling activities make a significant contribution to wood production from NRW woodlands over the temporal system boundary of this project. Because of this, in general, net GHG emissions from felling in Conifer clearfell woodlands contribute significantly towards reductions in net GHG removals over the period from 2015 to 2040. For some operational regions (see subsequent analysis under Step 3), the age distribution of Conifer clearfell woodland areas (and implied levels of clearfelling) can lead to progressively deeper reductions in overall net GHG removals associated with NRW woodlands over this period (because net emissions from the felling of Conifer clearfell stands offsets net carbon sequestration in other woodlands).

Summary of impacts associated with woodland categories

Based on the descriptions given above for the various woodland categories, Table 7.6 gives a summary qualitative assessment of the most likely impacts on trends in total net GHG removals over the system boundary of this study.

Table 7.6 Qualitative assessment of contributions of woodland categories to trends in total net GHG removals

Woodland category	Indicative impact on trend in total net GHG removals
Total broadleaves	+/0
Young broadleaves	++
Young conifers	++
Conifer reserves	+
Conifer CCF	+/--
Conifer clearfell	--

Note to Table 7.6: A "++" symbol indicates a strong contribution towards a rise in net GHG removals over the period 2015 to 2040; a "+" symbol indicates a notable contribution towards a rise in net GHG removals over the period 2015 to 2040; a "--" symbol indicates a strong contribution towards a decline in net GHG removals over the period 2015 to 2040; a "-" symbol indicates a notable contribution towards a decline in net GHG removals over the period 2015 to 2040; a "0" symbol indicates a negligible contribution to net GHG removals over the period 2015 to 2040.

Step 2: Characterisation of woodlands comprising operational regions

The composition and management of commercial woodlands in each operational region of the NRW estate were characterised with respect to the woodland categories defined in Step 1 above. The approach is illustrated below for the example woodland categories of "Total broadleaves" and "Young broadleaves".

Total broadleaves

For each operational region, the area of broadleaved commercial woodland was expressed as a percentage of the total area of all commercial woodlands in the operational region, based on data such as presented in Tables 6.2 to 6.4 in Section 6.2.1 but disaggregated for individual operational regions.

The percentage areas of broadleaved woodland in each operational region were then compared with one another and a rank assigned to each operational region. A rank of 1 indicates that the operational region has the highest percentage of broadleaved woodland within the total area of commercial woodlands. Table 7.7 shows a summary of the percentage areas obtained for "Total broadleaves" in each operational region and the assigned ranks.

Table 7.7 Percentage areas of "Total broadleaves" in NRW commercial woodlands by operational region

Operational region	Percentage area	Rank
Northwest	19.3	2
Northeast	10.8	5
Mid	17.1	3
Southwest	16.5	4
Southeast	25.5	1

Young broadleaves

For each operational region, the area of broadleaved commercial woodland with a planting year more recent than 1979 was expressed as a percentage of the total area of all broadleaved commercial woodlands in the operational region, based on data such as presented in Table 6.4 in Section 6.2.1 but disaggregated for individual operational regions.

The percentages derived for "Young broadleaves" in each operational region were then compared with one another and a rank assigned to each operational region. A rank of 1 indicates that the operational region has the highest percentage of Young broadleaves (relative to the total area of broadleaved woodland in the operational region). Table 7.8 shows a summary of the percentage areas obtained for "Young broadleaves" in each operational region and the assigned ranks.

Table 7.8 Percentage areas for "Young broadleaves" in NRW commercial woodlands by operational region

Operational region	Percentage area	Rank
Northwest	60.8	3
Northeast	67.0	2
Mid	72.2	1
Southwest	40.9	5
Southeast	55.9	4

Characterisation of other woodland categories

Commercial woodlands in each operational region of the NRW estate were characterised with respect to the other criteria defined in Step 1 above, according to a similar approach to that described above for the categories of "Total broadleaves" and "Young broadleaves". The woodland areas referred to in calculating percentage areas for each woodland category are summarised in Table 7.9.

The ranks assigned to commercial woodlands in the five operational areas of the NRW estate, with respect to the various woodland categories defined in Step 1, are summarised in Table 7.10.

Table 7.9 Woodland areas referred to in calculating percentage areas for woodland categories

Woodland category	Woodland areas in operational region	
	Numerator	Denominator
Total broadleaves	Total area of broadleaves in commercial woodlands	Total area of all commercial woodlands
Young broadleaves	Total area of broadleaves in commercial woodlands with planting year more recent than 1979	Total area of broadleaves in commercial woodlands
Young conifers	Total area of conifers in commercial woodlands with planting year more recent than 1979	Total area of conifers in commercial woodlands
Conifer reserves	Total area of conifers in commercial woodlands assigned with a management coupe of "Reserve/retention" (see Section 6.2.1)	Total area of conifers in commercial woodlands
Conifer CCF	Total area of conifers in commercial woodlands assigned with a management coupe of "Shelterwood" or "Selection" (see Section 6.2.1)	Total area of conifers in commercial woodlands
Conifer clearfell	Total area of conifers in commercial woodlands assigned with a management coupe of "Clearfell" (see Section 6.2.1)	Total area of conifers in commercial woodlands

Table 7.10 Ranks assigned to operational regions with respect to woodland categories

Category	Operational region				
	Northwest	Northeast	Mid	Southwest	Southeast
Total broadleaves	2	5	3	4	1
Young broadleaves	3	2	1	5	4
Young conifers	4	3	1	2	5
Conifer reserves	3	2	1	5	4
Conifer CCF	2*	1	4	5	2*
Conifer clearfell	3	4	2	1	5

Note to Table 7.10: Equal ranking for Northwest and Southeast operational regions with respect to category of "Conifer CCF".

Step 3: Assessment of relationships between woodland composition and trends in total net GHG removals

Table 7.11 presents a qualitative assessment of relationships between woodland composition and trends in total net GHG removals as exhibited by commercial woodlands in the five operational regions of the NRW estate.

For each operational region, the table shows the trend (rise or decline) in total net GHG removals associated with commercial woodlands. This is calculated as the difference between the total net GHG removals in 2040 (the time horizon of this study) and in 2015 (the base year of this study), based on the projections illustrated in Figures 7.9 and 7.10 in Section 7.3.4. A rise in total net GHG removals between 2015 and 2040 is reported as a positive number in the table; a fall in total net GHG removals is reported as a negative number

Table 7.11 also shows the individual trends (rise or decline) in total net GHG removals associated with the three major types of commercial woodlands, as defined in Section 6.4.1 (broadleaved woodlands, coniferous woodlands managed as reserves or according to continuous cover prescriptions and coniferous woodlands managed according to clearfelling prescriptions). These results indicate the contributions made by individual major woodland types to the overall result.

Table 7.11 Assessment of drivers in trends in total net GHG removals in operational regions

Region	Increase/decrease in total net GHG removals ($ktCO_2\ yr^{-1}$)				Drivers
	Total	Contributions due to trees and soils			
		Broadleaves	Conifers (reserves and CCF)	Conifers (clearfell)	
Northwest	0.2 increase	45.3 increase	9.8 decrease	35.2 decrease	Second-highest rank for Total broadleaves Second-lowest rank for Young conifers Equal second-highest rank for Conifer CCF
Northeast	13.3 increase	15.6 increase	0.1 increase	2.4 decrease	Lowest rank for Total broadleaves Second-highest rank for Young broadleaves Second-highest rank for Conifer reserves Highest rank for conifer CCF Second-lowest rank for Conifer clearfell
Mid	49.1 increase	74.5 increase	9.5 increase	34.8 decrease	Highest rank for Young broadleaves Highest rank for Young conifers Highest rank for Conifer reserves Second-highest rank for Conifer clearfell
Southwest	60.4 decrease	28.1 increase	0.9 decrease	87.6 decrease	Second-lowest rank for Total broadleaves Lowest rank for Young broadleaves Second-highest rank for Young conifers Lowest rank for Conifer reserves Lowest rank for conifer CCF Highest rank for Conifer clearfell
Southeast	20.1 increase	41.4 increase	6.4 increase	28.2 decrease	Highest rank for Total broadleaves Second-lowest rank for Young broadleaves Lowest rank for Young conifers Second-lowest rank for Conifer reserves Equal second-highest rank for Conifer CCF Lowest rank for Conifer clearfell

The final column of Table 7.11 provides an assessment of the likely drivers in trends exhibited in total net GHG removals, in terms of the significance (or otherwise) in each operational region of the various woodland categories defined in Step 1. Based on this assessment, it is suggested that it is possible to identify, with reasonable confidence, the most likely drivers of the trends in total net GHG removals associated with commercial woodlands in the five operational regions of the NRW estate. For example, the very distinctive trend in total net GHG emissions exhibited for the Southwest operational region (see Figure 7.11, Section 7.3.4) is almost certainly driven by a balance between:

- A relatively **small and declining** contribution to **carbon sequestration** from a relatively limited area of generally older broadleaved woodlands
- A relatively **large and potentially rising** contribution to **carbon sequestration** from a relatively large area of young coniferous woodlands; however, the oldest of these woodlands will reach an age suitable for **clearfelling** by around **2030** (see final bullet point)
- A relatively **small** contribution to **carbon sequestration** from a relatively limited area of coniferous woodlands managed as reserves
- A relatively **small** contribution to **carbon losses**, from a relatively limited area of coniferous woodlands managed according to continuous cover prescriptions
- A relatively **large and potentially rising** contribution to **carbon losses** from a relatively large area of coniferous woodland managed according to clearfelling prescriptions.

It should be noted that further detailed inspection of the CARBINE results for the Southwest operational region revealed that the contribution to wood production from clearfelling activities was highest in this region.

Principal drivers of GHG removals and trends

The analysis presented above indicates that two drivers are particularly important for determining levels of and trends in GHG emissions and removals in NRW woodlands:

1. The extent of broadleaved woodlands (in which management for wood production is assumed to be quite limited)
2. The extent of coniferous woodlands under management for wood production involving either continuous cover management or involving clearfelling.

This is highlighted by the results in Table 7.12, which shows, for each of the major woodland types defined in Section 6.4.1:

- Projected mean carbon stocks in trees and all woodland carbon pools (soil, litter, trees and HWP) for the period 2015 to 2040

- Projected mean net GHG emissions or removals due to trees and for the complete system modelled in this study (soil, litter, trees, HWP and woodland operations) for the period 2015 to 2040
- The trend (i.e. net change) in net GHG emissions or removals due to trees and for the complete system modelled in this study over the period 2015 to 2040.

Table 7.12 Contributions made by major woodland types to carbon sequestration and net GHG emissions or removals in NRW woodlands

Major woodland type	Carbon stocks[2] (ktC)		GHG emissions/ removals[3] (+/-) ($ktCO_2$-eq. yr^{-1})		Trend in GHG emissions/removals ($ktCO_2$-eq. yr^{-1})	
	Trees	**Total**	**Trees**	**Total**	**Trees**	**Total**
Broadleaves[1]	2 361	7 314	-153	-97	41 increase	204 increase
Conifers (reserves and CCF)	2 139	5 625	-138	-201	58 decrease	5 increase
Conifers (clearfell)	4 169	15 109	21	-112	7 decrease	187 decrease
Total[4]	**8 669**	**28 049**	**-270**	**-410**	**24 decrease**	**21 increase**

Notes to Table 7.12:

1 Results for broadleaves include non-commercial woodlands

2 mean carbon stocks over the period 2015 to 2040

3 Mean rate of net GHG emissions/removals over the period 2015 to 2040

4 Totals may not agree exactly with individual contributions due to rounding.

Contribution of broadleaved woodlands

Broadleaved woodlands constitute about 20% of the woodland area in the NRW estate (see for example Table 6.2, Section 6.2.1). The projected carbon stocks in broadleaved woodlands as reported in Table 7.12 (trees and total) are reasonably consistent with this percentage area (27% of carbon stocks in all NRW woodlands). The projected total net GHG removals contributed by broadleaved woodlands are also consistent with the relative area of broadleaved woodlands (24% of total net GHG removals). However, the projected contribution of trees in broadleaved woodlands to the total carbon sequestration in trees is significantly higher than would be suggested by the relative area of broadleaved woodlands (57% of total net GHG removals due to trees). This result reflects the assumptions made in modelling the BAU scenario in NRW woodlands (Table 6.6, Section 6.2.3), notably that:

- Broadleaved woodlands will be managed either as reserves or on alternative silvicultural systems (i.e. continuous cover management, avoiding clearfelling)
- Wood production from broadleaved woodlands will aim to meet a target level of about 5,000 m^3 per year over the period 2015 to 2040; this is a low target compared with the modelled capacity for wood production from broadleaved woodlands in the NRW estate.

As a consequence of these assumptions, generally, broadleaved woodland areas are predicted to grow with only limited harvesting activities taking place, resulting in relatively high rates of carbon sequestration in broadleaved trees in NRW woodlands.

A significant trend of rising net GHG removals is predicted for broadleaved woodlands over the period 2015 to 2040. This result is a reflection of the factors discussed immediately above, combined with the age distribution of broadleaved woodlands, which includes a significant proportion of area (slightly over 50%) consisting of trees planted since 1980 (see Table 6.4, Section 6.2.1). The assumed limited harvesting in broadleaved woodlands and avoidance of clearfelling lead to the prediction that tree carbon stocks are retained and inputs to soil carbon are sustained over time, giving a rising rate of carbon sequestration in trees and particularly soils.

Contribution of coniferous woodlands managed as reserves or for wood production with continuous cover ("non-clearfell coniferous woodlands")

Coniferous woodlands managed as reserves or for wood production but avoiding clearfelling (as modelled based on assumptions in this study) constitute about 23% of the woodland area in the NRW estate. The projected carbon stocks in these woodlands as reported in Table 7.12 (trees and total) are reasonably consistent with this percentage area (respectively, 25% and 20% of carbon stocks in all NRW woodlands). In contrast, the projected net GHG removals (trees and total) contributed by non-clearfell coniferous woodlands are significantly higher than would be suggested by the relative area of these woodlands (about 50% of net GHG removals for all NRW woodlands). This result is obtained for similar reasons to those described above for broadleaved woodlands. However, harvesting activities in non-clearfell coniferous woodlands not managed as reserves (nearly 80% of this major woodland type) were assumed as part of modelling to be more extensive than for broadleaved woodlands. As a consequence, inputs of carbon to soils from trees are sustained (because the growing stock is not clearfelled) but there are also relatively high inputs of carbon to the deadwood and litter pools (due to harvesting), which also enhances inputs of carbon to soils.

It is also very important to note that the contribution to net GHG removals made by non-clearfell coniferous woodlands looks relatively large partly because the contributions from coniferous woodlands managed with clearfelling are relatively small (see following discussion of coniferous woodlands managed for wood production with clearfelling).

Although non-clearfell coniferous woodlands make an important contribution to net GHG removals over the period 2015 to 2040, a significant trend of declining net GHG removals is predicted for the trees forming these woodlands over this period. This result is a reflection of:

- The relatively mature trees comprising non-clearfell coniferous woodlands, which are predicted to exhibit an age-related decline in the rate of carbon sequestration
- Progressive reductions in the mature growing stock of non-clearfell woodlands (as part of regular thinning activities), which have greater impact during the period 2015 to 2040 than the gradual replacement of the mature trees by regenerating younger trees. This is occurring because the woodlands are undergoing transformation from a mature even-aged structure to an uneven-aged structure. Once this has been completed, carbon stocks in the woodlands may stabilise.

When the combined contributions due to trees, litter, soils and HWP are considered, a modest increase in total net GHG removals is predicted for non-clearfell coniferous woodlands. This result reflects a predicted substantial rise in GHG removals contributed by soil carbon (see discussion immediately above), which compensates for the projected reduction in net GHG removals due to trees.

Contribution of coniferous woodlands managed with clearfelling (“clearfell coniferous woodlands”)

Coniferous woodlands managed for wood production involving clearfelling (as modelled based on assumptions in this study) constitute about 58% of the woodland area in the NRW estate. The projected carbon stocks in these woodlands as reported in Table 7.12 (trees and total) are reasonably consistent with this percentage area (respectively, 48% and 54% of carbon stocks in all NRW woodlands).

The results predicted for clearfell coniferous woodlands contrast sharply with those for broadleaved woodlands and non-clearfell coniferous woodlands. Net GHG emissions (rather than removals) are predicted for the trees forming clearfell coniferous woodlands over the period 2015 to 2040, although the magnitude of the emissions is quite small compared with the total net GHG removals estimated for all NRW woodlands.

This result reflects the relatively mature growing stock implied by the age class distribution of the current NRW clearfell coniferous woodlands and the consequent approximate balancing of carbon sequestration through tree growth and carbon stock losses due to harvesting activities, particularly clearfelling. It should be noted that detailed inspection of the projection for the trees of clearfell coniferous woodlands reveals a cyclical pattern between net GHG emissions and net GHG removals, alternating roughly around zero. Such a result is entirely consistent with the concept of sustainable wood production from established woodlands (i.e. growth and harvesting are in balance).

Whilst small net GHG emissions are predicted for trees forming clearfell coniferous woodlands, the overall projection for total net GHG emissions/removals (i.e. due to the combined contributions of trees, litter, soil and HWP) is still a significant net removal. This result is a consequence of:

- Relatively high predicted inputs of carbon to deadwood and litter as a result of significant harvesting activities (particularly clearfelling
- Relatively high inputs of carbon to HWP as a result of significant harvesting activities, leading to relatively high sequestration of carbon in HWP.

A small trend of rising net GHG emissions is predicted for trees forming clearfell coniferous woodlands over the period 2015 to 2040. As discussed above, a detailed inspection of the projection for the trees of clearfell coniferous woodlands reveals a cyclical pattern between net GHG emissions and net GHG removals, roughly around zero.

A significant trend of declining total net GHG removals is predicted for clearfell coniferous woodlands over the period 2015 to 2040. This result is a reflection of a progressively declining contribution to net GHG removals from soils and HWP associated with clearfell coniferous woodlands.

The result for soils reflects relatively low inputs of carbon to soils from living trees, e.g. via fine root turnover (compared with the other major woodland types of broadleaves and non-clearfell coniferous woodlands) due to periodic clearfelling of areas of growing stock in clearfell coniferous woodlands.

For HWP, as explained in Section 7.3.2, the projected annual level of wood production is held constant over the period 2015 to 2040. As a consequence, as more and more HWP accumulate in use, losses of carbon from decaying and disposed HWP will eventually come into balance with the inputs of carbon to the HWP pool, leading to zero net removals associated with HWP in the very long term. Hence, net removals due to HWP are predicted to very gradually decline towards zero.

7.3.7. Summary results for period 2015 to 2040

Table 7.13 shows a summary of projected annualised total net GHG emissions and removals (sequestration) for all NRW woodlands over the period 2015 to 2040, the temporal system boundary for this study. The results are expressed in units of $ktCO_2$-eq. yr^{-1} (thousand tonnes carbon dioxide equivalent per year). Carbon stock changes in NRW woodlands are projected to lead to a net sink over this period. The estimated annualised total net CO_2 sink of NRW woodlands (trees, deadwood/litter and soil) over the period is -394.2 $ktCO_2$-eq. yr^{-1}. When carbon sequestration in HWP is also included (-28.0 $ktCO_2$-eq. yr^{-1}), net annualised sequestration is projected for the period, at -422.2 $ktCO_2$-eq. yr^{-1}. If GHG emissions from woodland operations in NRW woodlands

(+12.7 $ktCO_2$-eq. yr^{-1}) are also accounted for, an estimate for the projected annualised total net CO_2 sink of -409.5 $ktCO_2$-eq. yr^{-1} is obtained.

Table 7.13 Summary of estimated annualised GHG emissions and removals in NRW woodlands for the period 2015-2040

Contribution	GHG emissions (+)/removals (-) ($ktCO_2$–eq. yr^{-1})
Soil	-119.7
Litter	-4.4
Trees	-270.1
HWP	-28.0
Total (no HWP)	**-394.2**
Total (with HWP)	**-422.2**
Woodland operations GHG emissions	+12.7
Total (with woodland operations)	**-409.5**

7.3.8. Comparison with estimates from GHG emissions inventory

Under the United Nations Framework Convention on Climate Change (UNFCCC, 1992), the UK is committed to annually compiling and reporting national inventories of GHG emissions. The GHG emissions are reported for various sectors of the UK economy, one of which is the Land Use, Land-Use Change and Forestry (LULUCF) Sector. Within the LULUCF Sector, net GHG emissions and removals are reported for a set of land categories, one of which is Forest Land. For domestic purposes, UK GHG inventories are also reported showing separate results for England, Wales, Scotland and Northern Ireland. Figure 7.13 shows results for net GHG emissions and removals for all Forest Land in Wales, as reported in the most recent published UK GHG inventory (compiled for the period 1990 to 2015). Results are plotted in Figure 7.13 for the total net GHG emissions and removals for Forest Land and the contributions due to trees, deadwood and litter, soils and harvested wood products (HWP).

In Figure 7.13, the results for net GHG emissions and removals are reported from 2015 and projected to the year 2040 (i.e. from the base year to the time horizon for this study). It is important to understand that such projections are not reported as part of official published national GHG inventories. However, projections such as those illustrated in Figure 7.13 are produced as a separate internal exercise to inform actions to meet domestic targets for GHG emissions.

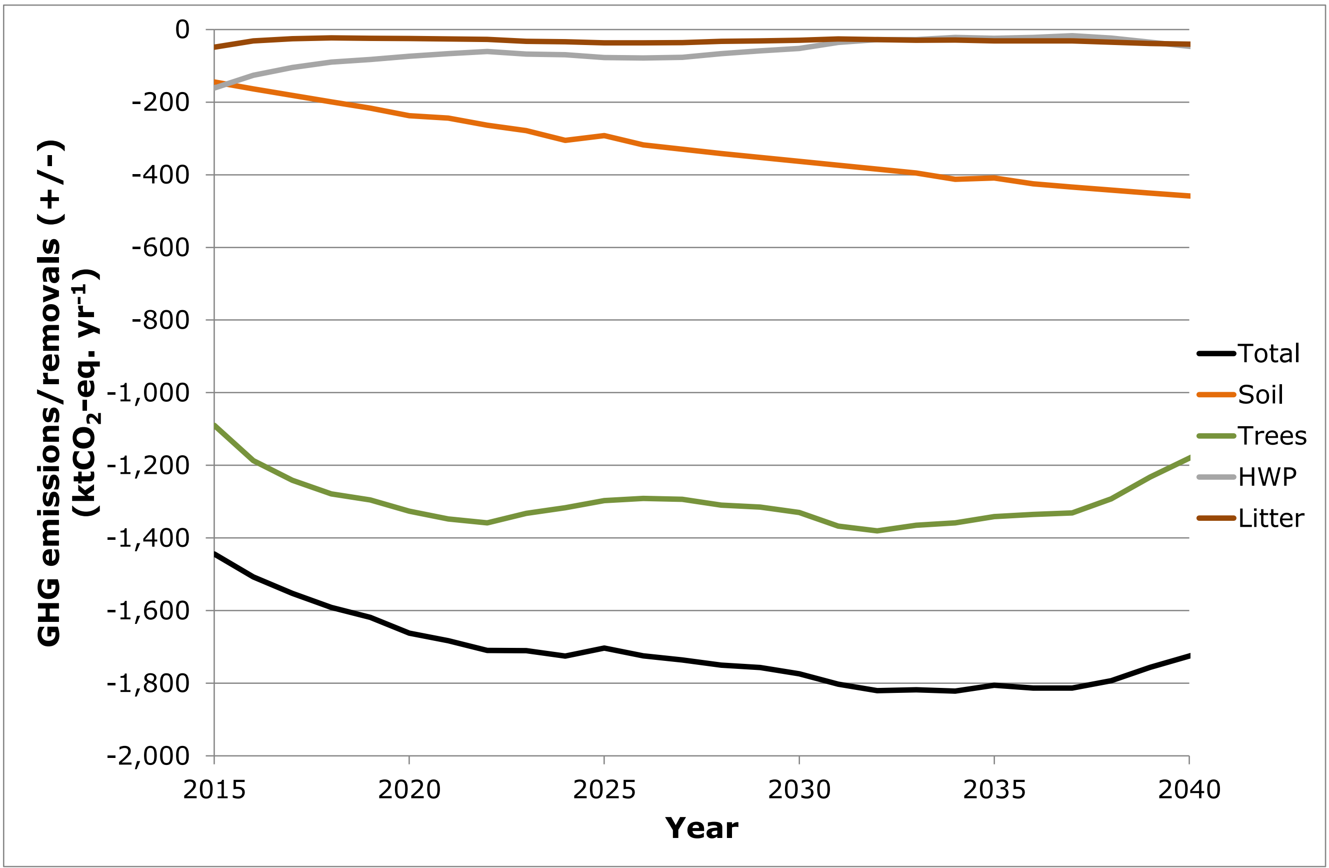

Figure 7.13. Projected development of net GHG emissions/removals for all Forest Land in Wales based on results of 1990-2015 national GHG inventory.

