Forest Research

NORTH ENERGY

Carbon impacts of using biomass in bioenergy and other sectors: forests

DECC project TRN 242/08/2011

Final report: Parts a and b

Robert Matthews, Nigel Mortimer, Ewan Mackie, Charlotte Hatto, Anna Evans, Onesmus Mwabonje, Tim Randle, Will Rolls, Marc Sayce and Ian Tubby

Report URN 12D/085

The Research Agency of the
Forestry Commission

Carbon impacts of using biomass in bioenergy and other sectors: forests

Robert Matthews[1], Nigel Mortimer[2], Ewan Mackie[1], Charlotte Hatto[2], Anna Evans[2],
Onesmus Mwabonje[2], Tim Randle[1], Will Rolls[1], Marc Sayce[1] and Ian Tubby[1]

[1]Forest Research, Alice Holt Lodge, Farnham, Surrey GU10 4LH, UK

[2]North Energy Associates Limited, 5 – 15 Watson's Chambers, Market Place, Castle Square, Sheffield S1 2GH, UK

The original version of this report has been updated to take account of several issues that have emerged during consultation on a bioenergy strategy developed by the Department of Energy and Climate Change. The report includes a number of revisions to results (due to updated assumptions about levels of biomass productivity from UK forests), which are most apparent in the figures and tables presented in Section 5 and the appendices of this report. In addition, several new sections provide clarifying discussion, particularly with regard to the typical mix of wood products derived from UK forests (Section 2.4), the option of suspending harvesting in forests currently managed for production (Section 3.6) and the definition, calculation and interpretation of GHG emissions, particularly when expressed as carbon impacts as referred to in this report (complete Section 6).

Report URN 12D/085

Contents

Contents......ii
Executive Summary......1
1. Introduction......8
  1.1 Background......8
  1.2 Aims and objectives......9
  1.3 Work programme......9
  1.4 Report structure......12
  1.5 Representing combined impacts of different greenhouse gases......13
2. Brief overview of UK forest sector......14
  2.1 Forestry in the UK......14
  2.2 Wood industries in the UK......16
  2.3 UK forestry in an international context......18
  2.4 The ‘conventional mix’ of UK wood production......21
  2.5 Conclusions on UK forestry......23
3. Fundamentals of forest GHG balances......25
  3.1 Understanding forest GHG balances......25
  3.2 Carbon dynamics in individual stands......28
  3.3 Carbon dynamics in populations of stands......35
  3.4 Influence of species and growth rate......44
  3.5 Impacts of changes to forest management......46
  3.6 Carbon sequestration due to suspension of harvesting in forests......50
  3.7 Key conclusions on forest GHG dynamics......51
4. Approach to GHG balance estimation......53
  4.1 Characteristic forest types......53
  4.2 Characteristic wood use options and counterfactuals......54
  4.3 Application of CSORT model......68
  4.4 Detailed LCA calculations for wood chains......70
  4.5 Important conventions in LCA calculations......72
  4.6 Results for standard scenarios......76
5. Results and interpretation 80
  5.1 ‘Absolute’ and ‘relative’ emissions......80
  5.2 Absolute emissions for example scenarios......82
  5.3 Relative emissions for example scenarios......91
  5.4 Reporting of ranked results......96
  5.5 Detailed analysis of results......97
6. Inferring carbon impacts 115
  6.1 Definition of carbon and GHG impacts......115
  6.2 Calculating carbon impacts......117
7. Conclusions and key messages......135
  7.1 Main conclusions......135

  7.2 Key messages....137
Acknowledgements....139
References....140
Glossary....145
Annex 1 General analysis of results....147
  A1.1 General considerations....147
  A1.2 Graphical analysis of ranked results....149
  A1.3 Summary analysis of ranked results....174
Annex 2 General conclusions....187

Executive Summary

This report was prepared by Forest Research and North Energy Associates Ltd to address Parts (a) and (b) of the technical specification from the Department of Energy and Climate Change (DECC) on the *Carbon Impacts of Using Biomass in Bio-energy and Other Sectors*, as set out in Tender Call Document TRN242/08/2011.

The aims and objectives of this work on Parts (a) and (b) are described in more detail in the introduction to this report (Section 1) but, in essence, this study has analysed the impacts on greenhouse gas (GHG) emissions of options for the utilisation of wood harvested from forests, with a primary focus on the UK forest resource. The aim has been to provide a consistent body of evidence that may be used to address key questions about GHG emissions impacts due to forestry and the use of wood, such as in the context of an overall GHG balance[1]:

- Is it better to leave wood in the forest or harvest it for timber, other wood products (e.g. panel boards) and/or fuel?
- Is it better to use harvested wood to provide materials or fuel?
- Are there particular options involving the use of (UK) wood that clearly offer the biggest benefits? Are there other options that should be avoided?
- What would be the impacts of using imported wood rather than UK-grown wood for timber, other wood products and/or fuel?

Forestry in the United Kingdom

A full understanding of the approach taken in this project and the results generated requires a consideration of the general extent, composition and 'status' of forests in the United Kingdom (UK), and of the current contribution to wood consumption within the UK. It is also important to understand where wood is supplied from non-UK sources, so that the potential impacts of changes to management of UK forests which affect levels of production can be appreciated. A comprehensive description of the current status of UK forests is beyond the scope of this report, but a summary overview is provided in Section 2 of this report.

Fundamentals of forest GHG balances

Before considering the full life cycle GHG emissions of different forestry and wood use options, it is important to understand the influence on GHG emissions balances specifically due to carbon stock changes in forests, as these can make an important contribution to the ultimate result. Misconceptions about forest GHG balances are quite commonplace. Therefore, a clear statement on the subject is needed, in particular addressing how decisions about forest management (and changes to forest

---

[1] It should be noted that the GHG estimates, derived for the wide range of scenarios that were considered in this study, calculated by means of full Life Cycle Assessment (LCA), do not take into account Governement requirements on sustainability standards for solid bioenergy that limit the LCA GHG emissions that can be emitted from bioenergy.

management) can cause changes to forest GHG balances. Consequently, a detailed discussion of the relevant issues is presented in Section 3 of this report.

Project methodology

Having set the scene in Sections 2 and 3, a description of the approach taken in this project to the estimation of GHG emissions balances for specific wood utilisation options, as dependent of wood supplied from different types of forest resource relevant to current UK conditions, is given in Section 4 of this report.

Three characteristic forest types were defined as relevant within the scope of this project:

1. Coniferous forests already under management for production of timber and/or woodfuel.
2. Broadleaf forests already under management for production of timber and/or woodfuel.
3. 'Neglected' broadleaf forests.

These three forest types were identified as broadly representative of the majority of forest areas in the UK as discussed in Section 2 of this report.

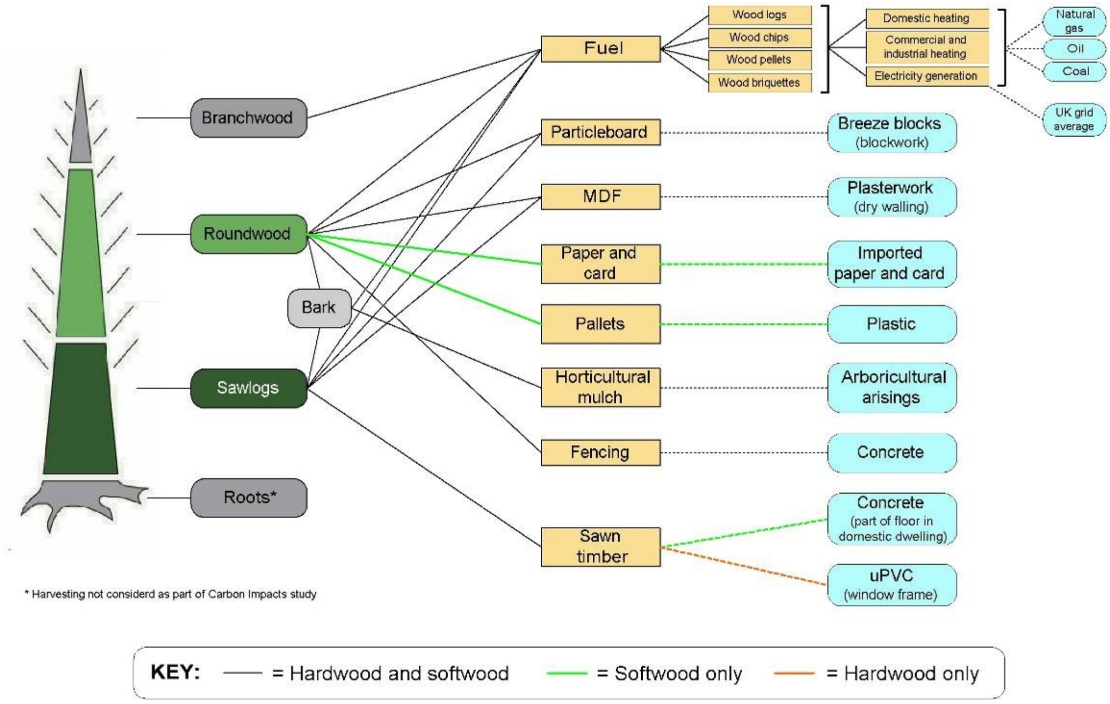
A series of options for the end use of wood were identified. For each type of wood end use, it was also necessary to identify relevant 'counterfactuals' which would fulfil specific energy or material end uses if UK-grown wood were not to be consumed. It was recognised that, for most existing applications, there were two fundamental ways of meeting needs for energy or materials, should consumption of UK-grown wood for a specific application be reduced or cease entirely:

1. Consumption of UK-grown wood could be substituted for by non-wood options. In the case of wood used for bioenergy, fossil fuels could serve as a substitute. For wood-based materials, there may be a wide range of possible non-wood substitutes based on plastics, metals, concrete etc., obviously highly dependent on the specific end use.
2. Consumption of UK-grown wood could be substituted for by importing wood from other (i.e. non-UK) sources.

Consequently, wherever possible and meaningful, two possible counterfactuals were identified for each wood end use option considered within the scope of this project – one involving use of a non-wood substitute and one involving use of imported wood.

A total of 5 fuel and 7 material final wood products were identified as relevant to the UK forest sector. Fuel products consisted of primary raw wood materials (specifically for supply direct to power stations), wood logs, wood chips, wood pellets and wood briquettes. Material products consisted of sawn timber, particleboard, Medium Density Fibreboard (MDF), fencing, palletwood, 'paper and card' and horticultural mulch.

The various possible production pathways from felled trees to final products and relationships to non-wood counterfactuals are illustrated in the diagram below.



* Harvesting not considerd as part of Carbon Impacts study

Representation of wood harvesting, processing and utilisation chains within this project, including relationships to non-wood counterfactuals.

The disposal of material wood products at end-of-life can have very large impacts on GHG emissions balances and it was recognised that different options for disposal of wood products needed to be represented within the scope of the project. A total of 7 disposal options were identified to ensure that all possibilities and their consequences, in terms of relative GHG emissions, would be covered in this study.

For the purposes of this project, detailed GHG emission calculations were performed in MS Excel. The resultant workbooks have identical structures although they assemble data from a variety of different sources in order to meet the aims and objectives of the technical specification.

The structure of the workbooks enables them to take into account variations in biomass chain parameters. These parameters include modes of wood transport and their round trip distances, wood losses for each relevant stage in the biomass chain, and specifications for bioenergy applications (ash content of the woodfuel, and net output rating, thermal efficiency and load factor of the bioenergy plant).

The Forest Research CSORT model was applied to provide key input estimates to the workbooks representing:

- Relevant changes in forest carbon stocks
- Levels of production of primary wood raw.
- GHG emissions associated with forest operations (i.e. forest establishment, forest maintenance, tree harvesting and extraction of wood products to forest roadside).

All other life cycle assessment (LCA) calculations were carried out explicitly in the workbooks.

Project results and interpretation

The key results of the project are presented in Section 5 and Annex 1 of this report, which also include a thorough discussion of how results can be interpreted. The main results are reported either as annualised 'absolute' GHG emissions or 'relative' GHG emissions expressed in units of kgCO_2–equivalent ha^{-1} yr^{-1} or tCO_2–equivalent ha^{-1} yr^{-1}, for specified scenarios for the management of conifer (282 production scenarios), the management of broadleaf forests (between 69 and 215 production scenarios) and the restoration of neglected broadleaf forests (215 production scenarios) in the UK over time horizons of 20, 40 and 100 years.

Absolute GHG emissions are calculated (on an annualised basis over a specified time horizon) as the sum of:

- The carbon stock change in forests
- The quantity of harvested carbon utilised in wood products
- The GHG emissions associated with forest operations
- The GHG emissions associated with wood harvesting and extraction
- The GHG emissions associated with wood transport
- The GHG emissions associated with wood processing
- The GHG emissions associated with disposal of harvested wood products at end-of-life.

Relative GHG emissions are calculated as:

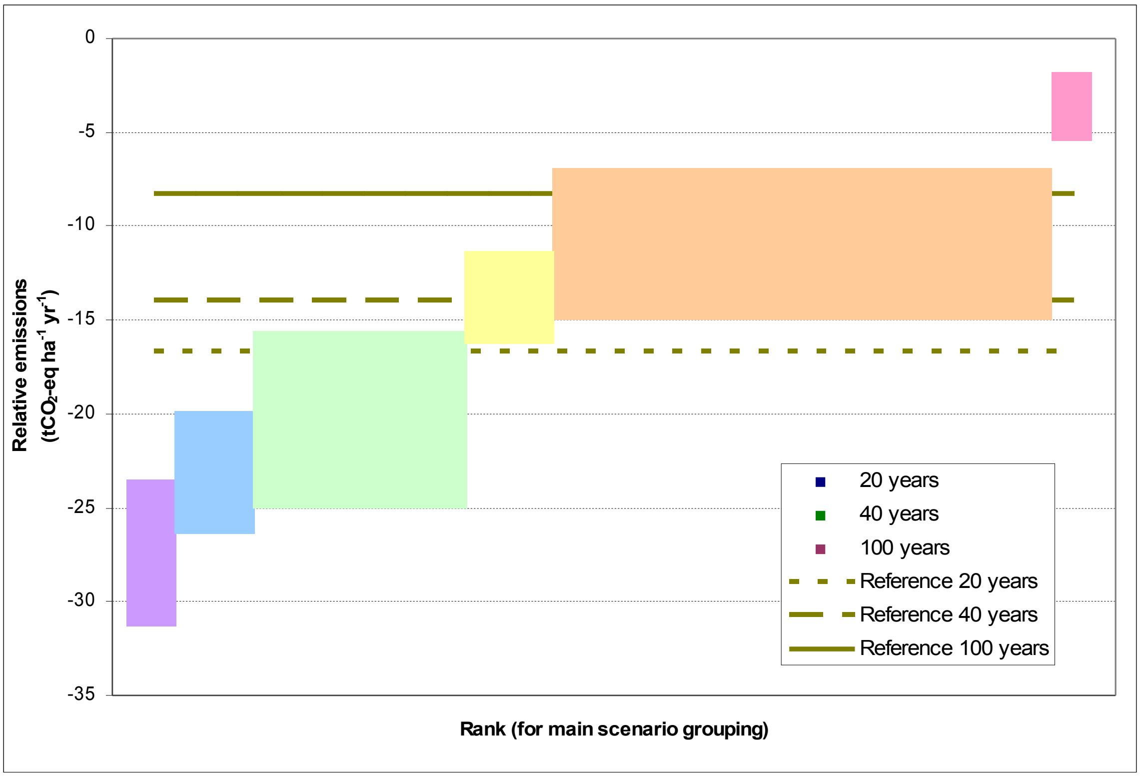
Relative GHG emissions = Absolute GHG emissions – Counterfactual GHG emissions.

The 'counterfactual' emissions are the emissions that would occur if UK wood was not harvested (and utilised as specified for a particular scenario) and the services that would have been supplied by the harvested wood were provided by other means (i.e. non-wood alternatives or imported wood).

It is important to note that the definitions for absolute, relative and counterfactual GHG emissions are specific to this project, as standard terminology/nomenclature has not been established fully in this area of research.

Complete sets of results, in the form of ranked relative GHG emissions for a standard set of wood utilisation scenarios, are provided separately in workbooks. The very large number of GHG emissions estimates resulting from so many different forestry and wood utilisation options presents some obvious challenges in presenting and interpreting results. As an illustration of the analysis and interpretation presented in Section 5 of this report, the figure below shows an example of the detailed graphical analysis of results in terms of relative GHG emissions for a specific selection of scenarios:

- UK coniferous forests already under management for production
- Non-wood counterfactuals
- A single option for disposal of wood at end-of-life (incineration in a WID-compliant power only plant)
- Bark assumed to be utilised for fuel only
- No application of carbon capture and storage technologies
- All three time horizons (20, 40 and 100 years).



An example of relative GHG emissions for individual scenarios plotted against rank number for groups of scenarios: UK conifer forests managed for production, non-wood counterfactuals, bark utilised for fuel (not mulch), carbon capture and storage technologies not applied, 20, 40 and 100 year time horizons. Note that results for a 20 year time horizon are almost coincident with those for a 40 year time horizon and are obscured. The coloured bands indicate groups of results in terms of similar levels of relative GHG emissions.

The analysis involved

- Grouping scenarios into related scenarios
- Estimating the mean relative GHG emissions for each scenario grouping
- Ranking individual scenarios in terms of mean relative GHG emissions for the main scenario grouping (from largest negative to smallest negative/largest positive)
- Plotting a graph of relative emissions for individual scenarios against the rank for the scenario grouping.

Also shown in the figure (as dark olive horizontal lines) are 'reference lines' for the three time horizons, based on a scenario which involves avoiding harvesting so as to accumulate forest carbon stocks.

Distinct 'groups' of results may be discerned (in terms of similar levels of relative GHG emissions), as indicated by the coloured bands in the figure.

Broadly, a hierarchy in terms of relative GHG emissions (from most negative to least negative) can be discerned involving scenario groupings organised as:

1. Sawn timber, particleboard and fuel
2. Sawn timber, particleboard, fencing and pallets, fuel
3. Sawn timber, particleboard and fuel, fencing, MDF and paper and card
4. Sawn timber, fuel, fencing and pallets
5. Sawn timber and a mix of products other than particleboard
6. Fuel only.

High ranking scenarios (groups of results shaded violet, blue, green and yellow in the figure) include what might be described as the 'conventional mix' for the use of harvested wood in the UK (in terms of the relative priorities given to processing timber into different products), specifically:

- Sawlogs used for sawn timber
- Roundwood used for particleboard, fencing, pallets and MDF
- Sawlog and roundwood co-products (offcuts) used for particleboard and MDF
- Bark used for fuel and horticultural mulch
- Fuel also produced from sawlog and roundwood co-products, also from bark and branchwood.

It is noteworthy that the majority of scenarios involve large negative relative GHG emissions, with nearly all results falling below the 'reference line' result representing the scenario of 'leaving carbon in the forest' (no harvesting). In the majority of cases the magnitudes of the estimates of relative GHG emissions drop when longer time horizons are considered (i.e. 100 years). However, the magnitude of the reference line also drops at longer time horizons. Over time horizons even longer than 100 years, the reference line would be expected to drop to zero.

Headline conclusions and key messages

Conclusions and key messages are presented in Section 6 and Annex 2 of this report.

The conclusions of this project and the wider discussion in this report may be summarised as a set of key messages relevant to policy on UK forests, wood production and in particular the utilisation of wood for fuel:

- Management of UK forests for wood production can contribute to UK carbon objectives e.g. to 2050. However, there are some wide variations in carbon emissions and removals, depending on the specific circumstances.
- Using wood as a construction material or in a product maintains a carbon stock and delays emissions of carbon to the atmosphere. Using wood for bioenergy can also reduce carbon emissions, compared to burning fossil fuels for energy.
- These results suggest that policy should support managing UK forests to produce wood for a mix of products and bioenergy.
- GHG emissions are influenced by the end-of-life destination of wood products. Policies should address the long term fate of wood products to ensure maximum GHG emissions benefits.
- Currently, only about 20% of the wood consumed for materials and bioenergy in the UK is produced from UK forests. This contribution is forecast to increase over the next 20 years but imports will remain the largest source of wood consumed in the UK.
- Using imported wood for materials or energy can result in low relative GHG emissions, but can also lead to large greenhouse gas emissions (see for example Figure 5.6, Section 5.3). Benefits in terms of GHG emissions will only be achieved if the harvesting of wood does not involve the permanent and long-term depletion of carbon stocks in forests, or if reductions in carbon stocks are managed carefully over time.
- If areas of ‘neglected’ forest in the UK are restored to management, this could lead to reductions of carbon stocks in some forest areas.
- Globally, an increased requirement for wood could lead to the intensification of harvesting in forests with potential adverse impacts on forest carbon stocks. Standards for forest management (such as the UK Forest Standard) and more general biomass sustainability standards can help ensure that supplies of harvested wood achieve GHG emissions savings.

1. Introduction

1.1 Background

This report was prepared by Forest Research and North Energy Associates Ltd to address Parts (a) and (b) of the technical specification from the Department of Energy and Climate Change (DECC) on the "Carbon Impacts of Using Biomass in Bio-energy and Other Sectors', as set out in Tender Call Document TRN242/08/2011. Part (a) of this specification involves assessment of the potential carbon impacts of using different types of wood for the generation of bioenergy set against the role played by forest stocks as carbon storage facilities. Part (b) of the specification refers to assessment of the impact on carbon emissions of diverting such wood from other uses to bioenergy. In a further aspect of the technical specification, Part (c), concerning evaluation of the potential of energy crops, has been addressed by ADAS UK Ltd and relevant results are documented in a separate report.

In the context of the technical specification, carbon impacts are defined as emissions of the three prominent greenhouse gases (GHGs); carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The main types of wood under consideration consist of the major outputs derived from forests in the United Kingdom (UK); softwoods from managed conifer forests and hardwood from managed broadleaf forests and neglected broadleaf forests that could be restored to management and production. The main forms of bioenergy examined in this work are domestic, commercial and industrial heating, commercial and industrial combined heat and power (CHP) generation and power only generation using different types of woodfuel including logs, briquettes, chips, pellets, and sawlogs, roundwood, and bark and branchwood bales in relevant applications. The work focuses on existing bioenergy conversion technologies which rely on combustion. Other uses of wood from forests consist of wood products such as sawn timber, particleboard, medium density fibreboard (MDF), fencing, pallets, paper and card and horticultural mulch.

For sound policy analysis and decision-making, it is important to establish the overall carbon impacts of forests, their management, the diverse uses of their potential woodfuels and products and the displacement of other products and services by these woodfuels and products[2]. This requires realistic and representative modelling of carbon stocks in forests over relevant periods of time, estimation of the temporary sequestration and eventual release of carbon in woodfuels and products, and calculation of associated GHG emissions of all stages of the production (biomass chains) of woodfuels and products, as well as end-of-life disposal, where relevant, using the

---

[2] It should be noted that the GHG estimates, derived for the wide range of scenarios that were considered in this study, calculated by means of full Life Cycle Assessment (LCA), do not take into account Government requirements on sustainability standards for solid bioenergy that limit the LCA GHG emissions that can be emitted from bioenergy.

appropriate means of life cycle assessment (LCA). In addition, it is also necessary to address the wide diversity of different possible production scenarios for woodfuel and products, and end-of-life disposal options. Furthermore, flexibility has to be incorporated to accommodate variations in key parameters and essential assumptions, especially concerning the displacement of other sources of energy and products, referred to here as 'counterfactuals', and their associated GHG emissions.

1.2 Aims and objectives

The aims and objectives of this work on Parts (a) and (b), as set out in the technical specification were as follows:

- An assessment of the potential carbon (GHG) impacts of using different types of bioenergy feedstocks (in the form of suitable woodfuels) to displace carbon (GHG) emissions from fossil fuels, against the role played by forests stocks as carbon storage facilities (including diverting wood from landfill/forest floor to bioenergy). The analysis should try to take into account key GHGs released in the tree's full life cycle. The analysis should also consider the different timescales; e.g. the amount of carbon stored in a plantation has a limit whereas transfer of carbon via sustainably-produced woody biomass can, in principle, continue indefinitely.
- An assessment of the impact on carbon (GHG) emissions of diverting these woody biomass feedstocks from a range of other uses (such as construction) and from landfill at the end of the product life to bioenergy. This should include an assessment of the potential carbon (GHG) impacts of changes in the patterns of use of biomass products in other sectors (e.g. carbon impacts of moving from the use of domestic biomass to imported). The assessment should consider not only carbon dioxide but also methane emissions where appropriate.