In principle, a comparison of the GHG inventory results in Figure 7.13 with the equivalent results from this study (Figure 7.8, Section 7.3.1) may be relevant for the purposes of this study for two reasons:

1. The two sets of results can be checked for consistency, serving as a quality check on both the GHG inventory results and the results of this study
2. The GHG inventory results are reported for all woodlands in Wales. Hence, the results may serve as a benchmark against which to assess the contribution of NRW woodlands towards net GHG removals, in the context of the overall contribution of the wider forestry sector in Wales.

It is very important to attach a number of caveats to the ensuing comparison of the GHG inventory results for net GHG emissions and removals due to Forest Land in Wales with the relevant results for NRW woodlands produced by this study, specifically with regard to:

- The definition of the system boundary adopted
- Assumptions made in defining the scenario on which the results were based

- Datasets referred to for model inputs
- Modelling methodologies.

System boundaries

Calculations as currently made in the compilation of UK national GHG inventories are based on a different system boundary to that adopted in this study:

- Most obviously, the spatial system boundary of the relevant GHG inventory encompasses all land classified as Forest Land in Wales
- In the results for the 1990-2015 GHG inventory, carbon associated with fermenting organic matter in litter was included in reporting for the litter pool, whereas this carbon is included in reporting for the soil pool in this study; note there is no overall impact on the total net GHG emissions/removals
- GHG emissions associated with woodland operations are excluded from the LULUCF GHG inventory (instead, in general, they are reported as a contribution to GHG emissions inventories for the Energy and Transport Sectors).

Scenario assumptions

As already highlighted, projections are not reported as part of official published national GHG inventories but projections are produced as a separate internal exercise to inform actions to meet domestic targets for GHG emissions. The projected GHG emissions and removals in Figure 7.13 are based on a type of BAU scenario but the scenario is defined differently to the BAU scenario developed in this study (see Sections 4, 6.2.3 and 6.2.4)

Specifically, the projection in Figure 7.13 was based on a number of key assumptions that are somewhat different to those adopted in this study:

- The modelling of the development of Forest Land allowed for deforestation activities, which were assumed to follow a constant annual rate based on an estimate for the year 2015 (353 ha).
- The modelling of the development of Forest Land allowed for afforestation activities, which were assumed to follow a constant annual rate from the year 2016 (about 142 ha).
- Business as usual woodland management was modelled by selecting levels of thinning and clearfelling in woodlands to match historical levels of wood production, based on timber production statistics for Wales. For the purposes of projection, the thinning prescriptions and clearfelling rotations applied to woodlands to meet the historical production targets were assumed to continue unchanged in the future. Note that this means that projected levels of wood production are predicted to vary from the historical target levels during the period 2015 to 2040.

- Detailed assumptions and rules, as referred to in specifying the BAU scenario for this study (see Table 6.6, Section 6.2.3) were not part of the specification for the scenario for the GHG inventory projection. For example, the special treatment of areas of larch was not considered in defining the scenario for the GHG inventory projection.
- The allocation of harvested wood to categories of HWP was modelled based on generic UK allocation factors. For example, this means that some harvested wood was allocated to paper production, whereas no harvested wood was allocated to paper production in this study (see Section 7.1.4 and Appendix 5).

Data sources

The compilation of the 1990-2015 UK national GHG inventory involved referring to some of the same data sources as used in this study, such as data on the composition and management of NRW woodlands, as stored in the Forester GIS database. However, a number of other datasets were also referred to:

- The National Forest Inventory for all woodlands in Wales
- Forestry Commission records on annual rates of woodland creation (afforestation) since 1920
- A dataset compiled by Forestry Commission England and Forest Research of estimates of annual rates of deforestation since 1990
- Forestry Commission yield models (for basic assumptions about rotations applied to woodland areas)
- A dataset developed by the Centre for Ecology and Hydrology on the areas of woodland planted on organic or mineral soils each year since 1920.

Modelling methodologies

The compilation of the 1990-2015 UK national GHG inventory involved some differences in modelling methodologies compared with this study. The main important difference involves the version of the soil carbon sub-model in the CARBINE model used for modelling soil carbon dynamics. This study has used an improved version of the soil carbon sub-model which gives broadly similar but somewhat different results for soil carbon dynamics when compared with the version used for the GHG inventory.

Comparison of projections

As might be expected, the predicted magnitudes of net GHG removals in the projection for all Forest Land in Wales (Figure 7.13) are bigger than predicted for NRW woodlands in the projection developed in this study (Figure 7.8, Section 7.3.1). Allowing for the difference in magnitudes, the contributions made by individual carbon pools to total net GHG removals and the general trends predicted are quite similar in the two projections.

Table 7.14 summarises the mean rates of net GHG removals over the period 2015 to 2040 as predicted by the two projections. Results are also given for the individual contributing carbon pools. The table also gives the percentage shares of removals in all woodlands in Wales due to NRW woodlands, based on the results for net GHG removals.

Table 7.14 Mean rates of projected total net GHG removals for all woodlands in Wales and for all NRW woodlands

Carbon pool	Total net GHG removals ($ktCO_2$-eq. yr^{-1})		Percentage share of removals (%)
	GHG inventory	This study	
Soil	-323.7	-119.7	37
Litter	-31.5	-4.4	14
Trees	-1299.8	-270.1	21
HWP	-61.2	-28.0	46
Total	**-1 716.2**	**-409.5**	**24**

When comparing the results in Table 7.14 for the contributions made by the soil and litter carbon pools, it is important to note that the results for the GHG inventory are not completely compatible with the results of this study and the results for soil and litter may be better considered when combined.

NRW woodlands represent about 36% of the total area of woodlands in Wales (based on results in Table 6.2, Section 6.2.1 and Forestry Commission, 2017). The share of removals due to the soil and litter pools of NRW woodlands is consistent with this relative area. However, the share of removals due to trees is somewhat lower than might be expected based on simple consideration of relative areas, whilst the share of removals due to HWP is somewhat greater than might be expected. These differences are likely to reflect:

- A lower proportion of broadleaved woodlands on the NRW estate, compared with other woodlands in Wales
- Higher projected levels of wood production from NRW woodlands, compared with other woodlands in Wales, leading to greater impacts on the growing stock of NRW woodlands due to harvesting
- Related to the higher projected levels of wood production from NRW woodlands, greater carbon sequestration in HWP supplied from NRW woodlands, compared with HWP supplied from other woodlands in Wales.

7.3.9. More detailed results for woodland GHG emissions/removals

Separate results for woodland GHG emissions and removals such as described above for all NRW woodlands in Figures 7.8 (Section 7.3.1) and 7.9 (Section 7.3.3), have been produced for combinations of operational woodlands and major woodland types, as described in Section 6.4.1. These results may be found in the MS Excel workbooks listed in Section 7.2.5.

8. Discussion and conclusions

8.1. Review of study outcomes

This report has presented a detailed description of modelling work undertaken to predict the likely future development of net GHG emissions and removals associated with woodlands on land owned or managed by Natural Resources Wales. The successful completion of this work has involved a number of key tasks:

- Defining a system boundary for the object of study
- Detailed specification of datasets, assumptions and rules defining a business as usual scenario for the composition and current and future management of NRW woodlands
- Developing and implementing a novel and complex modelling methodology to estimate GHG emissions and removals associated with NRW woodlands and predicted changes over the next 25 years
- Detailed investigation of the project results in relation to the underlying data and assumptions, to establish the most likely main drivers of magnitudes and trends in GHG emissions and removals associated with NRW woodlands.

This study is not the first example of an exercise in modelling the development of woodland GHG balances at a regional or country scale in relation to a defined scenario (see for example, Werner *et al.*, 2010; Böttcher *et al.*, 2011; Kallio *et al.*, 2013; Wang *et al.*, 2015). However, compared with previous studies, this current study has involved considerably more detailed representation of woodlands and their management in relation to predetermined targets for future levels of wood production from woodlands. This has required the development of a particularly sophisticated methodology for data fusion and scenario modelling.

The study has produced a substantial and detailed body of estimates and predictions of the carbon stocks and GHG emissions and removals associated with NRW woodlands and their future management as specified by NRW. The main results and findings have been presented in this report. The study results are consistent with estimates of the carbon stocks and net GHG emissions and removals of woodlands as reported by other closely relevant or prominent published studies.

The results indicate that, currently, the woodlands on land owned or managed by Natural Resources Wales are a net carbon sink, i.e. there are net GHG removals associated with NRW woodlands and their management. The projection for the BAU scenario predicts that NRW woodlands should continue to act as a net carbon sink at least to the year 2040.

The discussion in Sections 8.2 to 8.5 considers the implications of the study results, particularly in the context of the potential for NRW woodlands to contribute towards future climate change mitigation.

8.2. Longer-term prognosis for GHG removals

As discussed in Section 7.2.4 (see in particular discussion of Table 7.3), studies of woodland carbon stocks and stock changes usually identify woodlands to be accumulating carbon over time, thus acting as a net carbon sink. Research studies also indicate that woodlands are likely to remain a carbon sink for some time into the future. However, it is also generally understood that woodlands will not serve as a carbon sink in perpetuity and there may be periods, perhaps involving decades, when woodlands may be a net carbon source.

The main reason for the ultimate cessation of carbon sequestration by woodlands is due to a phenomenon known as "saturation". The capacity for terrestrial vegetation and soil to remove carbon from the atmosphere "saturates" because ultimately a steady state will occur in the balance of emissions and removals for a given area of land. The magnitude of the carbon stock at this saturation point, and the time taken to reach it, depend on various factors including soil type, vegetation type, long-term management and climate. For woodlands, the saturation point depends on tree species, growth rate (yield class) and management.

It is possible to distinguish the term saturation as applied in a "biological" sense and in a "technical" sense, although, very importantly, such distinctions are generally not made in discussions of vegetation carbon management.

Biological saturation occurs when a terrestrial ecosystem, completely unaffected by human intervention, achieves the maximum long-term average carbon stock that can be attained on a particular area of land (allowing for soil characteristics, climate etc.) as a result of the balance of natural processes (vegetation photosynthesis and respiration, in conjunction with processes of decomposition and transfers of carbon around the ecosystem). Effectively, this is the carbon stock that would be associated with a "climax" ecosystem. Even under such circumstances, there may be very large short-term fluctuations in carbon stocks as a result of the interplay between various natural disturbance processes (e.g. fire, storm and disease) and the processes of vegetation (re)growth, mortality and succession.

Technical saturation occurs when vegetation attains a maximum long-term average, subject to both the biological capacity of the land and vegetation and also the way in which the land is being managed. For example, consider the case of a new woodland area created by planting trees on an area that was previously grassland, in which the woodlands are subsequently managed for production involving periodic clearfelling and replanting. After the initial planting of trees, vegetation carbon stocks will most likely increase, however harvesting will reduce carbon stocks in individual woodland stands, with the consequence that overall carbon stocks for the woodland will be limited to a long-term average level (see for example Maclaren, 1996; Broadmeadow and Matthews, 2003). This long-term average carbon stock will be determined in large part by the balance between (re)growth of individual woodland stands and rate of harvesting (in particular the rotation period for clearfelling). Generally, the magnitude of this long-term average carbon stock will be smaller than that attained under biological saturation (i.e. in the absence of harvesting), although there may be cases where the magnitudes are comparable (e.g. where management includes the moderating of disturbance events).

As explained in Section 7.2.4, generally, a relatively high level of carbon sequestration in European woodlands (including UK woodlands) is understood to be a consequence of a relatively large proportion of younger woodland (Vilén *et al.*, 2012), in turn reflecting historical efforts to expand and restore areas of woodland. However, concerns have been expressed that the rate of increase in woodland carbon stocks in Europe and the UK is declining and may be close to reversal (Read *et al.*, 2009; Nabuurs *et al.*, 2013). In this context, it may be noted that this study identified the possibility of a progressive decline in GHG removals (i.e. rate of carbon sequestration) in trees in NRW woodlands after about 2030 (see Section 7.3.2).

It follows that, when considering how NRW woodlands can contribute towards climate change mitigation, now and in the future, it must be recognised that:

- Net carbon sequestration by NRW woodlands cannot be maintained indefinitely
- A decline in the rate of carbon sequestration by NRW woodlands over coming decades may be difficult to avoid
- There are likely to be periods in the future when NRW woodlands will be net emitters of carbon.

It is also important to recognise that woodland systems typically exhibit short-term and long-term cycles in woodland carbon stocks and associated carbon sequestration or emissions. It is important to allow for these trends and cycles in any assessment of possible actions to maintain the carbon sequestration function of woodlands.

8.3. Sequester or substitute?

A central concern when considering the potential management of woodlands for carbon sequestration arises from the fact that the resource of carbon constituted by woodland biomass makes two contrasting contributions in terms of climate change mitigation:

1. As is clear from the findings of this study, the carbon stocks in woodland biomass, litter and soil represent a natural reservoir of carbon sequestered from the atmosphere. In principle, this process of carbon sequestration could be "managed".
2. Woodland biomass can be harvested and used to manufacture a range of solid wood products (e.g. sawn timber, wood-based panels, card and paper) which also represent

a reservoir of sequestered carbon (although, arguably, a mainly temporary reservoir) and can be used in place of (i.e. to "substitute" for) generally GHG-intensive non-wood materials; wood harvested for use as fuel can replace fossil energy sources.

Several critical issues arise from the fact that the management of woodlands can make these two contributions. First of all, it follows that woodlands can be managed to conserve or enhance carbon stocks and/or to produce wood products to displace GHG-intensive materials and fossil fuels. There are certain specific situations in which efforts to increase the supply of wood products can also involve increased carbon stocks (see Section 8.4). The most obvious example is when non-woodland with low initial carbon stocks is converted to woodland through afforestation activities. In most circumstances, however, there is a trade-off in terms of carbon stocks (and resultant GHG emissions) between activities aimed at extracting wood to produce wood products, and activities aimed at sustaining or enhancing carbon stocks within woodlands. Essentially, attempting to enhance one of the twin contributions of woodlands to climate change mitigation tends to act in antagonism to the other function, and there is consequently a trade-off between them.

Generally, market-mediated trade-offs between the contributions made by woodlands are difficult to predict in detail but they are a real phenomenon with potentially major impacts. For example, suppose a policy decision were to be taken within a country or region to encourage the management of forests in the region to be changed to enhance carbon sequestration, at the expense of significantly reduced wood production (compared with historical levels). It is then effectively inevitable that one of three consequences (or some combination) will occur:

1. Certain socio-economic activities undertaken by the pre-existing consumers of the wood produced from the woodlands will need to be curtailed (e.g. there may need to be less construction of new buildings and/or less maintenance of existing buildings)
2. Pre-existing consumers of the wood produced by the woodlands will consume more wood supplied from other woodland areas, i.e. impacts on woodland carbon stocks due to wood harvesting will be transferred to woodlands in other locations, which may or may not be according to the same standards of stewardship as the woodlands in the consuming region.
3. Pre-existing consumers of the wood produced by the woodlands will consume more of other non-wood resources instead, such as in the scenario described at the start of this discussion.

When considering options for the management of woodland areas to increase the supply of wood products whilst sustaining carbon stocks, it may be appropriate to consider the potential for a "package" of measures undertaken in a population of stands on a site-by-site basis across large scales (Nabuurs *et al.*, 2008). This might involve, for example, a systematic and coordinated programme of management across woodland areas involving a combination of increased harvesting in some areas, conservation or enrichment of carbon stocks in other areas, and possibly also the creation of new woodland areas. Currently, there has been limited exploration of the potential for developing such a package of measures for a significant country or region.

8.4. Woodland management measures to reduce net GHG emissions

Following the discussions of Schlamadinger *et al.* (2007) and Nabuurs *et al.* (2007) and the detailed consideration of specific options presented by Mason *et al.* (2009) and Matthews and Broadmeadow (2009), it is possible to identify a number of specific woodland management activities that might help reduce net GHG emissions:

- Prevention of deforestation
- Afforestation
- Conservation or enhancement of carbon in existing woodlands, including protection against disturbances and extreme events such as fire
- Enhancement of production, e.g. through increased harvesting in existing woodlands, to achieve substitution impacts in other sectors.

The list defined above constitutes a simplified version of the range of woodland measures considered and evaluated in Schelhaas *et al.* (2006). The range of measures is also broadly similar to those considered in a report to the EU Standing Forestry Committee (SFC, 2010). These measures are considered in detail in Sections 8.4.1 to 8.4.4. Indicative estimates of per-hectare mitigation potentials included in the following discussion are based on a synthesis and interpretation of results presented in Broadmeadow and Matthews (2003; see in particular Figures 4 and 5), Bradley *et al*. (2005; see in particular Table 6), Szendrődi (2006), Morison *et al*. (2012; see in particular Table 3.1 and Table A7.1) and Matthews *et al*. (2014b; see in particular Section 3.6). Section 8.4.5 presents a summary of indicative per-hectare mitigation potentials for the various measures described in Sections 8.4.1 to 8.4.4.

Note that:

- Typically, estimates for mitigation potentials and other impacts of woodland management options on GHG emissions/removals are expressed in units of tCO_2-eq. ha^{-1} or tCO_2-eq. ha^{-1} yr^{-1} (carbon dioxide equivalent per hectare, or carbon dioxide equivalent per hectare per year)
- Negative results for carbon stock changes or GHG emissions/removals indicate net carbon sequestration or net GHG removals (or reductions in GHG emissions); positive results indicate net GHG emissions.

As discussed in Section 8.2, the carbon dynamics of woodland systems are innately time dependent and responses to management interventions can be complex. One common feature for all measures, however, is that any carbon sequestration will eventually saturate (biologically or technically, see Section 8.2) in the long term.

8.4.1. Prevention of deforestation

The conversion of woodland to other types of land generally involves a net reduction in vegetation and soil carbon stocks. To take an example relevant to Welsh conditions, if a woodland area managed for production were to be converted to a non-forest system (such as grassland or heathland), the net loss of carbon might ultimately amount to about 170 tCO_2–eq. ha^{-1} in vegetation and 220 tCO_2–eq. ha^{-1} in soil. The emission of GHGs to the atmosphere due to the vegetation loss (i.e. loss of trees) might be quite rapid (say, over 1 to 5 years, giving an emission rate of around 35 tCO_2–eq. ha^{-1} yr^{-1} for that period) but this depends strongly on what is done with the biomass in the felled trees. The loss of carbon in soil might take place over 30 to 50 years, suggesting a rate of emission of between 4.5 to 7.5 tCO_2–eq. ha^{-1} yr^{-1} for that period. Prevention of deforestation would be expected to mitigate these GHG emissions, suggesting mitigation potentials of equal magnitude the estimates given here but with opposite sign.

Whilst it may be generally the case that prevention of deforestation represents a GHG emissions mitigation measure, there may be certain specific exceptions. For example, the restoration of afforested peatlands in cases where the tree cover has low yield class may have the potential to reverse losses of carbon from peatland soils caused by their drainage and afforestation. However, uncertainty still surrounds the impacts on the GHG balance of peatland afforestation and/or restoration and this is still a subject of significant ongoing research (including currently an enquiry by the Peatland Commission).

8.4.2. Afforestation

The conversion of non-woodland to woodland, through tree planting or the encouragement of natural regeneration, generally involves a net increase in vegetation and soil carbon stocks (certainly when considered together). A quite extreme example of afforestation on former pasture to create a “wilderness woodland” (see Section 8.4.3) under Welsh conditions might lead to a net accumulation of carbon stocks of 780 tCO_2–eq. ha^{-1} in vegetation and 330 tCO_2–eq. ha^{-1} in the soil. Carbon stocks accumulated in woodlands created for production would be more modest, say 390 tCO_2–eq. ha^{-1} in trees and soil combined. Typically, carbon sequestration in response to afforestation is a slow process and this carbon stock might take 50 to 100 years to fully accumulate under conditions relevant to Wales, giving a rate of sequestration of between -7.8 and -11.1 tCO_2–eq. ha^{-1} yr^{-1} over the period. Furthermore, sequestration will only be sustained up to the time of final harvest in woodlands managed according to a regime involving clearfelling.

If newly created woodlands are managed for production of timber and fuel, there should also be significant positive impacts on GHG emissions in other sectors, compared with the option of simply allowing carbon stocks in the new woodlands to accumulate. The balance between removals from the atmosphere in the growing trees and cross-sectoral impacts from utilisation of harvested wood will depend on the type of woodland system considered. Major options involve:

- The accumulation of "carbon reserves" by creating wilderness woodlands
- Delivery of a mix of in-woodland and cross-sectoral benefits by creating new woodlands intended for producing high-quality wood suitable for use as a variety of materials (and for fuel), but notably construction timber.
- Prioritising energy production by creating new short rotation "biomass woodlands", including woodlands managed as coppice.

Caution is still necessary when pursuing afforestation activities. If carbon stocks on land are already high before the woodland is created (e.g. the site being considered is a peatland or a soil with very high levels of organic matter, which includes many types of grasslands), the net change in carbon stock due to creation of the woodland may be small and will probably involve an initial reduction. In situations where a net reduction in carbon stocks takes place, it may take decades to restore a carbon stock of similar magnitude. There is an ongoing debate about the response of soil carbon in the years immediately following tree planting, generally with regard to the initial loss of carbon stocks and time needed to replenish them. Cases involving the drainage of soils with high organic matter content in preparation for afforestation are likely to be unsuitable in terms of GHG mitigation. Drainage would increase aerobic conditions in the soil, which would be likely to result in oxidation of organic matter and increased emissions.

8.4.3. Conservation or enhancement of carbon in existing woodlands

When an area of woodland is being managed for wood production (through thinning of trees or periodic felling on a rotation), there is an impact on carbon stocks. Specifically, carbon stocks in woodlands managed for production are typically lower compared to similar woodlands left to develop into a wilderness (Broadmeadow and Matthews, 2003; Matthews and Robertson, 2006; Mason *et al*., 2009). By implication, carbon stocks could be increased in woodland areas (with consequent GHG removals) if appropriate changes were introduced in the way woodlands are managed for production (Mason *et al*., 2009). In effect, certain changes in woodland management can change the "technical saturation" level of carbon stocks in woodlands from an initial value (associated with the previous management of the woodlands) to an enhanced value. Relevant woodland management measures generally involve leaving trees to grow for longer before harvesting, or not harvesting them at all. The main options include:

- Longer rotations in even aged stands
- Avoidance of clearfelling
- Restricting production
- Conversion to wilderness woodland.