1.3 Work programme

The programme of work designed to meet the aims and objectives of Parts (a) and (b) of the technical specification was divided into the following 4 Tasks (A, B, C and D).

Task A: Confirming Scope

The precise scope to the work was discussed and agreed with the client at the kick-off meeting which occurred as soon as possible at the beginning of the project. To assist discussions, a preliminary scoping list was drawn up and circulated prior to this meeting. The scope addressed:

- the exact sources of woody biomass for consideration (type of forest, type of management regimes and national locations) including sources of clean and unclean waste wood,

- the range of energy end use applications, their biomass chains and their relevant technologies,
- the specific energy counterfactuals and their GHG emissions factors
- the range of material end use applications, their biomass chains and their end-of-life disposal options,
- the specific material counterfactuals and their GHG emissions factors,
- the time horizons for evaluating GHG emissions,
- the relevant calculation methodology for addressing the specific policy questions, and
- a list of proposed sources of data for use in the project.

It was proposed that consequential LCA would be applied as the most appropriate means of addressing the specified policy questions raised by the technical specification. This involved selecting globally spatial and specified temporal systems boundaries which required inclusion of particular sources of GHG emissions, especially those from machinery and equipment manufacture and maintenance) and co-product allocation procedures. The distinction between consequential LCA and attributional LCA, which is intended to form the basis of regulation, such as the European Commission's Renewable Energy Directive were discussed and explained at the beginning of this work.

It was recognised that this work would rely mainly on data from existing reports and studies, as well as spreadsheets and models either in the public domain or accessible to the Forest Research and North Energy Associates Ltd. This included concurrent work that was being conducted for the Scottish government via Forestry Commission Scotland. However, it was also necessary to undertake some new work using primary data to fill important gaps in the assessment.

Task B: Calculating Carbon Impacts – Using Woody Biomass to Bioenergy

This Task addressed Part (a) of the technical specification by assessing the potential carbon impacts of using different types of wood as bioenergy against the role played by forest stocks as carbon storage facilities. It was conducted in two phases consisting of the generation of interim and then final results. A simplified MS Excel workbook which has been developed previously in current work for the Scottish Government was adapted accordingly. The scope of this workbook was expanded to reflect the outcomes of Task A. Although this workbook does not contain the full functionality and absolute transparency of a complete tool such as the Biomass Environmental Assessment Tool ($BEAT_2$), it does include audit trails linked to original sources of data. These include the outputs of CSORT modelling by Forest Research, $BEAT_2$ workbooks, especially those which incorporate UK and international forestry[3], and relatively recent work on timber transport (Whittaker *et al*., 2011). The workbook was set up to examine the effects of

---

[3] Workbooks and a report produced in connection with the report of Bates *et al*. (2011).

key factors on unit total GHG emissions associated with the generation of bioenergy from woody biomass, including:

- the type (conifer and broadleaf) and national location (UK and overseas) of forest, management regime (sustainable management, recovery from neglect, and other relevant management practices) and time horizon (20, 40 and 100 years) based on CSORT modelling especially to address carbon stock changes,
- the type of woodfuel (wood logs, briquettes, chips, pellets, wood briquettes and "whole trees"; sawlogs, roundwood, and bark and branchwood bales) and associated processing requirements (storage, drying by woodfuels, log cutting, chipping, milling, pelletising and briquetting),
- the type of transport mode (road, rail and ship) and transportation distance (round trip transport distance with relevant effects of different load factors), and
- the operating parameters (thermal efficiency and, where relevant, heat-to-power ratio) of bioenergy plants (domestic, commercial and industrial heat only generation by combustion, commercial and industrial CHP generation by combustion, dedicated power only generation by combustion).

Workbooks were expanded to accommodate the effects of disease and forest fires on all woody biomass chains and their associated net carbon stock profiles (based on existing statistical data) and the effect of introducing carbon capture and storage (CCS) to relevant biomass chains (based on existing review results from the European Commission's NATURALHY project[4] and, if published in time, the Energy Technologies Institute's project on the "Techno-Economic Study of Biomass to Power with CCS").

Counterfactual results were generated for leaving woody biomass in forests under various management regimes and over different time horizons (to 2020, to 2050 and over 100 years) and for disposing of waste wood. Relevant comparative results, in the form of unit total GHG emissions, for counterfactual energy generation (fossil fuels; coal, oil and natural gas) were drawn up from existing sources. The workbooks enable total GHG emissions to be determined for each woody biomass chain under consideration. Initial results were presented in a brief Interim Report. Following subsequent discussions, the workbooks were modified and extended further so that final results could be derived for presentation in the Final Report.

Task C: Calculating Carbon Impacts – Diverting Woody Biomass to Bioenergy

This Task addresses Part (b) of the proposed project by assessing the impact on carbon emissions of diverting woody biomass feedstocks from other uses to bioenergy. As with Task B, this was conducted in two phases so that preliminary results can be made available for the Interim Report and then finalised for the Final Report. This Task relied,

---

[4] "NATURALHY: Preparing for the Hydrogen Economy Using the Existing Natural Gas System as a Catalyst" European Commission Contract SES6/CT/2004/502261, 2004 – 2010.

initially, on the workbooks used in Task B which will account for total GHG emissions associated with the diversion of woody biomass from the production of materials that has been confirmed in Task A. Other published sources were used to determine the full displacement impacts by evaluating the total GHG emissions associated with the production, utilisation and end-of-life disposal of material uses of woody biomass. Such sources have already been identified and adopted in existing work for the Scottish Government.

Preliminary results were prepared for the Interim Report. These consisted of indicative ranges of net GHG emissions savings. As such, these results were not as detailed as those from Task B. This is because further, more detailed work would have been required to ensure they address properly all the necessary factors which influence relative carbon impacts. In particular, this related to the secondary displacement effect in which diverted woody biomass has to been replaced by other sources of wood or other materials. Particularly important considerations were the coverage of published sources and their transparency (or lack of it). The two key issues relate to functional units for material displacement and the details of end-of-life disposal.

Task D: Reporting Results

Initial results from Task B and preliminary results from Task C were presented in a brief Interim. The draft of the Interim Report was circulated amongst all relevant participants. The Final Report has taken into account of feedback obtained on the Interim Report as well as incorporating the final results from Tasks B and C. There is an accompanying PowerPoint presentation to the Final Report.

1.4 Report structure

A full understanding of the approach taken in this project and the results generated requires an consideration of the general extent, composition and ‘status’ of forests in the UK, and of the current contribution to wood consumption within the UK. It is also important to understand where wood is supplied from non-UK sources, so that the potential impacts of changes to management of UK forests which affect levels of production can be appreciated. A comprehensive description of the current status of UK forests is beyond the scope of this report, but a summary overview is provided in Section 2.

Before considering the full life cycle GHG emissions of different forestry and wood use options, it is important to understand the influence on GHG balances specifically due to carbon stock changes in forests, as these can make an important contribution to the ultimate result. Misconceptions about forest GHG balances are quite commonplace, therefore a clear statement on the subject is needed, in particular addressing how decisions about forest management (and changes to forest management) can cause changes to forest GHG balances. A detailed discussion of the relevant issues is therefore presented in Section 3.

Having set the scene in Sections 2 and 3, a description of the approach taken in this project to the estimation of GHG balances for specific wood utilisation options, as dependent of wood supplied from different types of forest resource relevant to current UK conditions, is given in Section 4. The key results of the project are presented in Section 5, which also includes a thorough discussion of how results have been derived. Section 6 elaborates on Section 5 with a complementary discussion of how inferences about carbon impacts may be drawn from the project results, while clarifying the appropriate application of different types of results for GHG emissions and carbon impacts. Conclusions and key messages are presented in Section 7. A Glossary is provided at the end of the report, which explains a small number of key technical terms referred to in discussions of forestry.