Introducing longer rotations in even aged stands

If the period between clearfelling events in even aged stands forming a woodland is extended, then the overall carbon stock in the woodland should increase. To illustrate, consider a woodland composed of even aged stands at different points through a rotation of 50 years as specified under existing management. Suppose that the rotation of stands was to be extended by 30 years to 80 years. If such a measure were to be introduced in all of the stands close to 50 years of age, this would lead to a significant drop in timber production in the short term, so it seems likely that the longer rotation would be applied gradually across different woodland areas as part of a programme of woodland restructuring. However, the details would depend on the existing age class distribution of the woodlands. In those woodlands areas where the rotation is extended, the overall carbon stock in trees and soil (mainly trees) might increase by approximately 60 tCO_2–eq. ha^{-1}. This stock change would occur over the period taken for the stands to adjust to the longer rotations, which would depend on age class distribution but might take anything between 80 to 100 years, giving a net carbon sequestration rate of around -0.7 tCO_2–eq. ha^{-1} yr^{-1}. These magnitudes, periods and consequent rates depend on the details of how the woodlands were being managed for production originally and the extent of the change in rotation. The changes in carbon sequestration over time will be complex. It should also be noted that changing the management of woodlands areas in ways that do not always meet market requirements for production is likely to lead to increased imports and possibly associated GHG emissions arising from leakage (e.g. intensification of woodland harvesting elsewhere), in addition to having negative economic implications.

Avoidance of clearfelling

If a woodland is being managed as an ensemble of even aged stands with periodic clearfelling, then the practice of clearfelling could be changed to a system based on selective felling of individual trees or small groups of trees. Such a system is also likely to involve retaining some trees for longer than was the case under the previous clearfell system. However, other changes to the silvicultural system may involve increased harvest amongst trees of smaller sizes. There is some debate over the net impacts on stand carbon stocks due to the introduction of such "continuous cover" methods of management in woodland areas previously managed on a clearfell regime. However, there is also some evidence to suggest that long-term average carbon stocks in "continuous cover" stands may be somewhat larger than for "clearfell" stands (Seidl *et al*., 2007; Stokes and Kerr, 2009). In general, continuous cover management also reduces the extent of disturbance of the soil compared with clearfelling events. Avoidance of clearfelling (and adoption of continuous cover management) thus represents a possible measure for mitigation of GHG emissions, particularly in woodland areas with high soil organic matter content. It is difficult to estimate the precise impacts of such a measure in terms of overall carbon stock changes in trees and soil; a notional value of 115 tCO_2–eq. ha^{-1} is suggested here. This stock change might occur over the period taken for the stands to transform the stands to continuous-cover management, which would depend on age class distribution but might take anything up to 100 years, giving a net carbon sequestration rate of around -1.1 tCO_2–eq. ha^{-1} yr^{-1}. These magnitudes, periods and consequent rates depend on the details of how the woodlands were being managed for production originally and the extent of the transformation. The changes in carbon sequestration over time will be complex.

Restricting production

Where existing woodlands are being managed for production, the extent of this production could be greatly reduced, for example through limiting the felling of trees to very occasional small groups. It should be noted that this is effectively the same as managing the woodlands as an ensemble of very small clearfell stands on very long rotations. The impact of introducing such management is thus similar to the case of extending rotations but much greater in magnitude, with an overall change in carbon stock in trees and soil (and consequent GHG removal) perhaps as large as 260 tCO_2–eq. ha^{-1}. This additional carbon stock might accumulate over up to 100 years, giving a net carbon sequestration rate of around -2.6 tCO_2–eq. ha^{-1} yr^{-1}. As previously, these magnitudes, periods and consequent rates depend on the details of how the woodlands were being managed for production originally and the extent of the change in rotation (i.e. the change in extent of wood harvesting). The changes in carbon sequestration over time will be complex. Restricting production would have significant economic impacts on the forestry sector and risk shifting demand from Wales to wood supply from sources outside Wales.

Conversion to wilderness woodland

The logical final extension of the conservation options considered so far is to withdraw woodlands completely from management for production. The impact of stopping harvesting for production completely is greater than when production is merely restricted as discussed above, with an overall change in carbon stock in trees and soil (and consequent GHG removal) perhaps as large as 720 tCO_2–eq. ha^{-1}. This additional carbon stock might accumulate over more than 100 years, giving a net carbon sequestration rate of roughly -4 tCO_2–eq. ha^{-1} yr^{-1}. As previously, these magnitudes, periods and consequent rates of carbon sequestration depend on the details of how the woodlands were being managed for production originally. The changes in carbon sequestration over time will be complex.

Consideration of woodland carbon conservation options

Measures involving the conservation of carbon in existing woodlands have certain attractions. They should not require a significant change in land use (or at least land cover). Some options (such as extending rotations) are easy to understand and involve simple modifications to existing management approaches. However, the implementation of such measures may be difficult. A net increase in carbon stock of 115 tCO_2–eq. ha^{-1} (as potentially associated with avoiding clearfelling as described above) is not insignificant but, equally is of a modest scale and may be difficult to distinguish against the "background noise" of carbon stock changes taking place in individual stands across the woodland area (this has implications for monitoring, reporting and verification). Some of the proposed new approaches to management (e.g. avoidance of clearfelling) would involve the introduction of complex systems of tree and woodland management which can be relatively high cost and are not always well understood by forestry practitioners with no previous experience. Newly developed "wilderness" woodlands would need to be protected and may have to be actively managed to create the woodland ultimately desired (e.g. to achieve an appropriate species composition).

All of the woodland carbon conservation measures involve net removals of CO_2 from the atmosphere and sequestration of carbon in biomass – consequently the positive impacts eventually saturate (biologically or technically) and are potentially reversible. All options also imply a reduction in supply of harvested wood from the relevant woodland areas (although there is a debate over the case of introducing continuous cover management, see for example Stokes and Kerr, 2009). Therefore access to any existing supply of wood-based renewable resources would be restricted and there may be loss of revenue for the woodland owners and loss of jobs in within the sector. In addition, there will be market mediated effects, for example, consumption of biomass and timber may have to be replaced with consumption of other fuels and materials which may involve greater GHG emissions, or biomass and timber may have to be imported, possibly involving less well managed woodland resources elsewhere (see Section 8.3). The implications of these cross-sectoral effects are that woodland carbon conservation measures would need to be implemented carefully, in ways that would not compromise access by markets to supplies of biomass and timber. As a simple example, existing areas of woodland managed on very short rotations can actually produce more timber and biomass on an annualised basis if their rotations are extended, thereby also enhancing long-term average carbon stocks. However, the opportunity for this sort of complementary measure would need to be identified almost on a stand-by-stand basis. Moreover, not all situations are as easy to evaluate as in this example.

Climate change is likely to increase the likelihood of natural disturbances, such as storms, fires and pests and diseases, which could compromise woodland carbon stocks and potentially reverse carbon sequestration, including in woodland areas subject to carbon conservation measures. Managing the risks associated with these uncertainties may limit the potential for enhancing or maintaining large carbon stocks.

8.4.4. Enhanced production in existing woodlands

If production of biomass and/or timber from woodlands can be increased then the supply of renewable timber and woodfuel can be enhanced and there should be more opportunities to reduce emissions through their utilisation in place of more GHG-intensive materials and fossil-based energy. The main relevant options are:

- Adjusting rotations closer to the productive maximum
- More production from "low-production" woodlands
- Increasing the harvest of timber offcuts and branchwood
- Changing species composition and growth rate.

Adjusting rotations closer to the productive maximum

Trees (and stands of even-aged trees) have a characteristic rotation for which timber and biomass production are maximal. The period of this rotation and the magnitude of maximum productivity vary depending on tree species and growth rate and the types of material specified for production (e.g. raw biomass and/or structural timber). Typically such "optimum" rotations in Wales are between 30 and 120 years for conifers and between 30 and 150 years for broadleaves, depending on tree species, growth rate etc. If trees or stands are felled on a rotation shorter or longer than the optimum, then productivity (timber volume or biomass per hectare per year) will be less than the potential maximum. For example, if trees or stands are managed on rotations 20 years shorter or longer than the optimum, timber productivity may be lower by typically 0.5 m^3 ha^{-1} yr^{-1} (unpublished calculations based on British forest yield tables, taking examples of relevance to Wales). Consequently, changing rotations by 20 years to the optimum period should increase productivity by approximately this amount. Assuming a typical mix of end uses for the extra harvested material (i.e. biomass, small roundwood and sawlogs), the potential long term reductions in GHG emissions achieved through utilisation of bioenergy and timber can be estimated speculatively at approximately -0.6 tCO_2–eq. ha^{-1} yr^{-1}. It should be noted that this estimate reflects specifically the substitution benefit of the increased use of the timber and bioenergy; this needs to be considered in combination with any effects on woodland carbon stocks due to changes to rotations. Such a contribution may seem very modest but it could still be significant if it were possible to implement this sort of measure over very large areas of woodland. The benefits should also be indefinite (i.e. do not saturate). However because rotations are generally long, any positive effects of adjusting rotations may take time to implement and consequently for the impacts to become apparent.

More production in "low production" woodlands

Where woodlands are not being managed for production, or management for production is very limited, the possibility exists to significantly increase harvesting of timber and biomass for the manufacture of materials and use as renewable energy. Assuming a typical mix of end uses for the extra harvested material, the potential reductions in GHG emissions achieved through utilisation of additional supplies of timber and woodfuel can be estimated speculatively at approximately -5 tCO_2–eq. ha^{-1} yr^{-1}. These potential emissions reductions should be indefinite (i.e. do not saturate). The increased production and potential for substitution in the energy and construction sectors is generally at the expense of some reductions in woodland carbon stocks. The carbon stock change should be "one off", while the emissions reductions from wood utilisation continue. However, a number of research studies have suggested that the "break-even point" when emissions reductions exceed carbon stock reductions may take many decades to achieve (Matthews *et al*., 2014b)

Increasing the harvest of offcuts and branchwood

Until quite recently, conventional harvesting of timber and biomass in woodlands has concentrated on the stemwood of the trees, with "offcuts" (e.g. due to stem defects) and branchwood generally left on site in woodlands. However, there has been growing interest in also harvesting these as a potential source of biomass energy. The harvesting of offcuts and branchwood is already occurring in some areas of NRW woodlands and this is likely to continue in appropriate circumstances. However, such activities are regulated by a protocol that limits the site types where this can occur and the quantities of biomass that can be removed from sites, to ensure that soil nutrients are not depleted, that soil acidity is not adversely affected and that physical damage to soils is avoided or minimised.

The amount of biomass available to harvest from offcuts and branchwood would clearly be very site-specific but a typical level of productivity might be 0.8 oven-dry tonnes of biomass per hectare per year. The emissions reductions that might be achieved from the utilisation of this biomass as energy would depend on the energy conversion process and the type of fossil fuel replaced but a conservative estimate is -0.4 tCO_2–eq. ha^{-1} yr^{-1}. There is an ongoing debate about the effect of harvesting non-stem material on long-term site sustainability (e.g. in terms of soil fertility, acidity and structure). The need to protect site and soil quality is likely to place significant constraints on the harvesting of non-stem material. The removal of stumps and roots as part of biomass harvesting can add to the total biomass output and substitution benefits, but the increased disturbance of soil and litter, with associated GHG emissions, and the risk of a number of other potential impacts (on nutrient cycling, productivity, biodiversity) suggest that this option may have limited viability as a GHG emissions mitigation measure.

Changing the species composition and growth rate of woodlands

When trees are thinned or felled the possibility exists to replace them with trees of different species which have higher growth rates. This could increase the per-hectare productivity of stands while maintaining carbon stocks. The potential for increasing stand productivity in this way is likely to be very site specific. However, as a speculative specific example, restocking of productive stands of Sitka spruce with genetically improved stock might increase stand productivity by about 4 m^3 ha^{-1} yr^{-1}. It should be noted that NRW are already restocking at least 60% of Sitka spruce areas with "improved" trees. Assuming a typical mix of end uses for the extra harvested material (i.e. biomass, small roundwood and sawlogs), the potential long term reductions in GHG emissions achieved through utilisation of bioenergy and timber can be estimated at approximately -1.7 tCO_2–eq. ha^{-1} yr^{-1}. In principle the benefits should be indefinite (i.e. do not saturate).

Although further use of this option appears to offer some potential there are limitations and risks to its implementation. For example it may be difficult to predict the productivity increase actually realised on individual sites by changing species. In addition, in some situations, the replacement species may grow faster but the wood produced may not have the qualities necessary to be used for the same end uses as the original species, which may lead to marketing difficulties and a lower potential for GHG abatement through substitution. There are risks related to pests and diseases which would become significant if one or a restricted number of species were selected. Due to the period over which woodland trees are likely to grow, the effect of climate change will influence species selection which, again, will be difficult to predict.

Matthews *et al*. (2014b) identify a woodland management activity referred to as "enrichment" of woodland growing stock. Such an activity might involve, for example, replanting diseased stands or improving the growing stock in failed or degraded woodland stands, or in areas of scrub. Potentially, these types of activity could enhance the capacity of woodlands to produce timber and fuel, whilst also enhancing woodland carbon stocks. However, the extent of the potential for woodland enrichment activities is unclear.

Consideration of enhanced production options

Measures based on enhancing production in existing woodlands have clear strengths. The supply of an important renewable source of materials and energy (and potentially chemicals) is increased. Consequently there is potential for indefinite and permanent reductions in GHG emissions through substitution for more GHG-intensive and/or non-renewable products. Such measures could also be viewed as supporting an "energy security" (or wider "resources security") agenda. Capacity in the forestry, timber and biomass industries could expand and there could be benefits for rural development in terms of revenue for woodland owners, jobs within the sector and improvements in rural infrastructure.

There are also limitations, drawbacks and risks associated with such measures. For some options, the impacts in terms of GHG emissions abatement are relatively small, even though they should be indefinite and permanent. In many situations there will be practical limits to the enhancement of production in existing woodlands. For example, stands may be managed on non-optimum rotations or not managed for high production to ensure evenness of timber supply, to avoid negative impacts on the landscape or to protect important habitats. Generally, interactions between woodland management and impacts on landscape and habitat are highly location-specific and changes in management could have either positive or negative effects. Fundamentally, the case for increasing timber and biomass supply assumes that there is sufficient demand (and capacity) for its utilisation. This implies a need for concomitant measures to enhance the efficient use of timber and biomass to substitute for materials and fuels with higher life-cycle GHG emissions.

Nearly all options based on the enhancement of production in existing woodlands will involve negative impacts on tree carbon stocks. Estimates for potential increases in woodland carbon stocks due to woodland carbon conservation measures were presented earlier; essentially losses of carbon stocks of similar magnitude would be associated with some options being considered here. The emissions due to reduced carbon stocks would be important in the short term but eventually the long-term benefits of the enhanced production (through cross-sectoral impacts) should outweigh these losses, provided the measures are sustained and the assumptions indicated above apply. As already noted for some options (for example some of the activities involved in increasing production in "low production" woodlands), the "payback period" may be very long, perhaps as much as 100 years.

8.4.5. Indicative mitigation potentials of woodland management measures

Table 8.1 gives a summary of indicative per-hectare GHG emissions mitigation potentials for the range of woodland management measures described in Sections 6.4.1 to 6.4.4. The estimates in the table are based on a synthesis and interpretation of relevant research results (see start of Section 6.4). The estimated mitigation potentials are intended as a rough guide to assist with understanding and comparing the various measures considered in the preceding discussion, for example, to illustrate variable impacts of different woodland management measures on GHG emissions directly due to woodlands and across a range of other economic sectors (e.g. Energy and Construction). Note that, by convention, carbon sequestration in HWP is included as part of woodland carbon stock/stock change results, hence these contributions are not included in estimates of GHG emissions reductions in other sectors through product substitution.

The actual mitigation achieved by implementing specific measures will exhibit considerable variability due to the many factors involved (e.g. woodland composition, growth rates, patterns of wood use and materials and energy sources substituted etc.).

Table 8.1 Summary of indicative GHG emissions mitigation potentials of woodland management measures

Measure	Net carbon stock change[1] (tCO_2–eq. ha^{-1})			Period[2] (years)	Rate of C stock change[3] (tCO_2-eq. ha^{-1} yr^{-1})	Substitution impact[4] (tCO_2-eq. ha^{-1} yr^{-1})	Net impact[5] (tCO_2-eq. ha-1 yr^{-1})	
	Trees	Soils	Total				At 50 years	At 100 years
Avoid deforestation of productive woodland	-171	-330	-501	50	-10.0	-6	-16.0	-6.0
Convert pasture to productive woodland	-171	-330	-501	50	-10.0	-6	-16.0	-6.0
Convert pasture to "wilderness" woodland	-779	-440	-1219	100	-12.2	0	-12.2	-12.2
Extend rotations	-60	0	-60	80	-0.7	0.6	-0.1	+0.6
Avoid clearfelling (CCF)	-58	-55	-113	100	-1.1	0.6	-0.5	-0.5
Strong restriction on wood harvesting	-205	-55	-260	100	-2.6	5	+2.4	+2.4
Transform productive woodland to "wilderness"	-608	-110	-718	150	-4.8	6	+1.2	+1.2
Optimise rotations for production	29	0	29	50	0.6	-0.6	0.0	-0.6
Introduce harvesting in woodlands not in production	205	220	425	50	8.5	-5	+3.5	-5.0
Extract harvesting residues	11	50	61	30	2.0	-0.4	+1.6	-0.4
Change species on restocking	0	0	0	-	0	-1.7	-1.7	-1.7

Notes to Table 8.1:

1 Positive numbers indicate net carbon stock losses; negative numbers indicate net carbon sequestration.
2 Indicative period in years over which overall carbon stock changes in trees and soils may take place.
3 Total net carbon stock change divided by period in years.
4 Indicative impacts on GHG emissions in other sectors (e.g. Energy and Construction) due to increases or decreases in wood supply; positive numbers indicate net GHG emissions increases; negative numbers indicate net GHG emissions reductions.

5 Indicative overall impacts on rates of GHG emissions after 50 years and after 100 years, directly attributable to woodlands and in other sectors (e.g. Energy and Construction) due to increases or decreases in wood supply; positive numbers indicate net GHG emissions increases; negative numbers indicate net GHG emissions reductions. Green cells indicate net GHG emissions reductions; orange cells indicate net GHG emissions increases.

8.5. Possible climate change mitigation approaches in NRW woodlands

The discussion in Section 8.4 has described in some detail a range of measures that may be taken with regard to woodland management, aimed at mitigating GHG emissions. The following discussion offers some tentative suggestions for approaches that may be taken to supporting the management of NRW woodlands to contribute towards climate change mitigation. The general strategic approach is explored in Section 8.5.1, whilst Section 8.5.2 considers possible specific approaches and measures with apparent relevance to NRW woodlands.

8.5.1. Suggested strategic approach to woodland GHG management

Simplifying woodland GHG management options for strategic purposes

There is a long list of possible options for woodland management measures, as already described in Section 8.4. However, a simpler and more summarised set of options may be easier to consider when developing a broad strategy for managing the woodlands forming a large woodland estate with the aim of supporting climate change mitigation.

Broadmeadow and Matthews (2003) have suggested classifying woodland management measures into three contrasting generic options:

1. Woodland carbon reserve management (involving measures such as described in Sections 8.4.1, 8.4.2 and 8.4.3)
2. Substitution management (involving measures such as described in Sections 8.4.2 and 8.4.4)
3. Selective intervention carbon management (involving "light-touch" implementation of measures such as described in Sections 8.4.3 and 8.4.4, with the aim of achieving synergies where possible).

The three options as characterised by Broadmeadow and Matthews (2003) are outlined below.

1 Woodland carbon reserve management

This option is characterised by minimal intervention in woodlands, with a gradual long-term increase in carbon stocks. In addition to a climate change mitigation role, carbon reserve management may possibly also have significant amenity and biodiversity benefits, particularly if native species are involved. Loss of woodland carbon stocks through fire, drought, floods, storm damage or pathogen outbreaks needs to be minimised. For this reason, it is necessary to take account of wind-hazard, flood risk and climate change predictions regarding the suitability of a particular site-species combination to achieve this objective. Woodland carbon reserve management is particularly well suited to woodland stands with very low growth rates and poor stem quality, or in localities where there are limited opportunities for utilisation of harvested wood.

2 Substitution management

This form of carbon management and its objectives are not far removed from the production forestry that has been common practice in much of the UK forest estate in the last 100 years. Under this option, there is an emphasis on the production of good quality stemwood for use in product displacement along with the extraction of woody biomass for use as woodfuel. The option also includes the management of coppice for bioenergy production. The maintenance or enhancement of high on-site carbon stocks in woodland is of secondary importance. Soil disturbance during thinning and clearfelling operations needs to be minimised to limit litter and soil carbon losses. Substitution management is particularly well suited to even-aged woodland stands with moderate to high growth rates in localities with obvious opportunities for utilisation of harvested wood. Stem quality may also require consideration when options are being evaluated, because it will have an impact on the potential to convert stemwood into different products.

3 Selective intervention carbon management

This option is similar to carbon reserve management but, in addition, there is low-level harvesting of certain trees to clearly defined specifications in order to supply high-value niche applications. It is well suited to stands containing trees of variable quality where risk of significant natural disturbance is low and which may be some distance from centres of population or industry. Examples of this type of management include occasional tree harvests in stands to meet a requirement for fuelwood in a small local community and selective felling in continuous cover forestry systems to satisfy specialist timber markets.

GHG impacts of woodland management options

As a general guide, selective intervention and carbon reserve management will usually result in higher long-term carbon stocks within a given woodland ecosystem. On the other hand, only substitution and, to a lesser extent, selective intervention carbon management have the potential to deliver long-term reductions in GHG emissions due to woodland management beyond the potential one-off increase in woodland carbon stocks associated with new or conserved woodland.

Approach to strategy for woodland GHG management

A possible approach to developing a strategy or policy for managing existing NRW woodlands to support the objective of climate change mitigation could involve assigning specific areas of NRW woodlands to be managed according to one of the three broad options described above. Detailed management of the classified woodland areas could then be determined as part of the woodland planning process, referring to appropriate possible measures described in Section 8.4.

The strategic planning of the management of woodlands to meet climate change mitigation objectives requires an in-depth assessment of numerous factors including site conditions, potential productivity, vulnerability to natural events, proximity to point of use and the local practicalities of the best and most realistic options for end-use of harvested wood. The planning process could be supported by the development of practical guidance based on consideration of a range of simple relevant criteria. For example, Matthews and Robertson (2006) suggested a simple graphic to illustrate how broad classes of woodland system might be matched to GHG management objectives (see Figure 8.1). The graphic was designed in a different context but could be adapted and elaborated as part of wider guidance relevant to the planning of management in NRW woodlands.

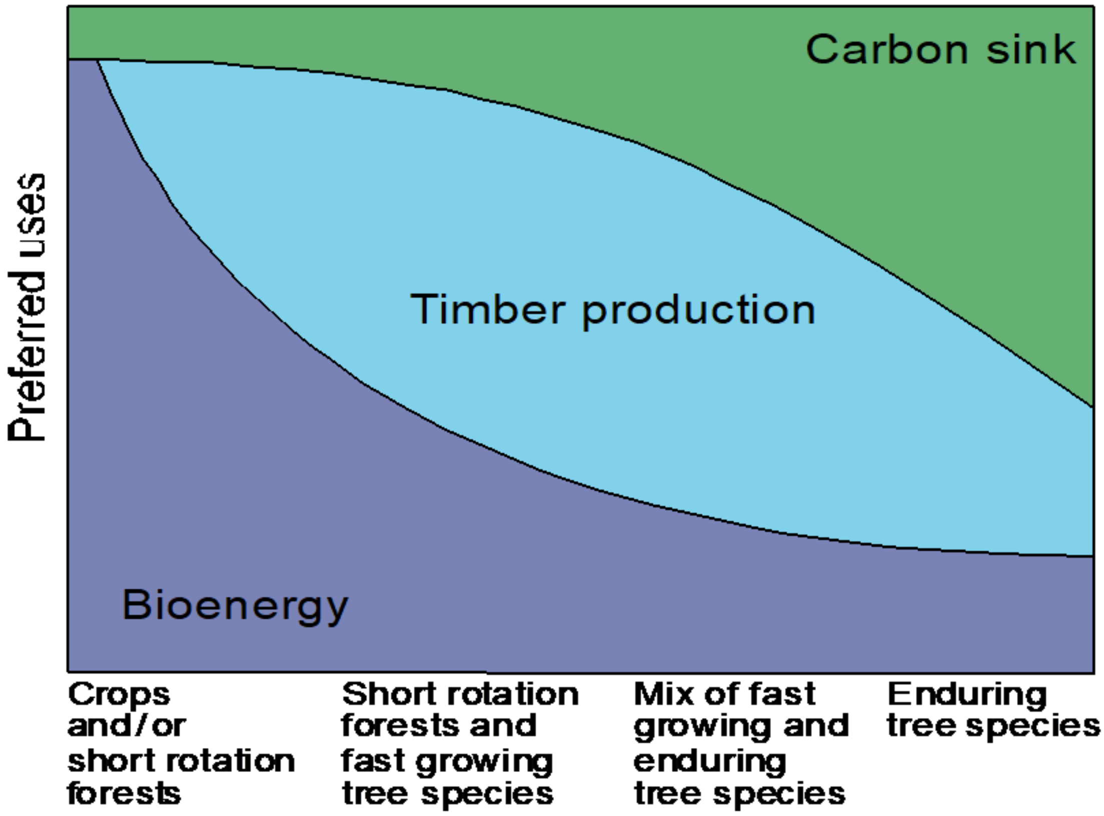

Figure 8.1. Developing guidelines for matching woodland management and wood utilization regimes with appropriate priorities for GHG management (after Matthews and Robertson, 2006).

8.5.2. Specific measures with potential relevance to NRW estate

It is possible to identify certain specific approaches and measures aimed at mitigating GHG emissions through woodland management that could be of particular relevance in the context of the management of the NRW estate. These specific approaches and measures are briefly considered below.

Broadleaves as woodland carbon reserves

The results of this study have highlighted that broadleaved woodland areas are predicted to make an important contribution to total net GHG removals in NRW (see Section 7.3.6). It is important to recognise that this finding is highly dependent on the assumed future management of broadleaved woodland areas on the NRW estate, specifically involving relatively low levels of wood production (see Table 6.6, Section 6.2.3). It follows that the study results indicate considerable potential for more active adoption of woodland carbon reserve management in many broadleaved woodlands. In a minority of cases, where wood production is supported in broadleaved woodlands, the option of selective intervention carbon management may be appropriate. There will be exceptions, for example areas of fast-growing coppice where substitution management may be more suitable.

Low impact silvicultural systems in coniferous woodlands

The results of this study have highlighted that coniferous woodland areas managed according to low impact silvicultural systems are predicted to make a moderate contribution to total net GHG removals in NRW (see Section 7.3.6). It is important to understand what types of woodland management are being included when referring here to low impact silvicultural systems and how these systems have been modelled in this study (see Sections 6.2.1, 6.2.2 and 6.2.3). The term low impact silvicultural systems is being used here to refer, collectively, to:

- Shelterwood management systems – management as uneven-aged, continuous cover woodland with a relatively simple structure (e.g. two storeys of trees, one or few tree species)
- Selection management systems – management as uneven-aged continuous cover woodland with a relatively complex structure (e.g. multiple storeys of trees, several tree species)
- Reserve/retention management systems – either managed on the basis of “minimum intervention”, not involving wood production, or managed based on long-term retention (i.e. no clearfelling or deferred felling).

The relevant coniferous woodland areas have also been referred to as “non-clearfell coniferous woodlands” in Section 7.3.6.

The modelling of these woodland areas in this study was based on data on the composition of NRW woodlands (Table 6.2, Section 6.2.1) and assumptions and rules supplied by NRW (Table 6.6, Section 6.2.3). The coniferous woodland area assumed to be managed on the basis of minimum intervention represented about 20% of the total area of woodlands managed according to low impact silvicultural systems. However, the contribution of these “reserve” woodlands was important for ensuring that, overall, woodland areas managed according to low impact silvicultural systems contributed net carbon sequestration (rather than net carbon stock losses). It follows that the study results indicate a moderate potential for some increased adoption of low impact silvicultural systems in some areas of coniferous woodlands but that it is important to consider the balance between management as reserves or for retention on the one hand, and management as shelterwood or selection systems on the other hand.

Species selection on restocking including improved Sitka spruce

A possible climate change mitigation measure could involve actively restocking clearfelled woodlands with the express intent of changing tree species to meet climate change mitigation (and possibly other) objectives. A notable example would involve restocking stands of unimproved Sitka spruce in NRW woodlands with “improved” Sitka spruce trees. As already noted, NRW are already restocking at least 60% of Sitka spruce areas with “improved” trees. There is evidence that stands of improved Sitka spruce trees can have significantly faster growth rates than stands of unimproved Sitka spruce (Matthews *et al*., 2017b). As a consequence, improved Sitka spruce stands have the potential to produce more timber on a given rotation, or the same amount of timber on a shorter rotation, when compared with unimproved Sitka spruce. At the same time, the impacts on rates of carbon sequestration and overall carbon stocks in relevant woodland areas should be positive. This is a practical example of a measure to enhance production in existing woodlands, involving changing the species composition and growth rate in woodlands (see Section 8.4.4).

Woodland restocking

As part of the modelling in this study, the assumption was made that, following the clearfelling of stands, restocking would occur promptly with 100% success. There are practical constraints on how rapidly restocking can be achieved (see Section 6.2.4). Nevertheless, it may be appropriate for restocking practice (in both clearfelled and non-clearfelled woodlands) to be reviewed, with the aim of ensuring full restocking occurs as quickly as possible throughout the NRW estate.

Woodland creation

Out of all the options, it is important not to forget the possibility of creating new woodland areas on the land owned or managed by NRW, where such opportunities may exist. As discussed in Section 8.4.2, the creation of new woodlands can contribute significantly to land-based carbon sequestration and also to the supply of wood products and biomass. However, it must be acknowledged that the potential for this option is limited given that 85% of the NRW Estate is currently woodland, and most of the rest consists of nature conservation sites protected for other habitats or land associated with other assets e.g. flood defences and pumping stations.

8.6. Relevance of GHG accounting approaches

National and international policy frameworks aimed at achieving climate change mitigation are supported by systems for accounting for GHG emissions (and removals).

Different types of accounting system can be devised and, in practice, different accounting systems have been adopted to support specific policy frameworks. This is important because the accounting systems determine the details of the GHG emissions and removals, as reported for different economic sectors, that are actually included in the national or international GHG emissions accounts of countries or economic regions (such as the EU).

For nearly all economic sectors, all these accounting systems adopt a simple and obvious approach to accounting for GHG emissions (and removals, where relevant). However, the accounting rules applied to GHG emissions and removals in the Land Use, Land-Use Change and Forestry (LULUCF) Sector (see Section 7.3.8) can be complicated and sometimes difficult to understand, particularly in the case of the rules applied to Forest Land. Moreover, different national and international frameworks refer to different accounting rules for the LULUCF Sector, notably with regard to Forest Land.

8.6.1. Types of Forest Land accounting approach

From the perspective of this discussion of Forest Land, there are four accounting approaches of relevance:

1 "Gross-net" accounting

2 "Gross-net" accounting "with cap"

3 "Reference level" accounting

4 "Reference level" accounting "with cap".

Brief explanations of these four approaches are given below.

Gross-net accounting

Under gross-net accounting, the total net GHG emissions or removals for a defined area of woodland are reported simply and taken to be the accounted emissions or removals. For example, if the total net GHG emissions or removals for an area of woodland for (say) the year 2017 are a net removal of -20 $ktCO_2$–eq. yr^{-1}, then the accounted GHG emissions or removals are simply equal to the net GHG removal of -20 $ktCO_2$–eq. yr^{-1}.

It should be noted that the results for the baseline scenario for management of NRW woodlands, as developed in this study and presented in Section 7 of this report, are straightforward estimates of GHG emissions and removals and so consistent with the gross-net accounting approach.

Gross-net accounting with cap

This system of accounting is similar to gross-net accounting, except that total net GHG removals can only be claimed up to a maximum assigned value or "cap". The value of the cap is negotiated amongst parties participating in the relevant accounting framework. For example, if the total net GHG emissions or removals for an area of woodland for (say) the year 2017 are a net removal of -20 $ktCO_2$–eq. yr^{-1}, and the assigned cap is -10 $ktCO_2$–eq. yr^{-1}, then the accounted GHG emissions or removals are set equal to the smaller of the two removals represented by the reported total net GHG removals and the cap, in this case -10 $ktCO_2$–eq. yr^{-1}. Typically, no cap is applied in the case of net GHG emissions.

Generally, in an international context, the rationale behind the adoption of a cap on removals associated with forests and woodland is to:

- Avoid situations in which certain countries with very large forest areas do not need to take any action to achieve net GHG removals or GHG emissions reductions
- Encourage countries to take additional actions to reduce GHG emissions, rather than simply continuing with business as usual.

Reference level accounting

The calculation of accounted net GHG emissions or removals under this system of accounting is more complicated than for the approaches described above:

- For a defined area of woodland, a projection is modelled of the total net GHG emissions or removals for future years (say for the year 2020), under a BAU scenario for woodland management, defined according to certain criteria. The projected total net GHG emissions or removals for a given future year are the “reference level” for that year.
- When the year comes (say 2020), the actual total net GHG emissions or removals for the year 2020 are calculated and reported.
- The accounted GHG emissions or removals for a given year (say 2020) are calculated as the difference between the actual reported total net GHG emissions or removals and the reference level.

As one example, suppose that the projected actual total net GHG emissions or removals for a defined area of woodland for the year 2020 are a net GHG removal of -20 $ktCO_2$–eq. yr^{-1}. Now suppose that, in the year 2020, the actual total net GHG emissions or removals reported for the area of woodland are calculated and found to be a net GHG removal of -15 $ktCO_2$–eq. yr^{-1}. The accounted GHG emissions or removals are calculated by subtracting the reference level from the reported net GHG removals, giving (in this case) net GHG emissions of -15 – (-20) = +5 $ktCO_2$–eq. yr^{-1}.

Reference level accounting with cap

This system of accounting is similar to reference level accounting, except that accounted net GHG removals (as calculated relative to the reference level) can only be claimed up to a maximum assigned value or “cap”. The approach to capping accounted GHG removals is similar to that described above for gross-net accounting with cap.

8.6.2. Application of accounting approaches in policy frameworks

Table 8.2 summarises the types of accounting approaches applied to Forest Land in a range of relevant domestic and international policy frameworks.

The Welsh Government has a statutory obligation to introduce a carbon budgeting framework in Wales through the Environment (Wales) Act of 2016. The Welsh Government sought evidence on how emissions should be accounted for in Wales from the UK Committee on Climate Change (UKCCC) who issued a wider call for evidence in December 2016. Their advice on the design of the Welsh carbon budgets was published in April 2017 (UKCCC, 2017), recommending a gross-net accounting approach for most if not all sectors, stressing the case for the overall accounting framework to be "based on actual emissions [and removals] in Wales". This advice has been subsequently accepted by the Welsh Government as the appropriate emissions accounting approach for Wales with it applying to all sectors.

Table 8.2 Accounting rules applied to Forest Land under domestic and international policy frameworks

Policy framework	Accounting rules for Forest Land
Welsh Government domestic climate policies	Gross-net accounting with 1990 baseline but yet to be formally established, see discussion immediately above table.
Kyoto Protocol (first accounting period of 2008 to 2012)*	Gross-net accounting for woodland areas created since 1990 and for deforestation since 1990 Gross-net accounting with cap for other woodlands
Kyoto Protocol (second accounting period of 2013 to 2020)*	Gross-net accounting for woodland areas created since 1990 and for deforestation since 1990 Reference level accounting with cap for other woodlands
EU domestic climate policies (2013 to 2020)*	Essentially the same as Kyoto Protocol (second accounting period)
EU and international climate policies post 2020	Currently under discussion

Note to Table 8.2:
*The UK had or currently has commitments under these policies.

8.6.3. Implications of accounting approaches

It is evident from the descriptions in Section 8.6.1 that the accounting approaches for Forest Land adopted by different policy frameworks (see Section 8.6.2) give different results for the same woodland management activities.

In the context of the NRW Carbon Positive project, Welsh Government domestic climate policy frameworks are of most immediate apparent relevance. Under the i accounting approach supporting the Environment (Wales) Act (see discussion of Table 8.2 above), simply maintaining BAU management of NRW woodlands (in particular, ensuring that NRW woodlands continue to act as a net carbon sink) would mean that NRW woodlands should contribute towards net GHG removals (as accounted for by the rules). In contrast, BAU management of NRW woodlands would most likely mean that no GHG removals arising from NRW woodlands would be accounted as contributing towards the UK's current international climate commitments, which are based on the reference level approach. For any contribution from the management of NRW woodlands to contribute towards international climate targets (under current accounting rules), it would be necessary for “additional” mitigation activities to be undertaken in NRW woodlands (such as some of the measures described in Section 8.4, aimed at conserving or enhancing woodland carbon stocks).

It should also be noted that the possibility exists that the management of NRW woodlands could deliver accounted GHG removals under the putative Welsh domestic policy framework but register as accounted GHG emissions in the context of international commitments. Such a situation might arise, for example, if the management of NRW woodlands was changed from BAU, involving increased biomass extraction from woodlands to support meeting renewable energy targets or greater use of timber in “green building construction”, whilst still maintaining NRW woodlands as a net carbon sink, but reduced in magnitude compared with the (projected) carbon sink associated with BAU management.

8.6.4. Accounting for GHG emissions and removals in different sectors

All accounting approaches currently applied to Forest Land in domestic and international policy frameworks involve reporting GHG emissions and removals for different economic sectors. Frequently, woodland management activities make potentially significant contributions to GHG emissions (or emissions reductions) in a number of sectors, not just the LULUCF sector (see Section 7.3.8). For example, the use of timber as part of “green building” initiatives and the use of woody biomass as fuel can lead to reductions in GHG emissions in the Construction and Energy Sectors, through the avoidance of use of GHG-intensive construction materials or fossil fuels. However, these contributions towards GHG emissions reductions will not be so obviously attributable to woodland management activities. Furthermore, different climate change mitigation measures will have variable impacts on changes in GHG emissions and removals across a number of GHG inventory sectors; sometimes these impacts will tend to be in antagonism with one another and sometimes there will be synergies (see Section 8.4).

8.7. Conclusions

This report has presented a detailed description of modelling work undertaken to predict the likely future development of carbon stocks and net GHG emissions and removals associated with woodlands on land owned or managed by Natural Resources Wales.

8.7.1. Carbon stocks

For the base year of this study of 2015, carbon stocks in the trees, deadwood/litter and soils of NRW woodlands and in wood products supplied from NRW woodlands are estimated at 26.6 MtC (million tonnes carbon).

About 50% of the carbon stocks are in woodland soils, 30% in trees, 15% in harvested wood products with the remaining 5% in deadwood and litter.

Under a business as usual scenario for woodland composition and management, as defined in this study, by the time horizon for this study of 2040, the total carbon stocks in NRW woodlands are predicted to increase to 29.5 MtC, an increase of 2.9 MtC compared with the base year of 2015.

About 64% of the projected increase in woodland carbon stocks is due to the accumulation of carbon stocks in trees, with about 28% contributed by accumulating soil carbon stocks, whilst deadwood/litter and harvested wood products contribute approximately 1% and 7% respectively.

Per-hectare results for total carbon stocks and total carbon stock changes in NRW woodlands, as predicted by this study, are consistent with estimates of carbon stocks as reported in a selection of scientific literature, either of relevance to Wales or the UK, or based on a meta-analysis of available results.

Different regions of NRW woodlands (commercial woodlands in the Northeast, Northwest, Mid, Southeast, Southwest operational regions and non-commercial woodlands) make variable contributions to total carbon stocks. Typically, these variations are simply related to differences in the total area of woodlands in each region. However, non-commercial woodlands make a disproportionately large contribution to total carbon stocks, compared with the contributions of commercial woodlands. This reflects higher per-hectare carbon stocks predicted for non-commercial woodlands, due to the assumptions that a large part of the non-commercial woodland area will be composed of mature trees, and that harvesting activities and natural disturbances in non-commercial woodlands have been, and will be, quite limited.

8.7.2. GHG emissions and removals

When considering the study results for projected GHG emissions and removals, it is important to recall the spatial system boundary for this study, which encompasses all woodlands owned or managed by Natural Resources Wales and includes contributions to GHG emissions due to:

- CO_2 emissions and removals due to carbon stock changes in the trees, litter and soil of NRW woodlands and harvested wood products
- The main GHG emissions (CO_2, CH_4 and N_2O) arising from woodland operations (tree establishment, woodland management and harvesting).

The system boundary does not include contributions to GHG emissions due to:

- CH_4 and N_2O emissions from woodland soils (particularly organic soils)
- GHG emissions arising from timber transport from the woodland
- GHG emissions arising from the processing of harvested wood and the manufacture and installation of finished wood products
- GHG emissions potentially avoided from using wood products (including woodfuel) in place of alternative products (possibly supplied or manufactured using other types of materials or fuels, including fossil fuel sources).

Note also that:

- Typically, results for GHG emissions/removals are expressed in units of CO_2-eq. (carbon dioxide equivalent)
- Negative results indicate net GHG removals; positive results indicate net GHG emissions.

Under a business as usual scenario for woodland composition and management, the projected annualised total net GHG removals (carbon sequestration) for all NRW woodlands over the period 2015 to 2040 are predicted to be -409.5 $ktCO_2$-eq. yr^{-1} (thousand tonnes carbon dioxide equivalent per year). This is the net result of:

- A projected annualised total net carbon sink in NRW woodlands (trees, deadwood/litter and soils) of -394.2 $ktCO_2$-eq. yr^{-1}
- Projected net carbon sequestration in harvested wood products supplied from NRW woodlands of -28.0 $ktCO_2$-eq. yr^{-1}
- Projected GHG emissions due to woodland operations in NRW woodlands of +12.7 $ktCO_2$-eq. yr^{-1}.

The projected total net GHG removals predicted for NRW woodlands are reasonably stable between 2015 and 2040, increasing by only 5% over this period.

The apparent stability of total net GHG removals between 2015 and 2040 masks some quite significant trends in the contributions made by individual carbon pools and by woodland operations:

- Woodland trees are predicted to make a significant and fairly stable contribution to net GHG removals but with a possible progressive decline after about 2030
- Woodland soils are predicted to make a moderately significant contribution to net GHG removals, with a pronounced progressive rise in the contribution between about 2025 and 2040
- Woodland deadwood/litter is predicted to make an almost negligible contribution to net GHG removals
- Harvested wood products are predicted to make a small contribution to net GHG removals, which declines gradually over the period from 2015 to 2040
- A very small contribution is predicted for GHG emissions arising from woodland operations, which is stable between 2015 and 2040.

Per-hectare results for total net GHG removals associated with trees in NRW woodlands, as predicted by this study, are consistent with previously published estimates for woodland trees in Great Britain.

Different regions of NRW woodlands (commercial woodlands in the Northeast, Northwest, Mid, Southeast, Southwest operational regions and non-commercial woodlands) make variable contributions to total net GHG removals between 2015 and 2040. Very broadly, these variations are simply related to differences in the total area of woodlands in each region. However, there is some complexity in the trends of relative contributions from regions:

- The rates of net GHG removals due to commercial woodlands in the Northeast, Northwest, Mid and Southeast operational regions are predicted to rise over the period from 2015 to 2040, being most marked for the Mid operational region
- In contrast to other operational regions, the rate of net GHG removals due to commercial woodlands in the Southwest operational region is predicted to decline progressively and significantly over the period from 2015 to 2040
- Projected net GHG removals are smallest for the non-commercial NRW woodlands and removals decrease gradually over the period from 2015 to 2040.

8.7.3. Causes of regional trends in woodland GHG removals

An investigation of the main causes of the trends exhibited in projections of net GHG removals for individual regions of NRW woodlands over the period 2015-2040 has identified, with reasonable confidence, a number of driving factors:

- The proportion of broadleaved woodland in the region (these woodlands are predicted to make a significant contribution to rate of net GHG removals but may decline over time)
- The proportions of coniferous and broadleaved woodland in the region composed of trees aged younger than 40 years (these woodlands are predicted to make a significant contribution to rate of net GHG removals that may rise over time)
- The proportion of coniferous woodland in the region either managed on the basis of "minimum intervention", not involving wood production, or managed based on long-term retention of the growing stock (these woodlands are predicted to make a significant contribution to rate of net GHG removals but declining gradually over time)
- The proportion of coniferous woodlands managed for wood production using either shelterwood or selection systems (these woodlands are predicted to make a moderate contribution to rate of net GHG removals, declining over time)
- The proportion of coniferous woodlands managed for wood production with clearfelling (these woodlands are predicted to make a significant contribution to rate of net GHG removals but declining significantly over time).

8.7.4. Contribution of NRW woodlands to LULUCF GHG inventory

A projection of net GHG emissions and removals due to all Forest Land in Wales over the period 2015 to 2040, based on the most recent published UK GHG inventory (compiled for the period 1990 to 2015), predicts a mean rate of total net GHG removals of -1 716.2 $ktCO_2$-eq. yr^{-1}.

NRW woodlands represent about 36% of the total area of woodlands in Wales. The share of total net GHG removals due to NRW woodlands (24%) is somewhat lower than might be expected based on simple consideration of relative areas. These differences are likely to reflect:

- A lower proportion of broadleaved woodlands on the NRW estate, compared with other woodlands in Wales
- Higher projected levels of wood production from NRW woodlands, compared with other woodlands in Wales, leading to greater impacts on the growing stock of NRW woodlands due to harvesting
- Related to the higher projected levels of wood production from NRW woodlands, greater carbon sequestration in HWP supplied from NRW woodlands, compared with HWP supplied from other woodlands in Wales, which compensates to an extent for higher levels of wood harvesting.

It is very important to attach a number of caveats to the comparison of the GHG inventory results for net GHG emissions and removals due to Forest Land in Wales with the relevant results for NRW woodlands produced by this study, specifically with regard to:

- The definition of the system boundary adopted
- Assumptions made in defining the scenario on which the results were based
- Datasets referred to for model inputs
- Modelling methodologies.

8.7.5. Possible options for management of NRW woodlands for climate change mitigation

It is possible to identify a number of specific woodland management activities that might help reduce net GHG emissions, generally involving:

- Prevention of deforestation
- Afforestation
- Conservation or enhancement of carbon in existing woodlands, including protection against disturbances and extreme events such as fire
- Enhancement of production in existing woodlands, e.g. through increased harvesting to achieve substitution impacts in other sectors

For simplicity, the various woodland management activities can be classified into the three contrasting generic options of:

1. Woodland carbon reserve management
2. Substitution management
3. Selective intervention carbon management.

A possible approach to developing a strategy or policy for managing existing NRW woodlands to support the objective of climate change mitigation could involve assigning specific areas of NRW woodlands to be managed according to one of these three broad options. Detailed management of the classified woodland areas could then be determined as part of the woodland planning process, referring to appropriate possible more detailed measures.