1.5 Representing 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 frequently expressed in units of equivalent CO_2. This is achieved by referring to quoted values of global warming potentials (GWP) 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 the IPCC Fourth Assessment Report (IPCC, 2007). Other studies referred to in this report may use different values of GWP for CH_4 and N_2O. However, it should be noted that the values of GWPs are treated as variables in the workbooks developed in this study and used to generate results for this report. Consequently, these values can be changed in the workbooks, if necessary, to produce results that are consistent with other studies. It should be pointed out that significant differences only arise when CH_4 and N_2O emissions make relative high contributions to total GHG emissions. This only occurs in very specific circumstances for CH_4 emissions and very rarely for N_2O emissions in relation to forest management, wood product and counterfactual manufacture and end-of-life disposal, woodfuel production and use, and energy counterfactual provision. This report also makes frequent reference to stocks of carbon in vegetation and soil, and to carbon sequestration in wood products. A stock of 1 tonne of carbon is equivalent to 44/12 = 3.67 tonnes of CO_2. Additionally, it is generally assumed that there is 50% carbon in 1 oven dry tonne of wood.

2. Brief overview of UK forest sector

A full understanding of the approach taken in this project and the results generated requires a consideration of the general extent, composition and 'status' of forests in the United Kingdom (UK), and of the current contribution to wood consumption within the UK. It is also important to understand where wood is supplied from non-UK sources, so that the potential impacts of changes to management of UK forests which affect levels of production can be appreciated. A comprehensive description of the current status of UK forests is beyond the scope of this report, but a summary overview is provided in this section.

2.1 Forestry in the UK

The total area of forest in the UK in 2011 is 3.1 million hectares, representing about 13% of the total land area of the UK. Of this total area, 1.4 million hectares (45%) is in Scotland, 1.3 million hectares (42%) is in England, 0.3 million hectares (10%) is in Wales and 0.1 million hectares (3%) is in Northern Ireland (Figure 2.1a). As shown in Figure 2.1b, approximately 56% of this total area is composed of conifer species with the remaining 44% being broadleaf species (Forestry Commission, 2011a).

The distribution of conifer and broadleaved species by individual country is shown in Figures 2.1c to 2.1f. The majority of the conifer area is found in Scotland and Northern England, whereas around two-thirds of the forest area in England is composed of broadleaf species. In Wales there is a more even mix between conifer and broadleaf area, whilst in Northern Ireland around three-quarters of forests are coniferous. Ownership is broken down by convention into Forestry Commission (FC) and (Northern Ireland) Forest Service owned forests and non-FC and Forest Service forests. The split of forest area is approximately 28 and 72% respectively (Forestry Commission, 2011a).

Historically the area of forest in the UK was very low (around 5% of total land area by the start of the 1900s). Planting increased from this point, particularly after the formation of the Forestry Commission in 1919. However, significant planting of forest areas did not occur until after the Second World War with two thirds of the current forest area in Great Britain being made up of trees planted since 1950. Although the rate of planting has fallen since around 1990, as already noted, forests currently constitute around 13% of the land area of the UK (Forestry Commission, 2011a).

The Government's approach to sustainable forest management in the UK is stated in the UK Forestry Standard (Forestry Commission, 2011b). This standard (and the series of supporting guidelines) outlines the context for forestry in the UK and defines standards and requirements for sustainable forest management, as well as giving the basis for regulation and monitoring, including national and international reporting.

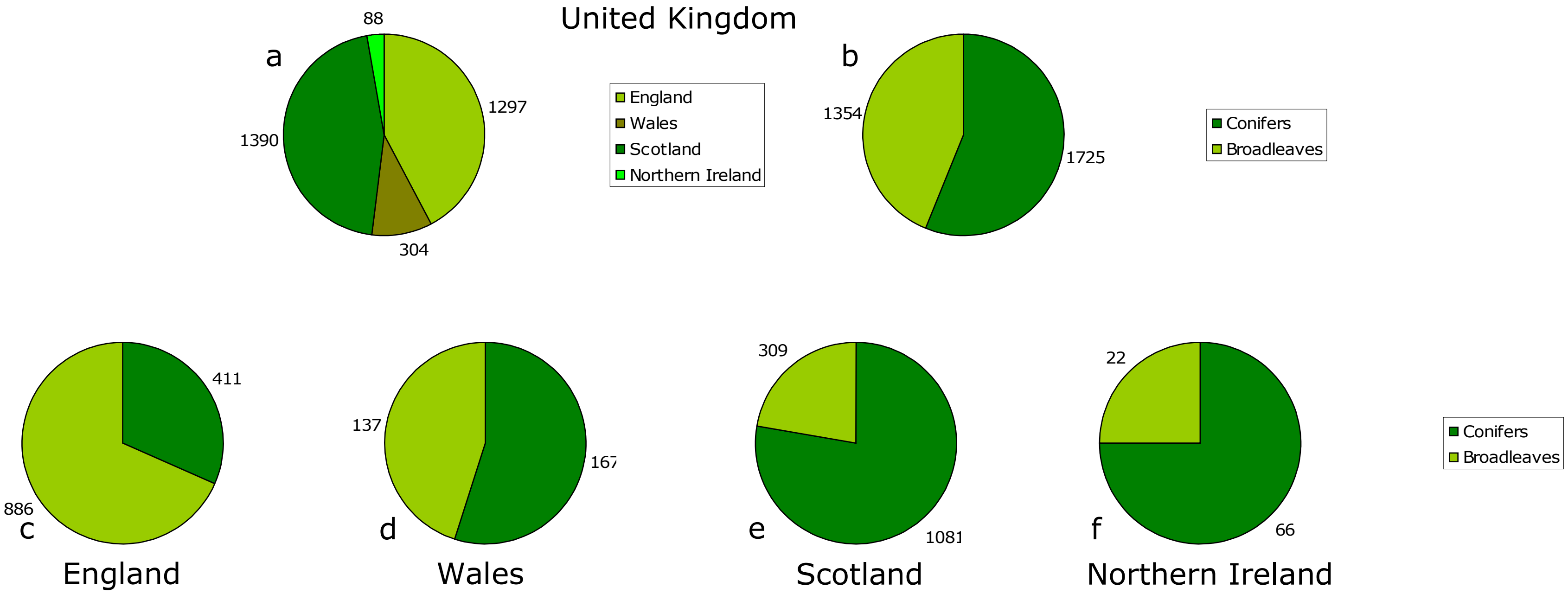


Figure 2.1. Distribution and composition of forest areas in the United Kingdom. Areas represented by sectors of pie charts are shown as labels, expressed in thousands of hectares. a: forest area by country; b: forest area by type; c: forest areas in England; d: forest areas in Wales; e: forest areas in Scotland; f: forest areas in Northern Ireland. Based on Forestry Commission (2011a).

The UK Forestry Standard considers independent certification of sustainable forest management and is the basis for the UK Woodland Assurance Scheme (UKWAS) which is used for voluntary independent certification in the UK. There are two main global forest certification schemes, the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC). The current area of certified forest in the UK is 1.3 million hectares. All FC forest is currently certified under the FSC.

2.2 Wood industries in the UK

A total of 9.6 million green tonnes of softwood (from conifer species) was produced in the UK in 2010. UK hardwood production (from broadleaf species) totalled 0.5 million green tonnes in 2010. A green tonne is a measure of the weight of freshly-felled timber. There will be a large amount of water in freshly-felled wood (around half of the total weight) which will evaporate as the wood dries out after felling. Approximately half of the softwood production for 2010 came from FC forests but only 13% of hardwood production was due to FC forests. Annual softwood production is currently predicted to increase to around 12 million green tonnes for the period 2017-2021 (Forestry Commission, 2011a).

Wood and wood fibre is used to produce many different products for a large number of end-uses. These products include solid timber for construction purposes, wood broken down into small pieces for wood-based panels such as particleboard and medium density fibreboard for use in furniture and for internal construction (e.g. as part of walls). Wood is also further broken down to individual fibres to produce pulp for the paper industry, as well as being used for fuel for producing heat and/or power. Figure 2.2 shows the percentage of delivered softwood and hardwood going to the main sectors of the wood-using industries in the UK for the year 2010.

An individual tree will often be cut into different sections with different markets and industries using each section, in part due of the tapering shape of tree stems. In general the roundwood or timber in the lower (and larger diameter) part of a stem will go to sawmilling and the timber in the upper part of the stem will go to the wood-based panel and pulp (paper) industries. However, this general rule is sensitive to the interaction between the market values for each wood product.

The majority of delivered UK softwood material is used by the sawmilling industry to produce sawnwood for uses such construction, for example for floor joists in houses. There are around 189 sawmills in the UK, 19 of which produced more than 50 thousand cubic metres of sawn timber in 2010 (Forestry Commission, 2011a).