As a general guide, selective intervention and carbon reserve management will usually result in higher long-term carbon stocks within a given woodland ecosystem but this will be a one-off increase in carbon stocks which takes place over a finite period. On the other hand, substitution management and, to a lesser extent, selective intervention carbon management have the potential to deliver long-term reductions in GHG emissions due to woodland management, through the long-term provision of additional supplies of timber and woodfuel.

It is possible to identify certain specific approaches and measures aimed at mitigating GHG emissions through woodland management that could be of particular relevance in the context of the management of the NRW estate:

- Increasing the area of broadleaves managed as woodland carbon reserves
- Identifying a mix of management approaches in coniferous woodland areas managed on low impact silvicultural systems (shelterwood and selection systems versus reserve/retention systems)
- Actively restocking clearfelled stands to achieve changes in the species composition of NRW woodlands to meet climate change mitigation objectives, notably restocking unimproved Sitka spruce with "improved" Sitka spruce trees
- Ensuring full restocking of clearfelled woodlands occurs as quickly as possible and the establishment of successor woodlands is achieved consistently across the NRW estate
- Out of all the options, it is important not to forget the possibility of creating new woodland areas on the land owned or managed by NRW, where such opportunities may exist.

8.7.6. Accounting for GHG emissions and removals due to woodland management

National and international policy frameworks aimed at achieving climate change mitigation are supported by systems for accounting for GHG emissions (and removals). Different types of accounting system can be devised and, in practice, different accounting systems have been adopted to support specific policy frameworks. This is important because the accounting systems determine the details of the GHG emissions and removals, as reported for different economic sectors, that are actually included in the national or international GHG emissions accounts of countries or economic regions (such as the EU).

The Welsh Government has a statutory obligation to introduce a carbon budgeting framework in Wales through the Environment (Wales) Act of 2016. The Welsh Government sought evidence on how emissions should be accounted for in Wales from the UK Committee on Climate Change (UKCCC) who issued a wider call for evidence in December 2016. Their advice on the design of the Welsh carbon budgets was published in April 2017 (UKCCC, 2017), recommending a gross-net accounting approach for most if not all sectors, stressing the case for the overall accounting framework to be "based on actual emissions [and removals] in Wales". This advice has been subsequently accepted by the Welsh Government as the appropriate emissions accounting approach for Wales with it applying to all sectors. The accounting system adopted to support Welsh domestic policy differs from approaches under UK and international agreements. The potentially different accounting approaches for Forest Land adopted in different policy frameworks will give different results for the same woodland management activities in Wales.

All accounting approaches currently applied to Forest Land in domestic and international policy frameworks involve reporting GHG emissions and removals for different economic sectors. When considering options for climate change mitigation activities involving the management of NRW woodlands, it is important to recognise that different climate change mitigation measures will have variable impacts on changes in GHG emissions and removals across a number of GHG inventory sectors; sometimes these impacts will tend to be in antagonism with one another and sometimes there will be synergies.

8.7.7. Recommendations

- The possibility could be explored of developing and adopting or integrating a strategic approach to the management of NRW woodlands to support climate change mitigation within the existing management framework.
- Further evaluation could be made of the viability, carbon benefits and costs of the specific approaches and measures identified for woodland management on the NRW estate to support climate change mitigation outlined in this report.
- Based on the strategic approach and evaluation of specific approaches described above, NRW could develop a series of scenarios involving changes to woodland management potentially contributing towards climate change mitigation goals. These scenarios could be modelled and evaluated through comparison with the baseline scenario developed in this project, through extension of the modelling approach developed in this study.

Glossary

There are many terms used in the modelling and reporting of woodland carbon stocks, carbon sequestration and greenhouse gas emissions that have apparently specialised meanings. In some instances, these terms have strict definitions that are broadly accepted and used. However, in other instances, there are terms which are less well-defined and often have ambiguous or unclear meanings. This situation has considerable potential for creating confusion for those engaged in this area of work and in subsequent debates over the interpretation of the results of such work. It is not the purpose of this glossary to impose strict definitions. Instead, the glossary is intended to establish reasonably precise terms as used in this study.

Glossary of terms

Additionality	Additionality refers to the positive (or potentially negative) net benefits in terms of climate change mitigation directly attributable to a mitigation activity or project (or mitigation measure). The concept generally refers to net greenhouse gas emissions reductions over and above that which would have occurred anyway in the absence of a given mitigation activity or project.
Afforestation	The direct human-induced conversion of land that has not been forested in the recent past to forested land through planting, seeding and/or the human-induced promotion of natural seed sources.
Bark	The outer layers of the stems and branches of woody plants and trees.
Baseline	In order to estimate the benefits of a climate change mitigation activity or measure in terms of "additional" greenhouse gas emissions reductions, it is necessary to compare the levels of emissions and removals estimated for the mitigation activity with those estimated assuming the mitigation activity is not carried out. The reference estimate or trajectory referred to in such a comparison is known as a baseline.
Biomass	Biological material derived from living, or recently living organisms. In the context of this report, this is taken to mean the biomass of vegetation.
Branchwood	Generally considered to be the portion of above ground woody biomass of a tree which is not defined as stemwood. May contain branches and stem tops below a certain diameter.
"Business as usual" scenario	A scenario describing specified plans, activities, services and processes, and associated flows, e.g. of energy and GHG emissions, intended to represent the current and future situation in the absence of policy interventions other than those already being implemented.
Carbon content	The proportion of the dry mass of a material composed of carbon.
Carbon dioxide equivalent (CO_2 equivalent)	A unit used to express GHG emissions in terms of the equivalent amount of CO_2. Since each non-CO_2 GHG gas has a different warming effect on the atmosphere, the weightings, also called Global Warming Potentials (GWPs) reflect this. The latest GWP values published by the IPCC in 2007, based on a 100 year time horizon, are 25 for methane and 298 for nitrous oxide. For example, this means that 1 tonne of methane would be expressed as 25 tonnes CO_2-equivalent.

Carbon pool	A component of a system, other than the atmosphere, which has the capacity to store, accumulate or release carbon. In the context of this study, woodland biomass, litter and soil and harvested wood products are all examples of carbon pools. The absolute quantity of carbon held within a pool at a specified time is called the carbon stock.
Carbon reservoir	See "carbon pool".
Carbon sequestration	In the context of agriculture, forestry and bioenergy, this is the process by which carbon dioxide is removed from the atmosphere by the growth of vegetation and carbon is retained in the living and dead biomass of vegetation, litter and soil organic matter. For sequestration to be said to have occurred, there must have been a reservoir which has increased in carbon stocks. Taking the example of a stand of trees, suppose a stand of trees grows by X tonnes of carbon per year, through removal of atmospheric carbon dioxide, but this is balanced by reductions in carbon stocks due to harvesting in another stand, so that the total quantity of carbon stocks in the forest stands does not change. Sequestration is not occurring because there is no increase in carbon stocks. In order to focus on changes of lasting consequence, most commentators would ignore sequestration that takes place on a daily, seasonal or even annual basis, and consider only activities that show a trend over longer time intervals.
Carbon sink	Any process, activity or mechanism which removes carbon dioxide from the atmosphere and retains the carbon in a reservoir. (See "carbon sequestration" and "carbon source").
Carbon source	Any process, activity or mechanism which releases carbon dioxide (possibly and/or methane) into the atmosphere from a reservoir of carbon (see "carbon sink" and "carbon sequestration").
Carbon stock	In the context of agriculture, forestry and bioenergy, a carbon stock is an amount of carbon sequestered in the living and dead biomass of vegetation, litter and soil organic matter comprising an agricultural field, a whole agricultural system, forest stand of whole forest. See "carbon pool".
Clearfelling	The periodic harvesting of trees in a woodland, involving the complete or near-complete removal of standing trees for commercial utilisation.
Commercial woodlands	In the specific context of this study, the term "commercial woodlands" refers to woodland areas on land owned or managed by Natural Resources Wales that are under commercial management, where timber production is one of the important objectives of the management of the woodlands. See "non-commercial woodlands".
Coppice	Trees felled close to the ground so as to produce shoots from the resulting stumps, giving rise to poles and sticks which are then harvested over successive rotations. (See "High forest".)
Continuous cover management/ silviculture	A system for the management of forest areas, generally aiming to maintain tree canopy cover in forest stands. Large-scale clearfelling is avoided, although there may be some small patches of clearfelling. Typically, stands managed according to continuous cover silviculture have a more complex structure (in terms of species composition and/or age distribution and size distribution), compared with even-aged forest stands managed according to a system involving periodic clearfelling and replanting/regeneration.

Cumulative volume production	An important measure of volume productivity in forestry that represents the total production of timber volume from a stand up to a given year in the stand's development. It is calculated as the standing volume per hectare attained by a forest stand in a given year plus the sum of per-hectare volumes removed as thinnings up to that year.
Deforestation	The direct human-induced permanent conversion of an area of woodland to non-forest land through the removal trees.
Direct GHG emissions	In the specific context of this study, the term "direct GHG emissions" refers to GHG emissions that occur in a specific part of an activity or process that is under consideration, e.g. when considering a specific forest operation, the GHG emissions due to combustion of fossil fuels (generally on site) in machinery carrying out the forest operation.
End of Life	This is the final phase in the life of a (wood) product which may consist of disposal or recycling.
Forest harvesting	Any activity involving the felling of trees for the purposes of extraction of timber and/or biomass. Harvesting is often differentiated into thinning and clear felling (or clear cutting). Thinning involves felling small proportions of the trees in an area during the growth of the stand to give the remaining trees more resources. Clear-felling or clear-cutting involves felling an entire stand when the trees have reached a particular target, e.g. maximum average volume growth or mean diameter.
Forester GIS	In the specific context of this study, the term "Forester GIS" refers to the GIS that stores information about commercial woodlands on land owned or managed by Natural Resources Wales, which used for planning the management of the woodlands. See "sub-compartment database".
GHG, greenhouse gas	All gases which absorb infra-red radiation in the atmosphere of any planet, thereby inducing a so-called greenhouse effect which results in trapping heat which would otherwise escape into space. Due to their ubiquity and magnitude, the prominent greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Other minor gases are included such as ozone and CFCs (Chlorofluorocarbons), however the latter two are often not included as usually production is small, and the effect of these gases in small quantities has little perceived effect on climate change.
GHG emissions, greenhouse gas emissions	The production of greenhouse gases as part of natural, domestic, commercial or industrial processes and, usually, their release to the atmosphere.
Growing stock	The population of trees forming an area of woodland. Growing stock is sometimes expressed as the number of trees per hectare or standing stem volume per hectare of different tree species forming a woodland area. Standing biomass and carbon stocks may also be referred to when considering growing stock.
Growth rate (of woodland)	In the context of this report, the growth rate of woodlands is usually defined in terms of the potential production of stem volume expressed in terms of cubic metres of volume per hectare, i.e. $m^3\ ha^{-1}\ yr^{-1}$. It is sometimes expressed in terms of potential biomass production.

Harvest residues, harvesting residues (or felling or forest residues)	The biomass material remaining in woodlands that have been harvested for timber. Because only timber of a certain quality can be used by sawmills, boardmills and other processing facilities, components of woody biomass material – harvesting residues – are often left in forests during harvesting operations. Harvesting residues can include very poorly formed trees, stem tips of small diameter, branches and offcuts from the butts of stems of large trees, or from other parts of the stems of trees where there are defects. Harvesting residues may also include dead trees and rough or rotten dead wood. Often, such residues are left to decay in the woodland or burned on site as part of woodland management and, in particular, as part of preparation for the establishment of new trees.
High forest	A very common woodland type where the individual trees are allowed to grow as single stems over the life of the stand, often becoming very tall and mature. This may be contrasted with coppice systems where individual trees may be cut at close to ground level on short rotations to encourage regrowth in the form of multiple shoots for the same stump/stool in suitable species.
Indirect GHG emissions	In the specific context of this study, the term "indirect GHG emissions" refers to: • GHG emissions that occur as part of the provisioning and processing of an energy source, such as coal, oil, natural gas, biomass or electricity consumed in a forest operation (i.e. the construction, maintenance and operation of the infrastructure and associated activities and processes involved in the supply and use of an energy source). • GHG emissions from wider activities or processes "connected to" a specific part of an activity or process that is under consideration, e.g. when considering a specific forest operation, the GHG emissions associated with the construction and maintenance of the machinery carrying out the forest operation (note that these contributions are reported separately, see details in table). Generally, indirect GHG emissions occur "upstream" from forest operations and do not occur in the forest.
Land Use, Land-Use Change and Forestry (LULUCF)	Under the United Nations Framework Convention on Climate Change (UNFCCC), countries are required to report inventories of GHG emissions to (and removals from) the atmosphere due to human activity. These national GHG inventories are broken down into a number of sectors, each dealing with a distinct aspect of human activity as defined by the IPCC, consisting of Energy (which includes transport), Industrial processes, Solvent and other product use, Agriculture, Waste and "Land use, land use-change and forestry". Land use, land-use change and forestry (LULUCF) is an inventory sector defined by the Intergovernmental Panel on Climate Change (IPCC) that covers human-induced emissions and removals of GHGs resulting from changes in terrestrial carbon stocks. It covers the carbon pools of living biomass (above and below ground), dead organic matter (dead wood and litter) and organic soil carbon for specified land categories (forest land, cropland, grassland, wetland, urban land and other land).

LCA, life cycle assessment	The evaluation of the total environmental and natural resource impacts of a product or service over its complete life cycle of creation, use and disposal. However, evaluation can be restricted to certain environmental impacts, such as greenhouse gas emissions and to certain parts of the life cycle depending on the goal and scope of the assessment.
Management prescription	The combination of initial planting spacing, thinning regime and age of felling (where relevant) applied to a stand of trees.
Mean annual increment (MAI)	A measure of the volume productivity of forest stands (usually even-aged). Mean annual increment is the average rate of cumulative volume production up to a given year. In even-aged stands, it is calculated by dividing cumulative volume production by age.
Non-commercial woodlands	In the specific context of this study, the term "non-commercial woodlands" refers to woodland areas on land owned or managed by Natural Resources Wales that are identified for their scientific and conservation value and not under commercial management. See "commercial woodlands".
NRW estate	All land owned and/or managed by Natural Resources Wales.
NRW woodlands	In the specific context of this study, the term "NRW woodlands" refers to all woodland areas on land owned or managed by Natural Resources Wales. Both commercial woodlands and non-commercial woodlands are included. See "commercial woodlands" and "non-commercial woodlands".
Overbark/over bark	The volume or diameter of wood including the bark.
Policy scenario	A scenario detailing how a policy or set of related policies will be implemented and developed. The scenario includes specified activities, services and processes relevant to the policy or policies, and associated flows, e.g. of energy and GHG emissions, intended to represent the future situation following enactment of the policy or policies. (See also "business as usual scenario".)
Removals	In the context of climate change mitigation and greenhouse gas emissions, and in the context of this study, the term "removals" generally refers to the process of sequestration of carbon into a carbon pool (such as woodland biomass), hence the removal of carbon dioxide from the atmosphere. See "carbon pool", "carbon sink", "carbon sequestration", and "carbon source". This use of the term "removals" should not be confused with an alternative use of the term to refer to quantities of timber or woody biomass harvested and extracted (removed) from woodlands.
Roundwood	In the context of this report, the term roundwood is based on the FAO definition, as all roundwood felled or otherwise harvested and removed. It includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form, e.g. branches, roots, stumps and burls (where these are harvested). See "small roundwood" and "sawlog".

Sawlog	In the context of this study, the definition of the term sawlog is based on the FAO definition as roundwood that will be sawn (or chipped) lengthways for the manufacture of sawn wood or railway sleepers (ties) or used for the production of veneer (mainly by peeling or slicing). It includes roundwood (whether or not it is roughly squared) that will be used for these purposes and other special types of roundwood (e.g. burls and roots, etc.) used for veneer production.
Scrub	The term scrub does not have a standardised meaning. In the context of this report, scrub refers to areas of land with some bush and shrub cover but limited or no tree cover, or including small trees with limited productivity. In some cases such land may derive from the degradation of forest areas.
Semi-finished wood products	The products made from wood as a result of processing of raw harvested wood. Examples include sawnwood and wood-based panels.
Small roundwood	In the context of this report the term small roundwood refers to stemwood of small diameter that does not fall into the sawlog category (see above in this glossary). Small roundwood may typically be used to make fencing, or chipped to make wood-based panels or pulped to make paper. It may also be used for woodfuel.
Stand	A distinct area of woodland, generally composed of a uniform group of trees in terms of species composition, spatial distribution, age class distribution and size class distribution.
Standing volume	A measure of timber volume within standing trees. Usually expressed as cubic metres overbark standing.
Stemwood or "main stem"	There is no international standard definition for stemwood but, in practice, definitions used in different countries and for different types of trees are generally very similar. For example, in the UK (Jenkins *et al*., 2012), the definition of stemwood is given as, "The woody material forming the above ground main growing shoot(s) of a tree or stand of trees. The stem includes all woody volume above ground with a diameter greater than 7 cm over bark. Stemwood includes wood in major branches where there is at least 3 m of "straight" length to 7 cm top diameter".
Sub-compartment database	In the specific context of this study, a database containing information describing the characteristics of stands of trees comprising the area commercial woodlands on land owned or managed by Natural Resources Wales. It is contained as a layer of data within the Forester GIS. See "Forester GIS".
Sustainable forest management	The concept of managing woodlands in a way which does not reduce the ecological, social or economic capacity of the woodlands for future generations. Sustainable forest management is often codified into national and international standards for management. Examples include the UK Forestry Standard and the Forestry Stewardship Council certification standard.
Sustainable yield, Sustainable yield management	The concept of managing forests in a way which does not reduce the long-term capacity of the forest to sustain a particular (volume) yield.
Thinning	The periodic harvesting of trees in a woodland, involving the removal of some trees for commercial utilisation and the retention of others for future production or long-term retention.

Top diameter	The diameter at the narrowest end of a log or length of stemwood or roundwood. Top diameter is used in the specification of different types of primary wood product such as sawlogs and small roundwood. For example, a sawlog is normally specified as having a minimum value of top diameter. Top diameter may be specified over bark or under bark.
Total tree biomass	The mass of the tree parts, both above and below-ground (stem, bark, branches, twigs, stump and roots) of live and dead trees. May also include foliage, flowers and seeds.
UNFCCC	The United Nations Framework Convention on Climate Change (UNFCCC) was adopted on 9th May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system (as caused by humans). It contains commitments for all Parties. Under the Convention, Parties included in Annex I aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered into force in March 1994.
Volume/volume per hectare	The stem volume, expressed in cubic metres, to 7 cm top diameter overbark of an individual tree, group of trees or all the trees in a woodland. Volume can be expressed on an individual tree, per hectare or whole-group/stand basis.
Woodland biomass	Biomass contained in, or extracted from, woodlands, typically in the form of woody material.
Woodland carbon	A general term referring to carbon stocks and carbon dynamics associated with woodland systems.
Woodland carbon dynamics	The flows of carbon within a woodland system due to processes such as growth and decay and effects due to management operations, e.g. planting, thinning and felling.
Woodland management	The process of managing a woodland, usually to a plan detailing the areas and programmes for tree establishment, tending and prescribed forest harvesting events, along with wider management of the infrastructure, biodiversity and social aspects of a woodland.
Woody biomass	The mass of the woody parts (stem, bark, branches, twigs and woody roots) of live and dead trees, excluding foliage, fine roots, flowers and seeds.
Yield class	An index used in Britain of the potential volume productivity of even-aged stands of trees, equivalent to the maximum potential mean annual increment that a stand of trees can achieve on an optimal rotation. Yield class is expressed in units of cubic metres per hectare per year (m^3 ha^{-1} yr^{-1}).

Units of measurement

ha	1 ha = 1 hectare = 10,000 m^2.
$kgCO_2$ or $kgCO_2$-eq.	1 $kgCO_2$ = 1 kilogram (10^3 grams) carbon dioxide or carbon dioxide equivalent.
kt	1kt = 1 kilotonne = 1 thousand (10^3) tonnes.
ktC	1 ktC = 1 kilotonne (10^3 tonnes) carbon
$ktCO_2$ or $ktCO_2$-eq.	1 $ktCO_2$ = 1 kilotonne (10^3 tonnes) carbon dioxide or carbon dioxide equivalent.
M^2	1 m^2 = 1 square metre.
m^3	1 m^3 = 1 cubic metre.
MtC	1 MtC = 1 megatonne (10^6 tonnes) carbon
t	1 tonne = 1 thousand (10^3) kilograms = 1 million (10^6) grams.
tC or tC-eq.	1 tC = 1 tonne carbon or carbon-equivalent.
tCO_2 or tCO_2-eq.	1 tCO_2 = 1 tonne carbon dioxide or carbon dioxide equivalent.
yr	1 yr = 1 year.

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Appendix 1. GHG emissions from woodland operations

A1.1. Introduction

The table in this appendix provides a description of the detailed results that have been estimated for GHG emissions arising from woodland operations in NRW woodlands under a business as usual scenario. These results may be found in worksheets included in the final results workbooks for the project, named:

- BDL raw operations results
- CON raw operations results
- CLFL raw operations results.

When interpreting the descriptions in the table, it is important to understand the definitions of "direct emissions" and "indirect emissions", as referred to for some categories of woodland operations.

In the context of this study, the term "direct GHG emissions" refers to GHG emissions that occur in a specific part of an activity or process that is under consideration, e.g. when considering a specific woodland operation, the GHG emissions due to combustion of fossil fuels (generally on site) in machinery carrying out the woodland operation.

The term "indirect GHG emissions" refers to:

- GHG emissions that occur as part of the provisioning and processing of an energy source, such as coal, oil, natural gas, biomass or electricity consumed in a woodland operation (i.e. the construction, maintenance and operation of the infrastructure and associated activities and processes involved in the supply and use of an energy source).
- GHG emissions from wider activities or processes "connected to" a specific part of an activity or process that is under consideration, e.g. when considering a specific woodland operation, the GHG emissions associated with the construction and maintenance of the machinery carrying out the woodland operation (note that these contributions are reported separately, see details in table).

Generally, indirect GHG emissions occur "upstream" from woodland operations and do not occur in the woodland.

Wherever possible, results for a woodland operation are reported separately for direct GHG emissions and the two categories of indirect GHG emissions described above. However, an exception is made in the case of results for GHG emissions associated with road construction and maintenance. In the case of these emissions, results were calculated by referring to emissions factors derived from Whittaker *et al.* (2010, 2011), as the most up to date and comprehensive sources. It was not possible to derive separate emissions factors for direct and indirect GHG emissions associated with woodland road construction and maintenance from the information available from these sources.

It should be noted that the GHG emissions estimates reported for road construction and maintenance include all consumption of fuels, materials (including aggregate) and use of machinery associated with relevant activities. However, no allowance has been made for possible GHG emissions arising from soil because of site disturbance. An attempt was made by Whittaker *et al.* (2010, 2011) to estimate such emissions but the results were considered to be highly uncertain and likely to be overestimates.

It is important to note that a number of the results reported for certain woodland operations are zero. Generally, this reflects situations in which individual woodland operations are considered not to be relevant or rarely practiced in NRW woodlands. The specific activities assumed not to occur and not to involve GHG emissions are:

- Woodland fertilisation
- Extraction of significant quantities of branchwood
- Chipping of wood (to make wood chips) at roadside in the woodland.

In some cases, contributions to GHG emissions appear as zero because they are of small magnitude.

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Table A1.1 Description of GHG emissions reported for woodland operations in results for NRW woodlands (Note: "Col" refers to the Column code in a Microsoft Excel worksheet)

Col.	Description
A	Reporting year
B	Combined (direct and indirect) CO_2 emissions associated with Type A road construction
C	Combined (direct and indirect) CH_4 emissions associated with Type A road construction
D	Combined (direct and indirect) N_2O emissions associated with Type A road construction
E	Combined (direct and indirect) CO_2 emissions associated with Type A road maintenance
F	Combined (direct and indirect) CH_4 emissions associated with Type A road maintenance
G	Combined (direct and indirect) N_2O emissions associated with Type A road maintenance
H	Combined (direct and indirect) CO_2 emissions associated with Type A road regrading
I	Combined (direct and indirect) CH_4 emissions associated with Type A road regrading
J	Combined (direct and indirect) N_2O emissions associated with Type A road regrading
K	Combined (direct and indirect) CO_2 emissions associated with Type B road construction
L	Combined (direct and indirect) CH_4 emissions associated with Type B road construction
M	Combined (direct and indirect) N_2O emissions associated with Type B road construction
N	Combined (direct and indirect) CO_2 emissions associated with Type B road resurfacing
O	Combined (direct and indirect) CH_4 emissions associated with Type B road resurfacing
P	Combined (direct and indirect) N_2O emissions associated with Type B road resurfacing
Q	Combined (direct and indirect) CO_2 emissions associated with Type B road regrading
R	Combined (direct and indirect) CH_4 emissions associated with Type B road regrading
S	Combined (direct and indirect) N_2O emissions associated with Type B road regrading
T	Direct CO_2 emissions due to consumption of diesel fuel associated with ground preparation
U	Indirect CO_2 emissions due to consumption of diesel fuel associated with ground preparation
V	Direct CH_4 emissions due to consumption of diesel fuel associated with ground preparation

Table A1.1 (continued) Description of GHG emissions reported for woodland operations in results for NRW woodlands (Note: "Col" refers to the Column code in a Microsoft Excel worksheet)

Col.	Description
W	Indirect CH_4 emissions due to consumption of diesel fuel associated with ground preparation
X	Direct N_2O emissions due to consumption of diesel fuel associated with ground preparation
Y	Indirect N_2O emissions due to consumption of diesel fuel associated with ground preparation
Z	Direct CO_2 emissions due to consumption of lubricating oil associated with ground preparation
AA	Indirect CO_2 emissions due to consumption of lubricating oil associated with ground preparation
AB	Direct CH_4 emissions due to consumption of lubricating oil associated with ground preparation
AC	Indirect CH_4 emissions due to consumption of lubricating oil associated with ground preparation
AD	Direct N_2O emissions due to consumption of lubricating oil associated with ground preparation
AE	Indirect N_2O emissions due to consumption of lubricating oil associated with ground preparation
AF	Indirect CO_2 emissions due to machinery manufacture, maintenance and spares associated with ground preparation
AG	Indirect CH_4 emissions due to machinery manufacture, maintenance and spares associated with ground preparation
AH	Indirect N_2O emissions due to machinery manufacture, maintenance and spares associated with ground preparation
AI	Indirect CO_2 emissions due to fence construction and maintenance
AJ	Indirect CH_4 emissions due to fence construction and maintenance
AK	Indirect N_2O emissions due to fence construction and maintenance
AL	Direct CO_2 emissions due to consumption of diesel fuel associated with weed control (herbicide application)
AM	Indirect CO_2 emissions due to consumption of diesel fuel associated with weed control (herbicide application)
AN	Direct CH_4 emissions due to consumption of diesel fuel associated with weed control (herbicide application)
AO	Indirect CH_4 emissions due to consumption of diesel fuel associated with weed control (herbicide application)
AP	Direct N_2O emissions due to consumption of diesel fuel associated with weed control (herbicide application)
AQ	Indirect N_2O emissions due to consumption of diesel fuel associated with weed control (herbicide application)
AR	Direct CO_2 emissions due to consumption of lubricating oil associated with weed control (herbicide application)
AS	Indirect CO_2 emissions due to consumption of lubricating oil associated with weed control (herbicide application)

Table A1.1 (continued) Description of GHG emissions reported for woodland operations in results for NRW woodlands (Note: "Col" refers to the Column code in a Microsoft Excel worksheet)

Col.	Description
AT	Direct CH_4 emissions due to consumption of lubricating oil associated with weed control (herbicide application)
AU	Indirect CH_4 emissions due to consumption of lubricating oil associated with weed control (herbicide application)
AV	Direct N_2O emissions due to consumption of lubricating oil associated with weed control (herbicide application)
AW	Indirect N_2O emissions due to consumption of lubricating oil associated with weed control (herbicide application)
AX	Indirect CO_2 emissions due to machinery manufacture, maintenance and spares associated with weed control (herbicide application)
AY	Indirect CH_4 emissions due to machinery manufacture, maintenance and spares associated with weed control (herbicide application)
AZ	Indirect N_2O emissions due to machinery manufacture, maintenance and spares associated with weed control (herbicide application)
BA	Indirect CO_2 emissions due to herbicide consumption associated with weed control
BB	Indirect CH_4 emissions due to herbicide consumption associated with weed control
BC	Indirect N_2O emissions due to herbicide consumption associated with weed control
BD	Indirect CO_2 emissions due to plant production and supply (both planting and beating up)
BE	Indirect CH_4 emissions due to plant production and supply (both planting and beating up)
BF	Indirect N_2O emissions due to plant production and supply (both planting and beating up)
BG	Direct CO_2 emissions due to consumption of diesel fuel associated with fertiliser application (where relevant)
BH	Indirect CO_2 emissions due to consumption of diesel fuel associated with fertiliser application (where relevant)
BI	Direct CH_4 emissions due to consumption of diesel fuel associated with fertiliser application (where relevant)
BJ	Indirect CH_4 emissions due to consumption of diesel fuel associated with fertiliser application (where relevant)
BK	Direct N_2O emissions due to consumption of diesel fuel associated with fertiliser application (where relevant)
BL	Indirect N_2O emissions due to consumption of diesel fuel associated with fertiliser application (where relevant)
BM	Direct CO_2 emissions due to consumption of lubricating oil associated with fertiliser application (where relevant)
BN	Indirect CO_2 emissions due to consumption of lubricating oil associated with fertiliser application (where relevant)
BO	Direct CH_4 emissions due to consumption of lubricating oil associated with fertiliser application (where relevant)

Table A1.1 (continued) Description of GHG emissions reported for woodland operations in results for NRW woodlands (Note: "Col" refers to the Column code in a Microsoft Excel worksheet)

Col.	Description
BP	Indirect CH_4 emissions due to consumption of lubricating oil associated with fertiliser application (where relevant)
BQ	Direct N_2O emissions due to consumption of lubricating oil associated with fertiliser application (where relevant)
BR	Indirect N_2O emissions due to consumption of lubricating oil associated with fertiliser application (where relevant)
BS	Indirect CO_2 emissions due to machinery manufacture, maintenance and spares associated with fertiliser application (where relevant)
BT	Indirect CH_4 emissions due to machinery manufacture, maintenance and spares associated with fertiliser application (where relevant)
BU	Indirect N_2O emissions due to machinery manufacture, maintenance and spares associated with fertiliser application (where relevant)
BV	Indirect CO_2 emissions due to fertiliser (N, P, K) consumption associated with fertiliser application
BW	Indirect CH_4 emissions due to fertiliser (N, P, K) consumption associated with fertiliser application
BX	Combined (direct and indirect) N_2O emissions due to fertiliser (N, P, K) consumption associated with fertiliser application
BY	Direct CO_2 emissions due to consumption of diesel fuel associated with stemwood harvesting
BZ	Indirect CO_2 emissions due to consumption of diesel fuel associated with stemwood harvesting
CA	Direct CH_4 emissions due to consumption of diesel fuel associated with stemwood harvesting
CB	Indirect CH_4 emissions due to consumption of diesel fuel associated with stemwood harvesting
CC	Direct N_2O emissions due to consumption of diesel fuel associated with stemwood harvesting
CD	Indirect N_2O emissions due to consumption of diesel fuel associated with stemwood harvesting
CE	Direct CO_2 emissions due to consumption of lubricating oil associated with stemwood harvesting
CF	Indirect CO_2 emissions due to consumption of lubricating oil associated with stemwood harvesting
CG	Direct CH_4 emissions due to consumption of lubricating oil associated with stemwood harvesting
CH	Indirect CH_4 emissions due to consumption of lubricating oil associated with stemwood harvesting
CI	Direct N_2O emissions due to consumption of lubricating oil associated with stemwood harvesting
CJ	Indirect N_2O emissions due to consumption of lubricating oil associated with stemwood harvesting
CK	Indirect CO_2 emissions due to machinery manufacture, maintenance and spares associated with stemwood harvesting

Table A1.1 (continued) Description of GHG emissions reported for woodland operations in results for NRW woodlands (Note: "Col" refers to the Column code in a Microsoft Excel worksheet)

Col.	Description
CL	Indirect CH_4 emissions due to machinery manufacture, maintenance and spares associated with stemwood harvesting
CM	Indirect N_2O emissions due to machinery manufacture, maintenance and spares associated with stemwood harvesting
CN	Indirect CO_2 emissions due to urea consumption associated with stump treatment (where relevant)
CO	Indirect CH_4 emissions due to urea consumption associated with stump treatment (where relevant)
CP	Indirect N_2O emissions due to urea consumption associated with stump treatment (where relevant)
CQ	Direct CO_2 emissions due to consumption of diesel fuel associated with stemwood extraction
CR	Indirect CO_2 emissions due to consumption of diesel fuel associated with stemwood extraction
CS	Direct CH_4 emissions due to consumption of diesel fuel associated with stemwood extraction
CT	Indirect CH_4 emissions due to consumption of diesel fuel associated with stemwood extraction
CU	Direct N_2O emissions due to consumption of diesel fuel associated with stemwood extraction
CV	Indirect N_2O emissions due to consumption of diesel fuel associated with stemwood extraction
CW	Direct CO_2 emissions due to consumption of lubricating oil associated with stemwood extraction
CX	Indirect CO_2 emissions due to consumption of lubricating oil associated with stemwood extraction
CY	Direct CH_4 emissions due to consumption of lubricating oil associated with stemwood extraction
CZ	Indirect CH_4 emissions due to consumption of lubricating oil associated with stemwood extraction
DA	Direct N_2O emissions due to consumption of lubricating oil associated with stemwood extraction
DB	Indirect N_2O emissions due to consumption of lubricating oil associated with stemwood extraction
DC	Indirect CO_2 emissions due to machinery manufacture, maintenance and spares associated with stemwood extraction
DD	Indirect CH_4 emissions due to machinery manufacture, maintenance and spares associated with stemwood extraction
DE	Indirect N_2O emissions due to machinery manufacture, maintenance and spares associated with stemwood extraction
DF	Direct CO_2 emissions due to consumption of diesel fuel associated with branchwood harvesting and extraction
DG	Indirect CO_2 emissions due to consumption of diesel fuel associated with branchwood harvesting and extraction

Table A1.1 (continued) Description of GHG emissions reported for woodland operations in results for NRW woodlands (Note: "Col" refers to the Column code in a Microsoft Excel worksheet)

Col.	Description
DH	Direct CH_4 emissions due to consumption of diesel fuel associated with branchwood harvesting and extraction
DI	Indirect CH_4 emissions due to consumption of diesel fuel associated with branchwood harvesting and extraction
DJ	Direct N_2O emissions due to consumption of diesel fuel associated with branchwood harvesting and extraction
DK	Indirect N_2O emissions due to consumption of diesel fuel associated with branchwood harvesting and extraction
DL	Direct CO_2 emissions due to consumption of lubricating oil associated with branchwood harvesting and extraction
DM	Indirect CO_2 emissions due to consumption of lubricating oil associated with branchwood harvesting and extraction
DN	Direct CH_4 emissions due to consumption of lubricating oil associated with branchwood harvesting and extraction
DO	Indirect CH_4 emissions due to consumption of lubricating oil associated with branchwood harvesting and extraction
DP	Direct N_2O emissions due to consumption of lubricating oil associated with branchwood harvesting and extraction
DQ	Indirect N_2O emissions due to consumption of lubricating oil associated with branchwood harvesting and extraction
DR	Indirect CO_2 emissions due to machinery manufacture, maintenance and spares associated with branchwood harvesting and extraction
DS	Indirect CH_4 emissions due to machinery manufacture, maintenance and spares associated with branchwood harvesting and extraction
DT	Indirect N_2O emissions due to machinery manufacture, maintenance and spares associated with branchwood harvesting and extraction
DU	Direct CO_2 emissions due to consumption of diesel fuel associated with wood chipping at roadside
DV	Indirect CO_2 emissions due to consumption of diesel fuel associated with wood chipping at roadside
DW	Direct CH_4 emissions due to consumption of diesel fuel associated with wood chipping at roadside
DX	Indirect CH_4 emissions due to consumption of diesel fuel associated with wood chipping at roadside
DY	Direct N_2O emissions due to consumption of diesel fuel associated with wood chipping at roadside
DZ	Indirect N_2O emissions due to consumption of diesel fuel associated with wood chipping at roadside
EA	Direct CO_2 emissions due to consumption of lubricating oil associated with wood chipping at roadside
EB	Indirect CO_2 emissions due to consumption of lubricating oil associated with wood chipping at roadside
EC	Direct CH_4 emissions due to consumption of lubricating oil associated with wood chipping at roadside

Table A1.1 (continued) Description of GHG emissions reported for woodland operations in results for NRW woodlands (Note: "Col" refers to the Column code in a Microsoft Excel worksheet)

Col.	Description
ED	Indirect CH_4 emissions due to consumption of lubricating oil associated with wood chipping at roadside
EE	Direct N_2O emissions due to consumption of lubricating oil associated with wood chipping at roadside
EF	Indirect N_2O emissions due to consumption of lubricating oil associated with wood chipping at roadside
EG	Indirect CO_2 emissions due to machinery manufacture, maintenance and spares associated with wood chipping at roadside
EH	Indirect CH_4 emissions due to machinery manufacture, maintenance and spares associated with wood chipping at roadside
EI	Indirect N_2O emissions due to machinery manufacture, maintenance and spares associated with wood chipping at roadside.

Appendix 2. Example calculations using the CARBINE model

A2.1. Introduction

The calculations made by the CARBINE model can be illustrated by considering simplified examples, such as provided in this appendix. It should be noted that examples of CARBINE simulations have been presented in several previous reports. It is suggested that reference is made to the examples already reported in Section 3 of Matthews *et al.* (2014a)[5] and Section 3 of Matthews *et al.* (2014b). These examples focus on results of CARBINE for woodland carbon stocks and stock changes. The following six examples presented here illustrate results for carbon stocks and also for other outputs of CARBINE of relevance to this project.

A2.2. Basic input data for example

The discussion in Section 6.1 of the main report describes the input data that need to be supplied to the CARBINE model. The example CARBINE results presented below are for a notional stand of 1 hectare of Scots pine, with full details of input data given in Table A2.1.

Table A2.1 Input data to CARBINE used in example simulation

Input data	Details
Area	1 ha
Year of planting or regeneration	1900
Soil type	100% mineral soil
Previous land use	Grassland
Species composition	Scots pine
Potential productivity	4 m^3 ha^{-1} yr^{-1}
Management prescription	Up to the year 2015: no thinning or felling (i.e. no management for production) Clearfell in year 2015 After year 2015: regular thinning (every 5 years starting at age 40) and felling on 100 year rotation. Thinning volumes specified to maximise productivity over the rotation.
Natural disturbance	No natural disturbance
Production of raw harvested wood	10% by mass of felled stemwood allocated to harvest residues 90% by mass of stemwood harvested and converted to raw wood products (small roundwood, sawlogs, bark)

[5] Note that examples of results for CARBINE reported in these previous studies were produced using an older version of the soil carbon sub-model of CARBINE to that used in this current study. The example results in this appendix are also based on an older version of the soil carbon sub-model. These previous versions produce somewhat different results to the current version.

In the basic example, management for production is introduced in 2015, involving clearfelling. The woodland component is then replanted or regenerated and managed for production through regular thinning interventions and clearfelling on a 100-year rotation.

A2.3. Example 1: wood production

Table A2.2 shows the pattern of wood production over time estimated by CARBINE for the example woodland component specified in Table A2.1. The initial clearfelling produces a total of 146.6 odt ha^{-1} of harvested wood, with 71.7 odt ha^{-1} of residual woody biomass (a combination of unutilised felled stemwood, plus roots, stumps branches and foliage) left on site in the woodland as unextracted harvest residues. Much of the biomass in the harvest residues will consist of branchwood. The trees felled in 2015 are relatively old and of large size, hence a significant proportion of the total biomass production is formed of sawlogs. Following clearfelling, the regrowth of the restocked woodland component is quite slow (the potential productivity of 4 m^3 ha^{-1} yr^{-1} is relatively low, although quite commonly observed in woodland of boreal or temperate regions (Matthews *et al.,* 2014b). Consequently, in this example, the first production from thinning of the restocked woodland component does not occur until 2055 (age 40 years).

Table A2.2 Wood production up to 2115 predicted by CARBINE for the woodland component described in Table A2.1

Year	Biomass by raw wood product (odt ha^{-1})						
	Left in wood-land	Total production	Extracted harvest residues	Small round-wood (under bark)	Small round-wood bark	Sawlogs	Sawlog bark
2015	71.7	146.6	0.0	3.7	0.7	120.9	21.3
2055	2.6	5.3	0.0	2.8	2.5	0.0	0.0
2060	2.6	5.3	0.0	2.8	2.5	0.0	0.0
2065	2.6	5.3	0.0	2.9	2.3	0.0	0.0
2070	2.6	5.3	0.0	4.0	1.3	0.0	0.0
2075	2.6	5.3	0.0	4.2	0.9	0.1	0.0
2080	2.6	5.3	0.0	4.0	0.8	0.4	0.1
2085	2.6	5.3	0.0	3.5	0.7	0.9	0.2
2090	2.6	5.3	0.0	2.9	0.6	1.5	0.3
2095	2.6	5.3	0.0	2.4	0.5	2.1	0.4
2100	2.4	5.0	0.0	1.8	0.3	2.4	0.5
2105	2.0	4.1	0.0	1.2	0.2	2.2	0.4
2110	1.5	3.1	0.0	0.8	0.1	1.9	0.4
2115	44.2	90.4	0.0	10.6	1.9	66.2	11.7

The mean size of trees predicted by CARBINE as felled in early thinnings is relatively small, with the result that no sawlogs are produced. The proportion of total biomass production formed by sawlogs becomes progressively bigger in later thinnings, and sawlogs represent the main component of harvested biomass at the end of the rotation in 2115. The pattern of production illustrated in Table A2.2 is typical of what is observed over the "forest management cycle" of a woodland stand managed on a long rotation (see Section 2.3 of Matthews *et al.,* 2014b).

A2.4. Example 2: finished wood products

The previous discussion has given an illustration of how the CARBINE model simulates wood production, through thinning and felling, within a stand of trees. The estimates in Table A2.2 show simulated production of raw wood products, i.e. extracted harvest residues, small roundwood, sawlogs and bark. As explained in Annex 1, the CARBINE model can also be applied to estimate quantities of finished wood products derived from the harvesting of these raw wood products. This involves specifying a set of allocation coefficients as inputs to CARBINE, which determine how raw wood products are converted into finished wood products.

Table A2.3 shows two examples of sets of allocation coefficients, applied in conjunction with the input data in Table A2.1, representing two possible scenarios for the utilisation of finished wood products:

1 A "low bioenergy" scenario, in which no harvest residues are extracted for use as bioenergy, there is some use of harvested small roundwood, sawlogs and bark for bioenergy, but with co-production of a range of material wood products.

2 An "enhanced bioenergy" scenario, in which 40% by mass of harvest residues are extracted for bioenergy, and harvested small trees/early thinnings are diverted entirely for use as bioenergy, along with 90% of associated branchwood. The diversion of small trees in this way has the effect of reducing the quantities of harvested biomass utilised for material wood products (with the exception of structural timber).

Table A2.4 shows example results for the projected out-turn of finished wood products, as simulated by the CARBINE model, based on the input data in Table A2.1 and the two scenarios for wood utilisation in Table A2.3. Results are shown for two example harvesting interventions:

1 The clearfelling event taking place in 2015

2 The first thinning event in the regenerating successor stand of trees in 2055.

For the clearfelling event in 2015, the trees involved are relatively large and contain significant sawlog volume. Consequently, there is negligible diversion of harvested wood in the form of small trees for use as bioenergy, and the pattern of utilisation of stemwood, simulated by the CARBINE model, is the same in both the "low bioenergy" scenario and the "enhanced bioenergy" scenario. The key difference in the results in Table A2.4 for the two scenarios in 2015 concerns the extraction of a proportion of harvest residues (about 29 odt ha^{-1}) under the "enhanced bioenergy" scenario, which is left in the woodland under the "low bioenergy" scenario.

Table A2.3 Examples of allocation coefficients for two scenarios for the conversion of raw harvested wood products into finished wood products

<table>
<tr><th rowspan="2">Raw wood product</th><th colspan="2">Allocation coefficients (%) by scenario</th></tr>
<tr><th>"Low bioenergy"</th><th>"Enhanced bioenergy"</th></tr>
<tr><td>Tree stumps and roots</td><td colspan="2">100% left in woodland</td></tr>
<tr><td>Branchwood and other harvest residues, not including stumps and roots</td><td>100% left in woodland</td><td>60% by mass left in woodland

40% by mass extracted for use as bioenergy

See also entry for small roundwood for treatment of small trees/early thinnings</td></tr>
<tr><td>Bark</td><td colspan="2">30% by mass used for bioenergy

70% by mass used for non-bioenergy applications (horticultural mulch)</td></tr>
<tr><td>Small roundwood</td><td>20% by mass used for bioenergy

10% by mass used for paper

35% by mass used for wood-based panels (20% MDF, 60% particleboard, 20% OSB)

35% by mass used for pallets and fencing products (50% fencing, 50% pallets)</td><td>As baseline, except the threshold for small trees/early thinnings set so that trees are harvested completely for bioenergy, along with 90% of associated branchwood, if the harvested trees have mean proportion of sawlogs less than 5%.</td></tr>
<tr><td>Sawlogs</td><td>20% by mass used for bioenergy

55% by mass used for sawn timber products (40% structural timber, 30% fencing products, 30% pallets)

25% by mass used for wood-based panels (20% MDF, 60% particleboard, 20% OSB)</td><td>As baseline, except see entry for small roundwood for treatment of small trees/early thinnings</td></tr>
</table>

For the early thinning event in 2055, the differences in results for the two scenarios are more extensive. Firstly, as with the felling event in 2015, a proportion of harvest residues are extracted under the "enhanced bioenergy" scenario, whereas these residues are left in the woodland under the "low bioenergy" scenario. Secondly, there is no production under either scenario of structural timber (from sawlogs), or of sawlog co-products for fuel, since the trees are too small to contain significant material with the dimensions of sawlogs. Finally, the effect of diverting small trees for use entirely as bioenergy under the "enhanced bioenergy" scenario is very apparent in the results in Table A2.4. Specifically, under the "low bioenergy" scenario, there is significant production of a range of material wood products alongside some bioenergy production. In contrast, under the "enhanced bioenergy" scenario, all of the harvested stemwood is used for bioenergy and there are no material wood co-products.

It should be stressed that the preceding example illustrates just one possible set of changes that can be made to the wood product allocation coefficients referred to by the CARBINE model. All of the coefficients described in Table A2.3 can be varied dynamically over time, as specified by the model user.