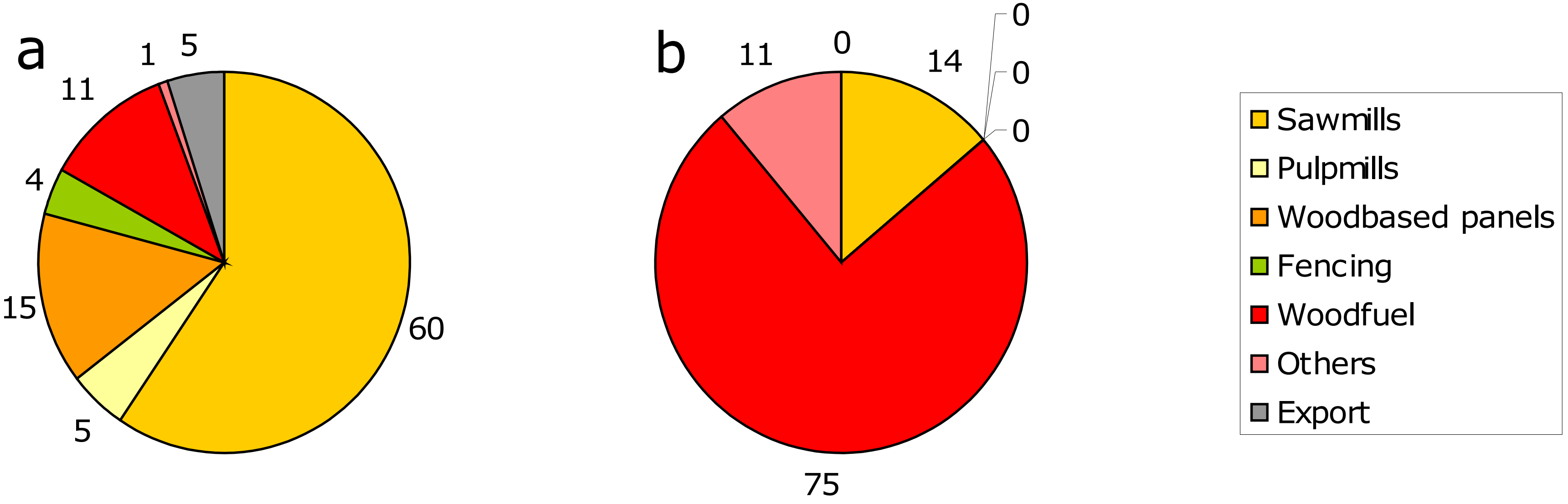


Figure 2.2. Deliveries of UK-grown wood to the different sectors of the wood-using industries in 2010, expressed as percentages of green tonnes. a: softwoods; b: hardwoods. The value reported under 'Others' for hardwoods includes hardwood round fencing and export. Based on Forestry Commission (2011a).

The next largest consumption of delivered UK-grown softwood is in the production of wood-based panels, for example particleboard, oriented strand board (OSB) and medium density fibreboard (MDF). These panel products are known as engineered wood products because the wood is reconstituted through a variety of processes to manufacture products with specific characteristics such as density and bending strength, tailoring them for different end uses such as flooring, furniture manufacture and worktops. Plywood can be grouped with other wood-based panels, however there are currently no plywood mills in the UK. There are fewer than 10 wood-based panel mills in the UK using UK-grown softwood roundwood.

The third largest sector using UK softwood in 2010 was the woodfuel sector. Woodfuel used for bioenergy has only been included in the softwood delivery statistics since 2007, when woodfuel constituted only around 2% of total deliveries of UK-grown softwood.

The fourth largest sector using UK softwood in 2010 was the pulp and paper sector. As of 2006 there were only two pulp and paper mills in the UK using UK-grown softwood roundwood directly; however some other mills use recycled wood material and other non-roundwood sources to produce pulp in the UK.

The breakdown of consumption of UK hardwood deliveries by the different wood-using sectors is quite different from that for softwood. Although appreciable amounts of pulp and paper and wood-based panels were previously produced using UK-grown hardwood, in 2010, the two main consuming sectors were woodfuel and sawmills. Nearly three-quarters of hardwood deliveries went to the woodfuel sector in 2010. The increase in hardwood woodfuel deliveries is similar to that for softwood, including a significant increase since 2005 (when the only hardwood pulp and paper mill closed).

2.3 UK forestry in an international context

Forest management

As described in Section 2.1, the area of forest in the UK has increased significantly in the last century from around 5% to around 13% of total land area. Because of this the characteristics of the UK forest estate and how it is managed differ from those in many other countries. As much of the forest area in the UK was planted, rather than regenerated naturally, large areas of forest are characterised by stands of trees of single species which are even-aged, i.e. the trees in a particular area were all planted or regenerated at the same time. Most conifer forests and a significant proportion of broadleaf forests in the UK are usually managed for production of timber as a primary objective, and the simplest way to achieve this is to use a “clearfell” management system in which a forest is created as a series of even aged stands which are clearfelled and then replanted or regenerated. The timing of clearfelling and regeneration of individual stands is controlled to ensure maintenance of forest cover. This is different from many (especially continental European) countries where forests have developed over long periods of time and the main objective may be to ensure a sustained and relatively low level of timber production whilst maintaining the canopy cover of the forest. This 'continuous cover' management system has often been used to ensure continuity of habitat for species for hunting or for protection of hillsides to reduce the risk of avalanches in mountainous regions. The area of forest in the UK managed according to 'continuous cover' principles is increasing, and is encouraged at least implicitly by UKWAS. It has been an explicit policy objective in Wales for over a decade.

In addition to forests managed for production, there are significant areas of broadleaf forest in England which are sometimes referred to as neglected. Typically, these broadleaf forest stands were planted from the 1940s onwards on private land in response to incentives. The stands may have been subject to active management in early years (e.g. thinning operations may have been carried out) but subsequently interest in such forest areas declined and active management was abandoned. As a consequence, many of these forest areas are now 'overstocked', i.e. trees within the stands are undergoing intense competition, some trees are becoming suppressed and dying, the forest canopy is completely closed, suppressing understorey vegetation. The lack of thinning will also have resulted in the presence of many poor quality trees (e.g. in terms of health, vigour and stem form) within these stands.

Currently there is interest in encouraging the restoration of management in neglected broadleaf forest stands in England, with the objectives of improving stand quality, encouraging understory vegetation and habitat diversity, supporting rural development and (potentially as part of forest harvesting/thinning), increasing the potential supply of woodfuel and timber.

Trade

The wood-using sectors consuming UK-grown wood have been discussed in Section 2.2 and Figure 2.2 shows that only a small proportion of UK softwood production and essentially no UK-grown hardwood are exported. However, in 2010, the UK imported around 81% of the wood material consumed internally, i.e. only around 1 cubic metre of wood material in 5 consumed in the UK was sourced from the UK.

There are a number of difficulties in interpreting apparent consumption and trade of wood materials in the UK. Firstly, apparent consumption is calculated as UK production plus imports minus exports, however, some of the material exported may have actually come from imports within a given reporting year. Secondly, because of the different forms in which wood is consumed, the unit of measurement needs to allow for this. In UK reporting this issue is dealt with by using the metric of 'wood raw material equivalent' (WRME). Forestry Statistics 2011 (Forestry Commission 2011a) lists the conversion factors to permit conversion of different units of wood products into equivalent units of WRME. For example, one tonne of writing and printing paper is equivalent to 3.5 cubic metres WRME. These issues need to be understood and appreciated when considering international trade in wood and wood products.

Apparent consumption by wood product type

The apparent consumption of wood, by product, in the UK for 2010 is shown in Table 2.3.

Table 2.3 Apparent consumption of wood products* in the UK in 2010

Product	UK production	Imports	Exports	Apparent consumption
Sawnwood (thousands m^3)				
Softwood	3053	5230	164	8120
Hardwood	48	469	31	485
Woodbased panels (thousands m^3)				
Veneer sheets	0	28	2	26
Plywood	0	1264	75	1190
Particleboard	2594	649	278	2965
Fibreboard	776	760	155	1381
Paper and paperboard (thousand tonnes)				
Newsprint	1195	806	297	1704
Other graphic papers	442	3562	355	3649
Sanitary & household papers	729	195	38	886
Packaging materials	1640	2208	507	3341
Other paper & paperboard	294	55	24	325

Based on Forestry Commission (2011a). * Excludes woodfuel, round fencing and roundwood and intermediate products (e.g sawmill products) to avoid double counting.