Table A2.4 Two scenarios for the out-turn of finished wood products in 2015 and 2055 predicted by CARBINE for the woodland component described in Table A2.1

Finished product	Biomass production for scenario (odt ha^{-1})			
	Low bioenergy		Enhanced bioenergy	
	2015	2055	2015	2055
Extracted harvest residues	0.00	0.00	28.66	1.80
Small roundwood for fuel	0.75	0.56	0.75	2.80
Sawlog co-products for fuel	24.17	0.00	24.17	0.00
Bark for fuel	6.60	0.75	6.60	2.49
Paper	0.37	0.28	0.37	0.00
MDF	6.30	0.20	6.30	0.00
Chipboard	18.91	0.59	18.91	0.00
OSB	6.30	0.20	6.30	0.00
Pallets and packaging	20.60	0.49	20.60	0.00
Fencing and joinery	20.60	0.49	20.60	0.00
Structural timber	26.59	0.00	26.59	0.00
Bark for mulch	15.39	1.74	15.39	0.00
Total	**146.58**	**5.29**	**175.25**	**7.09**

A2.5. Example 3: woodland carbon stocks

Figure A2.1 shows the development over time of carbon stocks (in trees, litter and soil), as simulated by the CARBINE model, for the example stand of trees as represented by the input data in Table A2.1. As can be seen in Figure A2.1, prior to the initial clearfelling intervention in 2015, the combined carbon stocks in the trees, litter and soil forming the woodland stand are relatively high, at just over 250 tC ha^{-1} in total. The felling event in 2015 causes a significant reduction in tree carbon stocks (essentially, because the trees have been cut down and extracted). In contrast, carbon stocks in deadwood and litter rise sharply in 2015. This occurs because a significant proportion of the biomass of the trees (roots, stumps, branchwood, foliage and some stemwood) is not converted into products and is left on site in the woodland rather than extracted. Hence, this unutilised biomass forms a large additional contribution to carbon stocks in litter in 2015. Subsequently, the enhanced carbon stocks in deadwood and litter decrease as a result of progressive decay, returning to the levels observed prior to felling over a period of about 20 to 30 years.

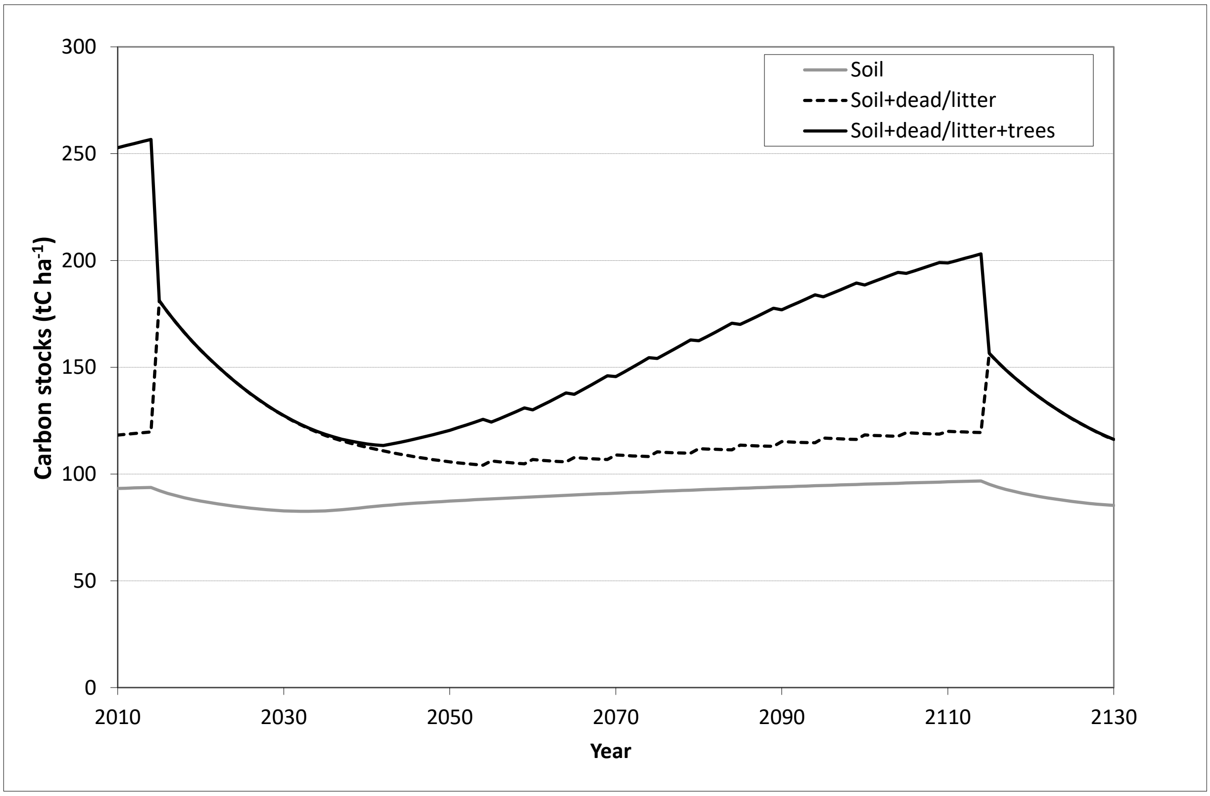

Figure A2.1. Development of carbon stocks over time predicted by CARBINE for the woodland component described in Table A2.1.

Following felling, the carbon stocks in trees steadily increase over many decades, as a successor stand regenerates and becomes established. However, the carbon stocks in trees do not return to the same levels as in 2015 prior to felling, because the successor stand is subjected to regular thinning from 2055 onwards and is clearfelled again in 2115.

The results in Figure A2.1 also show changes in soil carbon stocks over time, in response to the felling of the stand of trees in 2015, and the subsequent regeneration of a successor stand. Following the felling of the stand disruption of the soil leads to a progressive loss of carbon stocks over about 20 years. However, soil carbon stocks recover subsequently, as a result of enhanced inputs of carbon to the soil from decaying litter (see earlier), and the reinstatement of carbon inputs to soil from trees, as the successor stand becomes established.

The results in Figure A2.1 illustrate the very long timescales involved in the dynamics of woodland carbon stocks in response to stand management.

In Figure A2.2, the simulated total woodland carbon stocks for the example stand, as represented by the input data in Table A2.1, are compared with results for an alternative scenario, in which management for production is *not* introduced in 2015 and, instead, the stand continues to grow and accumulate carbon stocks, in the absence of significant natural disturbance.

As can be seen in Figure A2.2, carbon stocks in the stand not managed for wood production continue to accumulate at a relatively slow rate. However, the cumulative increase in carbon stocks over 100 years is significant, rising from just over 250 tC ha^{-1} in 2015 to about 290 tC ha^{-1} by 2115. The extent of the short-term and long-term reductions in carbon stocks caused by introducing management for production in the example stand, as opposed to not managing for production, are very apparent in Figure A2.2.

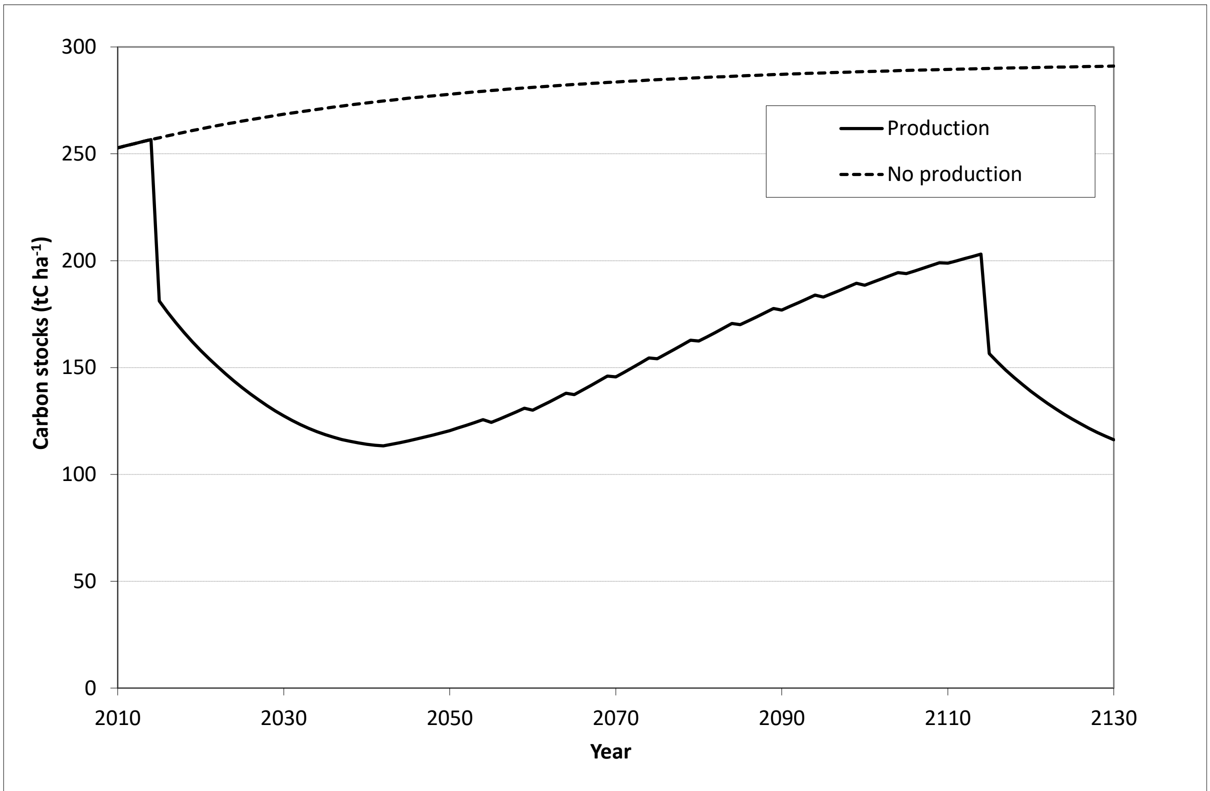

Figure A2.2. Development of carbon stocks over time predicted by CARBINE for the woodland component described in Table A2.1, under “Production” and “No production” scenarios.

A2.6. Example 4: Woodland net carbon stock change

Figure A2.3 shows the development of the net carbon stock change, as simulated by the CARBINE model for the example stand of trees as represented by the input data in Table A2.1. Results are also shown for the same woodland stand under the alternative scenario in which management for production is *not* introduced in 2015. The results in Figure A8.3 are very closely related to the results for carbon stocks in Figure A2.2, and are calculated as simple annual differences in woodland carbon stocks, i.e. results for the net woodland carbon sink/source over time are imputed from net annual woodland carbon stock changes.

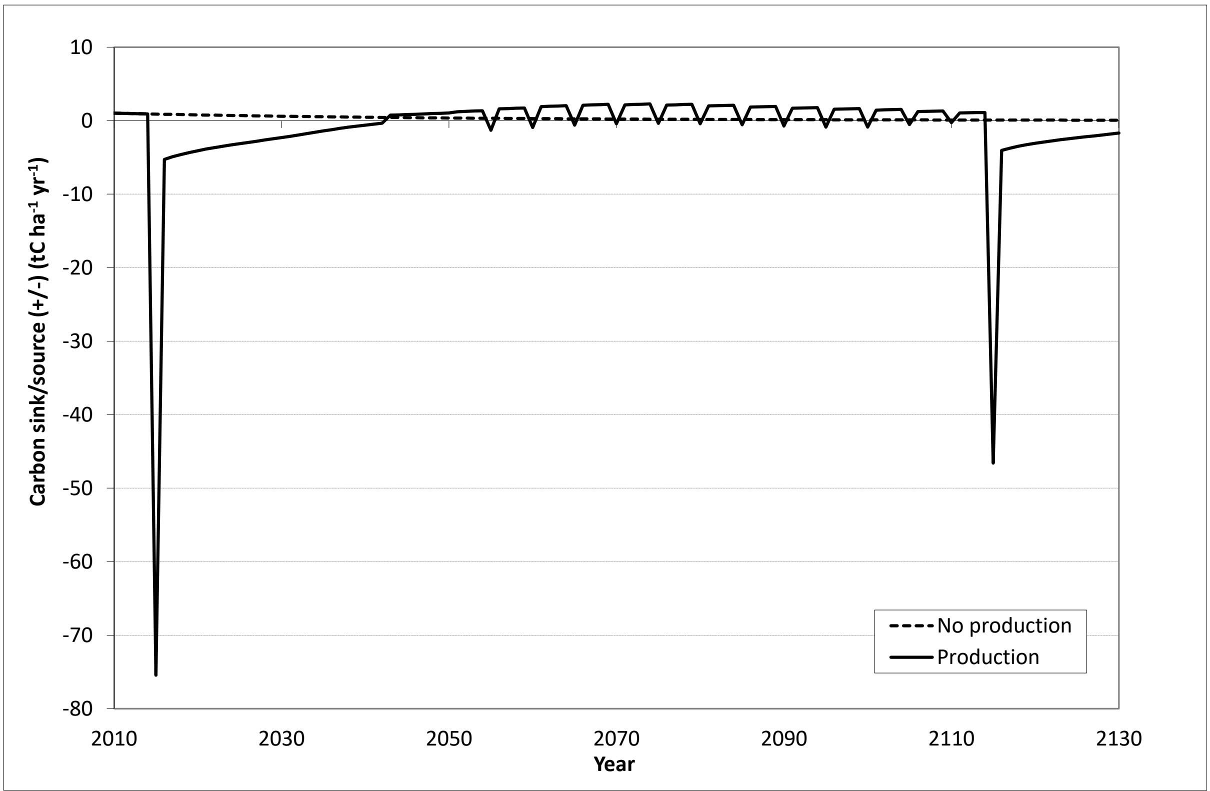

Figure A2.3. Development of the net carbon sink/source over time predicted by CARBINE for the woodland component described in Table A2.1, under "Production" and "No production" scenarios.

The results for the "production" and "no production" scenarios are strongly contrasting. For the "no production" scenario, the CARBINE model results suggest a small but noticeable net carbon sink associated with the woodland stand. The magnitude of this sink decreases over time, as the stand grows older, and becomes very small, whilst never reaching zero. In contrast, the results for the "production" scenario exhibit a very large carbon source in 2015, due to the felling of the trees and the extraction and removal from the woodland of the harvested wood. The carbon dynamics of the woodland stand do not recover and return to being a net carbon sink until about 25 years after this harvesting event. Subsequently, for a period of many decades, the net carbon sink in the woodland stand under the "production" scenario is actually bigger than would be the case under the "no production" scenario. This reflects the fact that the trees forming the regenerating successor stand are relatively young and faster growing, and sequester carbon at a faster rate than the older trees that would be left to grow on under the "no production" scenario. Periodically, the net carbon sink associated with the successor stand becomes a short-term source, due to scheduled thinning interventions. Under the "production" scenario, a further significant carbon source occurs in the year 2115, when the successor stand is itself clearfelled for wood production. The magnitude of this source is not as great as exhibited in 2015, mainly because the carbon stocks in the successor stand at time of felling in 2115 are not as large as prior to felling of the original unmanaged stand in 2015.

Although the net sink in the successor stand is generally enhanced compared with the sink due to the older trees under the "no production" scenario, over a period of many decades, the overall effect on carbon sequestration of the balance of sinks and sources over time in the woodland stand is a net source under the "production" scenario, compared with the modest net sink under the "no production" scenario. This remains the case over the 100 year period illustrated in Figure A2.3.

A2.7. Example 5: Soil carbon

Figure A2.4 is similar to Figure A2.3, in that it shows the development of the net carbon sink or source, as simulated by the CARBINE model for the example stand of trees as represented by the input data in Table A2.1. However, the results in Figure A2.4 illustrate how the outputs of the CARBINE model are sensitive to assumptions about the characteristics of soils associated with woodland areas.

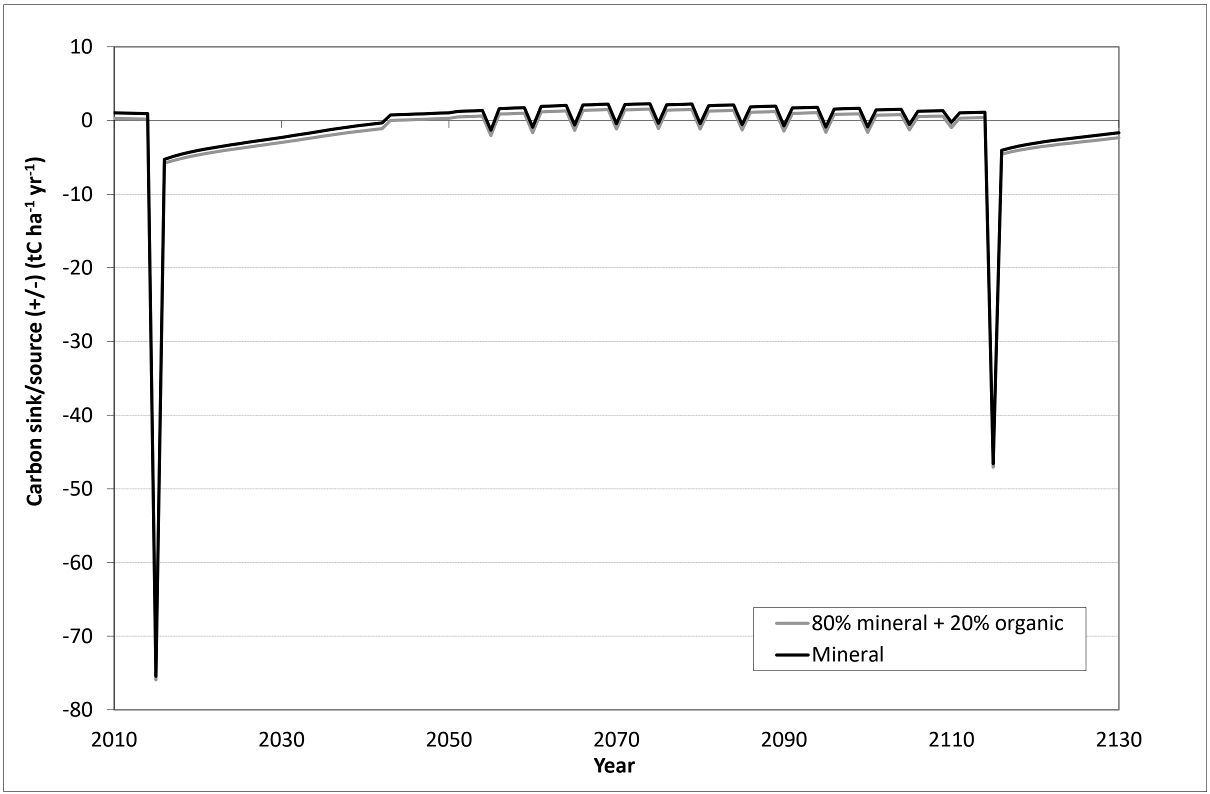

Figure A2.4. Development of the net carbon sink/source over time predicted by CARBINE for the woodland component described in Table A2.1, for two examples of associated woodland soils.

Results for two scenarios are shown in Figure A2.4:

1 A scenario based on the unmodified input data in Table A2.1, which includes an assumption that 100% of the woodland area is on soils of the "mineral" type (including brown earths, gleys and sandy soils, generally without a high organic component such as a layer of peat).

2 As for the first scenario, but with 20% of the woodland area on soils of the "organic" type, i.e. including a significant peaty layer or, essentially, consisting of a peat soil in entirety.

The projected development of net carbon stock change for the woodland stands representing these two scenarios look very similar. This is because the biggest impacts on the development of the net woodland carbon sink/source are due to management interventions, notably clearfelling events. However, there are notable secondary influences due to the types of soil associated with the woodland stands. For example, in the period 2010 up to 2015, the woodland stand associated with 100% mineral soil(s) exhibits a small but noticeable net carbon sink, whereas the woodland stand associated with 80% mineral soil(s) and 20% organic soil(s) exhibits a negligible carbon sink over this period.

In general, it is important to represent variations in woodland carbon dynamics due to the types of soils associated with woodland stands.

A2.8. Example 6: GHG emissions from woodland operations

Figure A2.5 shows an example of results for GHG emissions due to woodland operations, as simulated by the CARBINE model for the example stand of trees as represented by the input data in Table A2.1. Types of woodland operations represented include:

- Routine woodland maintenance (e.g. repairs to roads and fences)
- Tree establishment (e.g. ground preparation, growing of young plants in nurseries, weed and pest control, fertilisation where appropriate/relevant)
- Thinning and felling of trees for wood production
- Extraction of felled wood (including harvest residues, as appropriate) for utilisation as bioenergy or for material wood products

The CARBINE model calculates results for emissions of notable greenhouse gases, i.e. CO_2, CH_4 and N_2O, which can be expressed in units of $kgCO_2\ ha^{-1}\ yr^{-1}$, and added together to estimate total GHG emissions associated with woodland operations, as shown in Figure A2.5. Some contributions to indirect GHG emissions from woodland operations cannot be disaggregated into the individual greenhouse gases, due to the non-availability of disaggregated emissions factors for use in calculations. These aggregated GHG emissions are shown in Figure A2.5 using CO_2-equivalent units. The calculations in the CARBINE model to produce these results are too numerous and complex to describe in detail in this appendix. However, it may be noted that the magnitudes of GHG emissions due to woodland operations are small, compared with the GHG emissions/sequestration due to woodland carbon dynamics (i.e. biogenic carbon).

As already observed, the results in Figure A2.5 indicate that GHG emissions associated with woodland operations involved in wood production are small in magnitude. However, peaks in GHG emissions are apparent in Figure A2.5, generally associated with wood harvesting and extraction operations at times of felling and thinning. These occur against a low level background of annual GHG emissions associated with woodland operations involved in routine maintenance of woodland stands (see bullet list above).

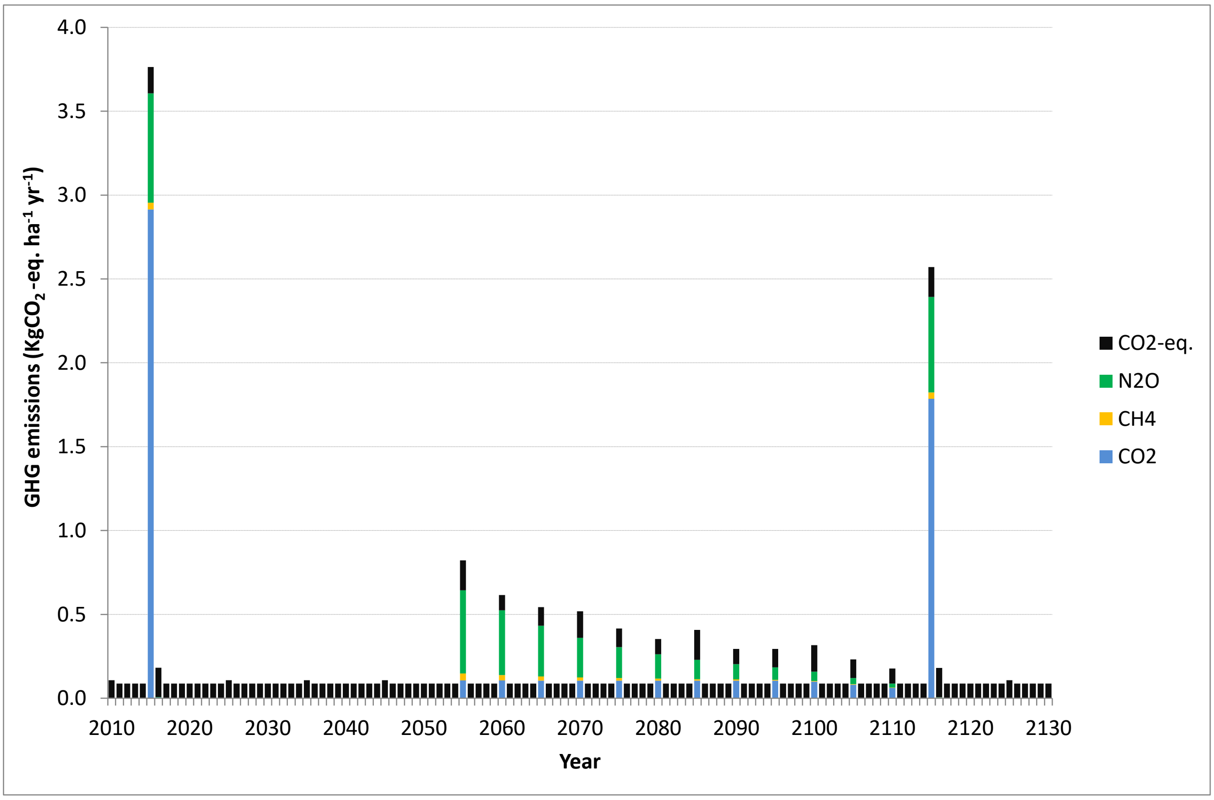

Figure A2.5. GHG emissions due to woodland operations in an example woodland area predicted by the CARBINE model for the woodland component described in Table A2.1, associated with management for wood production.