It can be seen that UK imported more softwood sawnwood than was produced domestically in 2010. Relatively large amounts of plywood were also imported, in part due to there being no domestic production. The majority of certain paper products were also imported, particularly graphic (e.g. writing) paper and paper materials for packaging (some of which will come from recycled sources).

Origin of imported wood products

The country/region of origin of wood material will be influenced by the type of wood product, for example (and most obviously) whether the country produces the particular product. The source of wood material will also vary annually due to changes in the markets, and relative and absolute values for each wood product type. Figure 2.3 shows the percentage of each wood product imported in 2010 by the country of origin. For example, in 2010, more than 60% of the total softwood sawnwood imported into the UK came from just three countries, i.e. Sweden (43%), Latvia (14%) and Finland (12%). Imports of softwood sawnwood, particleboard, fibreboard and paper and paperboard in 2010 came mainly from within the EU. Imports of sawn hardwood, plywood and wood pulp in 2010 came mainly from outside the EU.

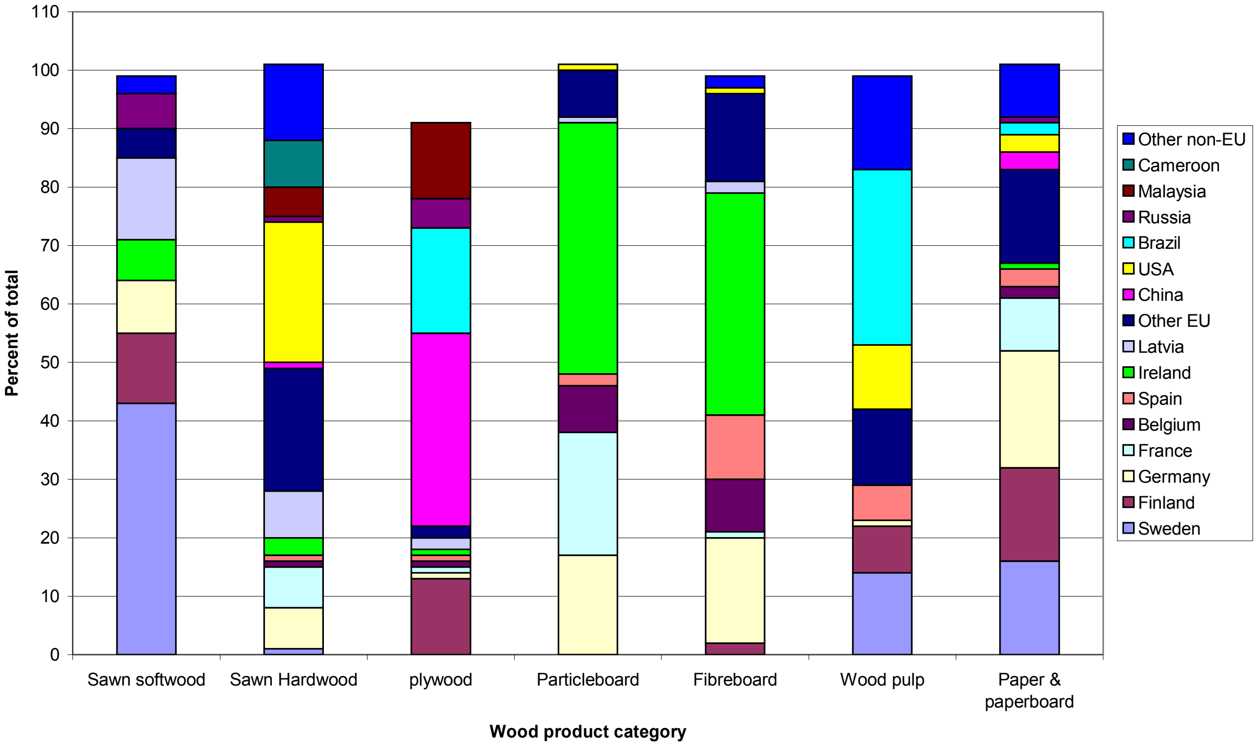


Figure 2.3. Bar chart showing the country of origin by percentage of total imports of each wood product into the UK in 2010. Based on Forestry Commission (2011a). Some categories exceed 100% due to rounding.

2.4 The 'conventional mix' of UK wood production

Later in this report reference is made to the concept of a 'conventional mix' when referring to wood production from UK forests and patterns of utilisation of harvested wood. This term needs to be defined in the context of this report.

Earlier in this section a description is given of the current situation in UK forestry, in particular a description of wood industries in the UK is given in Section 2.2 while Section 2.3 considers UK forestry in an international context.

Section 2.2 explains that softwood production from UK forests in 2010 accounted for 95% of total forest production (9.6 million green tonnes for softwoods, 0.5 million green tonnes for hardwoods). Figure 2.2 in the same section shows deliveries of UK-grown wood to the different sectors of the wood using industries in 2010, expressed as percentages of green tonnes. In the case of softwoods (wood harvested from conifers), ignoring the categories of "Exports" and "Other", deliveries to "Sawmills" and "Wood-based panels" accounts for 80% of UK-grown wood consumption. For hardwoods (wood harvested from broadleaves), "Woodfuel" alone accounts for 75% of UK-grown wood consumption.

For softwoods and hardwoods combined, sawmills, wood-based panel mills and woodfuel account for the bulk of wood consumption derived from UK forests, at 57%, 14% and 14%, respectively. Fencing production and pulpmills represent smaller but still important consumers.

It is important to clarify the quantity and relative mix of sawn timber products actually manufactured by sawmills. For wood-based panels, it is also important to clarify the relative mix of different panel products, notably "particleboard-type" products as opposed "fibre-type" products.

Table 2.3 in Section 2.3 shows apparent consumption of wood products in the UK for the year 2010, based on timber trade statistics. It should be noted that the product definitions and units of measurement are not directly comparable with the values for total softwood and hardwood production in the UK reported earlier, or with the values in Figure 2.2. Table 2.3 reports sawn timber production from UK forests (softwood and hardwood combined) of about 3.1 million cubic metres. This value is for sawn timber produced by sawmills, not consumption of raw sawlogs by sawmills. More detailed statistics reported by the Forestry Commission (not explicitly referred to in this section) suggest that, of this sawn timber, approximately one third is used as construction timber, one third as fencing, and one third for packaging and pallets. For wood-based panels produced from UK wood, particleboard is the dominant product (about 2.6 million cubic metres or about 77% of panel production) with fibreboard products accounting for a smaller but important contribution (about 0.8 million cubic metres or about 23% of panel production). It should be noted that comparison of statistics in Table 2.3 with the results reported earlier for total UK wood production and in Figure 2.2 suggest significant consumption of sawmill co-products within the wood-based panel sector.

On the basis of the above interpretation of the results reported in this section, the term ‘conventional mix’ for production based on wood harvested from UK forests is defined as a combination of sawn timber (consisting of construction timber, fencing, pallets and packaging), particleboard and woodfuel as the main products, with smaller but important levels production of fibreboard (e.g. MDF) and paper. This definition applies most closely to coniferous forests under current conditions; in the case of broadleaf forests (which represent the minority contribution in terms of volume of wood currently produced in the UK), almost no wood produced from broadleaf forests is utilised for particleboard or panel products (see Figure 2.2, Section 2). Rather it is estimated that the bulk of broadleaf (i.e. hardwood) production is utilised for sawn timber, woodfuel and (round) fencing.

It should also be noted that the discussion earlier in this section points out that the share of wood biomass being consumed for woodfuel has increased significantly in recent years (although it is also true that total wood supply has been increasing over the same period, and also that reporting of woodfuel has become more comprehensive in recent years).

2.5 Conclusions on UK forestry

UK forests cover 3.1 million hectares, constituting 13% of the total land area. Forest cover is greatest in Scotland and Wales (18% and 15% of land area respectively), and lowest in Northern Ireland (6%). Forests constitute 10% of the land area in England. Although the proportions of UK forest area composed of coniferous and broadleaf species are roughly equal, the area of conifers is predominantly in Scotland and Northern Ireland whilst the area of broadleaf forests is greater in England. The proportions of coniferous and broadleaf forest areas in Wales are roughly equal. Broadly speaking, the area of conifer forest has expanded significantly in recent times, particularly since 1950, and the majority of coniferous stands are already under management for production. A significant area of broadleaf forest area is also under management for production but there is also a significant area of ‘neglected’ broadleaf forest. The precise areas of broadleaf forest under management or in ‘neglect’ are unknown.