References for Appendix 2

Matthews, R., Mortimer, N., Mackie, E., Hatto, C., Evans, A., Mwabonje, O., Randle, T., Rolls, W., Sayce, M. and Tubby, I. (2014a) *Carbon Impacts of Using Biomass in Bioenergy and Other Sectors: Forests*. Final Report for Department of Energy and Climate Change. Revised 2014. Forest Research: Farnham.

Matthews, R., Sokka, L., Soimakallio, S., Mortimer, N., Rix, J., Schelhaas, M-J., Jenkins, T., Hogan, G., Mackie, E., Morris, A. and Randle, T. (2014b) *Review of literature on biogenic carbon and life cycle assessment of forest bioenergy*. Final Task 1 report, EU DG ENER project ENER/C1/427, Carbon impacts of biomass consumed in the EU. Forest Research: Farnham. At: http://ec.europa.eu/energy/sites/ener/files/2014_biomass_forest_research_report_.pdf.

Appendix 3. Representation of non-commercial woodland areas

A3.1. Introduction

The discussion in this appendix describes information provided by NRW on the tree species composition and management in non-commercial woodlands within the NRW estate.

A3.2. Woodland areas and tree species composition

The total area of non-commercial woodlands within the NRW estate is estimated at 1626.74 ha.

Non-commercial woodlands consist of 75% oak by area and 25% other broadleaves. For the purposes of modelling using CARBINE, the area of other broadleaves was assumed to consist of equal areas of ash, beech and birch.

A3.3. Yield class

A relatively low yield class of 4 should be assumed for all non-commercial woodlands.

A3.4. Age distribution

It is estimated that 90% of the area of non-commercial woodlands are older than 100 years. A further 5% consists of coppice, whilst the remaining 5% may be assumed to have a stand age distribution consistent with that observed for naturally regenerating woodland (data for this age distribution were provided separately by NRW).

A3.5. Land-use change

It should be assumed that new woodland areas are not being created and that no deforestation is occurring in non-commercial woodlands (but see description of broad management prescriptions). Such assumptions are consistent with the definition of a business as usual scenario as specified in this study (see Sections 4 and 6.2.3).

A3.6. Broad management prescriptions

It should be assumed that 98% of the area of non-commercial woodlands does not receive any active management. Of the remainder, 1% of area is managed as "long rotation coppice", whilst a further 1% of area is being progressively removed for conservation reasons.

A3.7. Rotations applied to woodland areas

Rotations are only applicable for the area managed as "long rotation coppice". Typically, this area produces 60 tonnes of small diameter roundwood annually, of which 90% is used as fuel and 10% is used for fencing and maintenance in situ. For the purposes of modelling using CARBINE, a notional rotation of 40 years was assumed to apply to areas managed as "long rotation coppice".

It should be noted that the majority of wood from trees felled to meet conservation objectives is retained on site as deadwood.

A3.8. Fertilisation of woodland areas

No fertilisation (nitrogen or other) activities take place in non-commercial woodland areas.

A3.9. Woodland areas affected by disturbance

For the purposes of modelling using CARBINE, an assumption was made that no significant natural disturbances occur within non-commercial woodlands.

Appendix 4. Estimation of relative areas of mineral and organic soils

A4.1. Introduction

The discussion in this appendix describes how the relative areas of mineral and organic soils were estimated for the key woodland categories represented in the modelling of woodland carbon stocks in NRW woodlands.

A4.2. Available data

As described in Table 6.1, in Section 6.2 of the main report, soils were classified as either mineral or organic (i.e. deep peats). The classification of woodland areas as on mineral or organic soils was based on a comparison of the National Forest Inventory 2015 woodland map (clipped to the area of NRW woodlands) with the Wales-wide unified peat map, developed as part of the Welsh Government-funded GMEP (Glastir Monitoring and Evaluation Programme) project to quantify deep peat stocks in Wales (Evans *et al*., 2015). Specifically, data were provided to Forest Research on areas of NRW woodlands associated with mineral soils and organic soils, classified according to:

- NRW operational region (and separately for NRW non-commercial woodlands)
- NFI woodland habitat category.

The relevant data are shown in Tables A4.1 to A4.6.

Table A4.1 Area of woodland in northeast operational region by NFI woodland habitat category and by mineral/organic soil type

NFI woodland habitat category	Total area (ha)	Area not on deep peat[1] (ha)	Area on deep peat[2] (ha)	Percentage of habitat on deep peat (%)
Assumed woodland	10.28	8.30	1.98	19.23
Broadleaved	310.14	307.53	2.61	0.84
Conifer	6730.57	6297.81	432.75	6.43
Cloud/shadow	0.00	0.00	0.00	0.00
Felled	1815.06	1598.12	216.94	11.95
Ground prep	26.07	26.07	0.00	0.00
Low density	55.35	55.33	0.01	0.02
Mixed mainly broadleaved	72.46	71.57	0.89	1.23
Mixed mainly conifer	67.90	67.90	0.00	0.00
Young trees	2023.76	1750.14	273.63	13.52
Shrub	12.00	12.00	0.00	0.00
Windthrow	32.47	23.07	9.39	28.94
Uncertain	0.00	0.00	0.00	0.00
Coppice	0.00	0.00	0.00	0.00
Total	**11156.06**	**10217.86**	**938.20**	**8.41**

Notes to Table A4.1:

1 Taken to represent woodland areas on mineral soils

2 Taken to represent woodland areas on organic soils.

Table A4.2 Area of woodland in northwest operational region by NFI woodland habitat category and by mineral/organic soil type

NFI woodland habitat category	Total area (ha)	Area not on deep peat[1] (ha)	Area on deep peat[2] (ha)	Percentage of habitat on deep peat (%)
Assumed woodland	31.42	31.36	0.07	0.22
Broadleaved	614.19	609.81	4.37	0.71
Conifer	8664.62	8343.75	320.87	3.70
Cloud/shadow	0.00	0.00	0.00	0.00
Felled	2186.51	2016.71	169.79	7.77
Ground prep	18.10	7.76	10.34	57.12
Low density	41.57	40.05	1.53	3.67
Mixed mainly broadleaved	358.54	353.73	4.81	1.34
Mixed mainly conifer	291.29	288.23	3.06	1.05
Young trees	2333.52	2224.09	109.42	4.69
Shrub	31.54	31.54	0.01	0.03
Windthrow	8.15	8.14	0.01	0.09
Uncertain	0.00	0.00	0.00	0.00
Coppice	0.00	0.00	0.00	0.00
Total	**14579.45**	**13955.18**	**624.27**	**4.28**

Notes to Table A4.2:

1 Taken to represent woodland areas on mineral soils

2 Taken to represent woodland areas on organic soils.

Table A4.3 Area of woodland in mid operational region by NFI woodland habitat category and by mineral/organic soil type

NFI woodland habitat category	Total area (ha)	Area not on deep peat[1] (ha)	Area on deep peat[2] (ha)	Percentage of habitat on deep peat (%)
Assumed woodland	63.43	41.90	21.53	33.94
Broadleaved	915.57	911.66	3.91	0.43
Conifer	16221.58	15658.40	563.18	3.47
Cloud/shadow	0.00	0.00	0.00	0.00
Felled	7705.31	7409.68	295.64	3.84
Ground prep	454.60	410.83	43.77	9.63
Low density	151.24	149.85	1.39	0.92
Mixed mainly broadleaved	296.86	295.24	1.61	0.54
Mixed mainly conifer	219.87	219.42	0.44	0.20
Young trees	3988.29	3675.37	312.92	7.85
Shrub	36.18	36.14	0.04	0.11
Windthrow	12.97	12.97	0.00	0.00
Uncertain	0.00	0.00	0.00	0.00
Coppice	0.00	0.00	0.00	0.00
Total	**30065.89**	**28821.46**	**1244.43**	**4.14**

Notes to Table A4.3:

1 Taken to represent woodland areas on mineral soils

2 Taken to represent woodland areas on organic soils.

Table A4.4 Area of woodland in southeast operational region by NFI woodland habitat category and by mineral/organic soil type

NFI woodland habitat category	Total area (ha)	Area not on deep peat[1] (ha)	Area on deep peat[2] (ha)	Percentage of habitat on deep peat (%)
Assumed woodland	135.42	133.05	2.37	1.75
Broadleaved	3146.73	3145.75	0.98	0.03
Conifer	16921.63	15532.72	1388.90	8.21
Cloud/shadow	0.00	0.00	0.00	0.00
Felled	5662.84	4876.76	786.07	13.88
Ground prep	694.64	500.38	194.25	27.96
Low density	156.85	155.86	0.99	0.63
Mixed mainly broadleaved	404.80	403.02	1.78	0.44
Mixed mainly conifer	379.15	379.14	0.01	0.00
Young trees	2896.14	2724.69	171.45	5.92
Shrub	22.76	22.76	0.00	0.00
Windthrow	15.09	15.09	0.00	0.00
Uncertain	5.36	5.36	0.00	0.00
Coppice	0.06	0.06	0.00	0.00
Total	**30441.47**	**27894.65**	**2546.81**	**8.37**

Notes to Table A4.4:

1 Taken to represent woodland areas on mineral soils

2 Taken to represent woodland areas on organic soils.

Table A4.5 Area of woodland in southwest operational region by NFI woodland habitat category and by mineral/organic soil type

NFI woodland habitat category	Total area (ha)	Area not on deep peat[1] (ha)	Area on deep peat[2] (ha)	Percentage of habitat on deep peat (%)
Assumed woodland	112.95	107.72	5.23	4.63
Broadleaved	1792.49	1787.98	4.51	0.25
Conifer	18144.45	17733.64	410.81	2.26
Cloud/shadow	0.00	0.00	0.00	0.00
Felled	5356.69	5115.69	241.00	4.50
Ground prep	369.76	325.84	43.92	11.88
Low density	44.59	43.23	1.36	3.05
Mixed mainly broadleaved	478.46	476.93	1.53	0.32
Mixed mainly conifer	371.20	371.20	0.00	0.00
Young trees	3856.26	3772.41	83.85	2.17
Shrub	31.62	31.49	0.13	0.40
Windthrow	39.86	39.47	0.39	0.99
Uncertain	0.00	0.00	0.00	0.00
Coppice	0.00	0.00	0.00	0.00
Total	**30598.34**	**29805.60**	**792.74**	**2.59**

Notes to Table A4.5:

1 Taken to represent woodland areas on mineral soils

2 Taken to represent woodland areas on organic soils.

Table A4.6 Area of non-commercial woodland by NFI woodland habitat category and by mineral/organic soil type

NFI woodland habitat category	Total area (ha)	Area not on deep peat[1] (ha)	Area on deep peat[2] (ha)	Percentage of habitat on deep peat (%)
Assumed woodland	9.21	9.15	0.06	0.69
Broadleaved	1070.99	894.58	176.41	16.47
Conifer	228.29	205.88	22.41	9.82
Cloud/shadow	0.00	0.00	0.00	0.00
Felled	98.79	50.52	48.27	48.86
Ground prep	4.59	4.52	0.06	1.39
Low density	46.20	11.20	35.00	75.75
Mixed mainly broadleaved	24.08	16.91	7.17	29.79
Mixed mainly conifer	28.09	27.99	0.10	0.34
Young trees	66.20	40.42	25.78	38.94
Shrub	50.14	42.10	8.05	16.05
Windthrow	0.17	0.17	0.00	0.00
Uncertain	0.00	0.00	0.00	0.00
Coppice	0.00	0.00	0.00	0.00
Total	**1626.74**	**1303.43**	**323.31**	**19.87**

Notes to Table A4.6:

1 Taken to represent woodland areas on mineral soils

2 Taken to represent woodland areas on organic soils.

A4.3. Interpretation of data

In order to refer to the above data in the modelling of woodland carbon stocks for this project, it was necessary to map the NFI woodland habitat categories on to the three major woodland types of (see Section 6.4.1):

- Broadleaved woodland (assumed all to be managed according to various LISS prescriptions)
- Conifer woodland managed according to various LISS prescriptions
- Conifer woodland managed according to clearfelling/restocking prescriptions.

In this context, “LISS” (low impact silvicultural systems) refers to woodlands managed according to a range of possible prescriptions not involving clearfelling, including shelterwood, selection, coppice and reserve/retention systems (see discussion of Table 6.2, Section 6.2.1 of main report).

Certain NFI woodland habitat categories were excluded as of limited relevance to woodland areas.

For the non-commercial woodlands, the entire area of woodland was assumed to be associated with broadleaved woodland, regardless of the classification suggested by the categorisation of non-commercial woodlands in Table A4.6. This approach was consistent with advice received from NRW about the tree species composition of NRW woodlands (see Appendix 3).

For areas of commercial woodlands, the mapping of areas adopted for this project is shown in Table A4.7. The subsequent estimation of percentage woodland areas on mineral and organic soils, for each of the three key woodland categories, is illustrated for the example of the mid operational region in Table A4.8.

Table A4.9 shows the estimated percentage woodland area on mineral and organic soils, for each of the three key woodland categories, for each NRW operational region and for the non-commercial woodlands.

Table A4.7 Mapping of woodland areas for NFI woodland habitat categories to major woodland types referred to in this study

NFI woodland habitat category	**Allocation to key woodland category**		
	Broadleaf	**Conifer LISS**	**Conifer clearfell**
Assumed woodland	Pro rata according to total area for each key woodland category		
Broadleaved	100%	0%	0%
Conifer	0%	Pro rata according to total area for each key woodland category	
Cloud/shadow	Excluded (invariably zero area)		
Felled	0%	0%	100%
Ground prep	0%	0%	100%
Low density	100%	0%	0%
Mixed mainly broadleaved	60%	40%	0%
Mixed mainly conifer	40%	60%	0%
Young trees	Pro rata according to total area for each key woodland category		
Shrub	100%	0%	0%
Windthrow	0%	0%	100%
Uncertain	Excluded (very small area)		
Coppice	100%	0%	0%

Table A4.8 Illustration of calculations to estimate percentage woodland areas on mineral and organic soils (example of Mid operational region)

NFI Habitat category	Total area[1](ha)		Percentage allocation			Woodland area on mineral soils (ha)			Woodland area organic soils (ha)		
	Mineral	Organic	Broadleaf	Conifer LISS	Conifer clearfell	Broadleaf	Conifer LISS	Conifer clearfell	Broadleaf	Conifer LISS	Conifer clearfell
Assumed woodland[2]	41.90	21.53	14.2	22.6	63.1	5.96	9.48	26.46	3.06	4.87	13.59
Broadleaved	911.66	3.91	100	0	0	911.66	0.00	0.00	3.91	0.00	0.00
Conifer[3]	15658.40	563.18	0	26.4	73.6	0.00	4131.48	11526.92	0.00	148.60	414.58
Felled	0.00	0.00	0	0	100	0.00	0.00	7409.68	0.00	0.00	295.64
Ground prep	7409.68	295.64	0	0	100	0.00	0.00	410.83	0.00	0.00	43.77
Low density	410.83	43.77	100	0	0	149.85	0.00	0.00	1.39	0.00	0.00
Mixed mainly broadleaved	149.85	1.39	60	40	0	177.15	118.10	0.00	0.97	0.64	0.00
Mixed mainly conifer	295.24	1.61	40	60	0	87.77	131.65	0.00	0.18	0.27	0.00
Young trees[2]	219.42	0.44	14.2	22.6	63.1	523.00	831.76	2320.62	44.53	70.81	197.57
Shrub	3675.37	312.92	100	0	0	36.14	0.00	0.00	0.04	0.00	0.00
Windthrow	36.14	0.04	0	0	100	0.00	0.00	12.97	0.00	0.00	0.00
Coppice	12.97	0.00	100	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Total area (ha)						1891.53	5222.47	21707.47	54.07	225.19	965.17
Percentage of area[4]						97.2	95.9	95.7	2.8	4.1	4.3

Notes to Table A4.8:

1 From Table A4.3.

2 Allocation for categories of "Assumed woodland" and "Young trees" on a pro-rata basis according to the total areas for the three major woodland types in the Mid operational region of 3,826.9 ha (broadleaf), 6,086.2 ha (conifer LISS) and 16,980.6 ha (conifer clearfell).

3 Allocation for category of "Conifer" on a pro-rata basis according to the total areas for the two coniferous major woodland types in the Mid operational region of 6,086.2 ha (conifer LISS) and 16,980.6 ha (conifer clearfell).

4 Percentage woodland area on mineral and organic soils calculated separately for each major woodland type based on the estimated total areas immediately above in the table.

Table A4.9 Estimated percentage woodland areas on mineral and organic soils

Region	Percentage area on mineral soils			Percentage area on organic soils		
	Broadleaf	Conifer LISS	Conifer clearfell	Broadleaf	Conifer LISS	Conifer clearfell
Northeast	95.4	92.2	90.9	4.6	7.8	9.1
Northwest	98.0	96.4	95.2	2.0	3.6	4.8
Mid	97.2	95.9	95.7	2.8	4.1	4.3
Southeast	99.1	92.6	89.8	0.9	7.4	10.2
Southwest	99.3	97.9	97.1	0.7	2.1	2.9
Non-commercial[1]	80.1	-	-	19.9	-	-

Note to Table A4.9:

1 For non-commercial woodlands, all area allocated to broadleaf woodland category based on advice from NRW on tree species composition of non-commercial woodlands (hence result based on percentage estimated total area in Table A4.6).

References for Appendix 4

Evans, C., Rawlins, B., Grebby, S., Scholefield, P. and Jones, P. (2015) *Glastir Monitoring & Evaluation Programme: Mapping the extent and condition of Welsh peat*. Report to Welsh Government (Contract reference: C147/2010/11). NERC/Centre for Ecology and Hydrology: Bangor.

Appendix 5. Information on utilisation of harvested wood from NRW woodlands

A5.1. Introduction

The discussion in this appendix describes information provided by NRW on the utilisation of wood harvested from woodlands within the NRW estate. A description is also provided of how this information was interpreted for the purposes of representing the dynamics of carbon stocks in harvested wood products in the CARBINE model.

A5.2. Basis of estimates

Estimates are based on harvesting in a typical year, which amounts to 800,000 m^3 over bark standing. It should be noted that the level of harvest will vary annually in practice. It may also be noted that the level of harvesting is likely to be slightly higher over the next 5 years but that over 25 years the quoted annual estimate of 800,000 m^3 should be typical. The proportions of wood harvested as sawlogs and roundwood should be relatively consistent. This appears to be supported by recent Forestry Commission forecasts (see Table 8 in www.forestry.gov.uk/forecast for 25 year softwood forecast).

The estimates provided are for all production from NRW woodlands. A conversion factor of 0.81 has been assumed in converting estimates of standing volume in cubic metres to harvested and extracted wood in units of green tonnes.

A5.3. Branchwood

It is estimated that approximately 200,000 tonnes of branchwood is felled each year. Although most of this is not recoverable for a range of logistical reasons, it is estimated that approximately 20,000 tonnes of branchwood is extracted annually for use as fuel.

A5.4. Stemwood

The typical total annual wood harvest from NRW woodlands is taken as 650,000 tonnes (converted from 800,000 m^3 over bark standing). Of this quantity, typically 60% goes to sawmills which gives 390,000 tonnes (650,000 x 60%). Recovery by mills averages out at 57% of intake, implying that 222,000 tonnes goes into sawn products. The sawnwood is divided up as follows:

- 25% structural, giving 55,500 tonnes
- 50% fencing, giving 111,000 tonnes (the sawnwood industry in Wales is heavily geared to the fencing industry with all mills having it as their main product outlet)
- 20% pallet and sawn boards, giving 44,400 tonnes

- 5% joinery (short and long lived), giving 11,100 tonnes.

The offcuts from sawlogs used in the production of sawnwood products (168,000 tonnes) go into one of three uses:

- 15% bark and peelings to horticulture, giving 25,000 tonnes
- 75% chips for board, giving 126,000 tonnes
- 10% fuelwood, made up from some bark, peelings and some chip, giving 17,000 tonnes.

The remainder of the harvested stemwood (260,000 tonnes of small roundwood) is divided between:

- 10% bark and peelings to horticulture, giving 26,000 tonnes
- 15% round fencing and other round products, giving 39,000 tonnes
- 35% fuelwood, giving 91,000 tonnes
- 40% board industry, giving 104,000 tonnes.

It follows that, in summary, the total production of stemwood is allocated to:

- 51,000 tonnes bark and peelings to horticulture
- 108,000 tonnes fuel wood
- 230,000 tonnes board industry (chips sawdust and roundwood)
- 55,500 tonnes structural
- 111,000 tonnes fencing
- 44,400 tonnes pallet and sawn board
- 11,100 tonnes joinery
- 39,000 tonnes round fencing and other round products.

A5.5. Interpretation of estimates for use in modelling

In order to use the information presented above in the modelling work for this study, it is necessary to translate the wood product categories referred to above into the categories of semi-finished products referred to in IPCC Guidance (see Section 5.5 in the main report). The mappings between the various wood product categories adopted for the purposes of this study are shown in Table A5.1.

Table A5.1 Mappings between NRW and IPCC wood product categories

Wood product category in NRW information	IPCC Guidance wood product category
Branchwood	Fuel
Bark and peelings to horticulture	Fuel
Fuel wood	Fuel
Board industry	Wood-based panels
Structural	Sawnwood
Fencing	Sawnwood
Pallet and sawn boards	Sawnwood
Joinery	Sawnwood
Round fencing and other round products	Sawnwood

Based on the mappings in Table A5.1, the data provided by NRW could be interpreted to estimate the percentage of wood harvested from NRW woodlands being used for the four IPCC categories of semi-finished products, as shown in Table A6.1.

Table A5.2 Estimates of percentages wood harvested from NRW woodlands used for IPCC wood product categories

IPCC wood product category	NRW wood product categories	Total supply (green tonnes)	Percentage of total harvested volume
Fuel	Branchwood, bark and peelings to horticulture, fuelwood	179,000	27
Paper	None	0	0
Wood-based panels	Board industry	230,000	34
Sawnwood	Structural, fencing, pallet and sawn boards, joinery, round fencing and other round products	261,000	39
Total	**All categories**	**670,000**	**100**

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