Wood production from UK forests currently constitutes approximately 20% of wood consumption in the UK and is forecast to increase over the next 20 years, at least in terms of available timber. UK production is important in supporting major wood processing industries, notably sawmills and wood-based panel mills. Broadleaf forest areas supply significant amounts of woodfuel and woodfuel production is increasing rapidly from both coniferous and broadleaf sources.

Typically, but very broadly, currently non-UK softwood sawn timber is supplied by Fennoscandia and the Baltic States, hardwood sawn timber is supplied from outside the

EU (notably the USA), whilst wood-based panels are supplied from within the EU, particularly from Eire. Paper is supplied from a range of EU countries.

For the purposes of this study the term ‘conventional mix’ for production based on wood harvested from UK forests is defined as a combination of sawn timber (consisting of construction timber, fencing, pallets and packaging), particleboard and woodfuel as the main products, with smaller but important levels production of fibreboard (e.g. MDF) and paper. This definition applies most closely to coniferous forests under current conditions; in the case of broadleaf forests (which represent the minority contribution in terms of volume of wood currently produced in the UK), it is estimated that the bulk of production is utilised for sawn timber, woodfuel and (round) fencing.

These conclusions need to be borne in mind when considering the details of the methodology adopted in this project and when interpreting the results.

3. Fundamentals of forest GHG balances

Before considering the full life cycle GHG emissions of different forestry and wood use options, it is important to understand the influence on GHG emissions balances specifically due to carbon stock changes in forests, as these can make an important contribution to the ultimate result. There has also been some debate in recent times about the impacts of harvesting wood for energy use on forest carbon stocks, and whether these negate the benefits due to utilising woodfuel in place of fossil fuels (see for example Birdlife International, 2010; Croezen *et al.*, 2010; Oneill and Lippke, 2010; Zanchi *et al.*, 2010; Bates *et al.*, 2011; Lippke *et al*., 2011; McKechnie *et al.*, 2011; Sedjo, 2011; EEA Scientific Committee[5]; Haberl *et al*., 2012). Whilst this debate has raised some valid issues and concerns, it has also led to some confusion concerning the impacts of harvesting and utilising wood on GHG emissions balances, and has also caused the general perception that the GHG impacts associated with bioenergy, timber and wood fibre utilisation are complex and uncertain.

Whilst the GHG emissions balances of forest management and wood utilisation systems may not be simple and immediately obvious, they are nevertheless relatively easy to understand in terms of the influence of a few key factors, notably:

- Soil carbon (generally depending on soil type)
- Scale (e.g. for individual stands or for whole populations of stands)
- Tree species and growth rate (notably distinctions between conifer and broadleaf forests in a UK context)
- How forests have been managed historically and whether and how this management is changed.

This section describes the fundamentals of forest carbon stock dynamics, illustrating the potential impacts of these factors.

3.1 Understanding forest GHG balances

As illustrated in Figure 3.1, the complete carbon balance of a forest 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). It is important to stress that both emissions and removals of carbon may occur in forests. Estimating these emissions and removals requires an understanding of how natural processes affecting greenhouse gas dynamics *interact in response* to the interventions of humans.

The main GHG concerned in forest GHG balances is carbon dioxide (CO_2) from carbon stock changes. Other GHGs include nitrous oxide (N_2O) from, for example, nitrogen inputs (when fertilising forest land, currently not common practice in the UK), and

---

[5] http://www.eea.europa.eu/about-us/governance/scientific-committee/sc-opinions/opinions-on-scientific-issues/sc-opinion-on-greenhouse-gas

methane (CH_4) which is involved in the GHG balances of forests growing on highly organic soils such as peatlands.

Forest GHG dynamics involve ‘removals (or ‘sinks’) as well as emissions (or ‘sources’) of GHGs. Vegetation and soil dynamics can result in the uptake and sequestration of carbon from the atmosphere (e.g. as vegetation grows or organic matter accumulates in the soil) as well as the release of carbon to the atmosphere (e.g. when vegetation respires, decays or burns, or when microbes break down soil organic matter, see Figure 3.1). Vegetation and soil carbon dynamics thus involve a balance between emissions and removals, depending on specific circumstances, and the net result can be an emission to the atmosphere or removal from it.

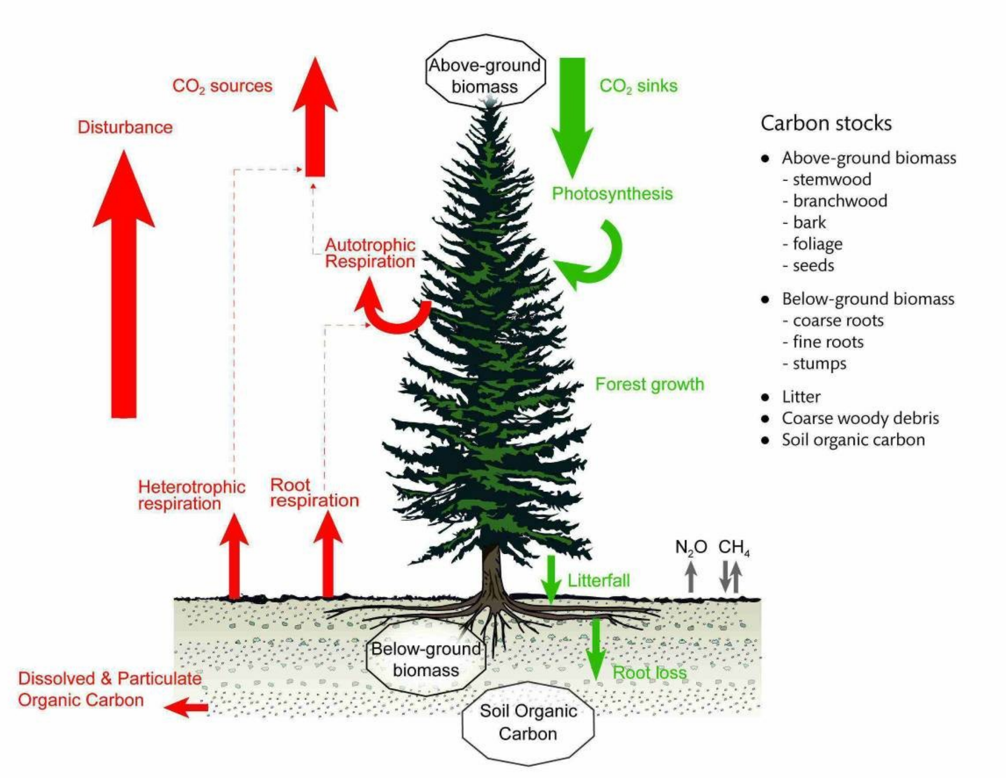


Figure 3.1. Illustration of the carbon pools and naturally occurring GHG dynamics associated with forests. After Morison *et al.* (2012).

Human management of forests can have a strong influence on the pattern of emissions and removals although the associated impacts may follow complex time-courses and be difficult to predict. Managed forests are part of a dynamic system and so these processes are never entirely under human control. Forest systems are susceptible to natural disturbances e.g. forest fires, storms, drought and pest outbreaks, which can lead to substantial release of carbon to the atmosphere or reduced sequestration from the atmosphere.

Understanding forest carbon balances as stock changes

The range of carbon pools involved in forest GHG balances and the types of issues raised in the preceding discussion can lead to the impression that forest GHG balances are difficult to understand and quantify, particularly in terms of the impacts of changes to forest management. However, as has been pointed out by Maclaren (2000), for most purposes forest carbon or GHG balances can be understood and modelled more simply by considering changes in carbon stocks. Maclaren (*Op cit.*) uses the example of the carbon budget of a pig (Figure 3.2) to illustrate this point. Suppose it was necessary to know whether a pig was a carbon sink or carbon source. The question itself suggests the need to focus on the flows of carbon into and out of the pig – all these flows (e.g. associated with the intake of food, excretion of dung, inhalation and exhalation etc.) would need to be monitored and measured, requiring complex apparatus and the chances of error. Alternatively, the pig's carbon balance can be estimated by monitoring its change in carbon stock over time, i.e. by weighing the pig and seeing how its weight changes over time. This approach applies equally to forest carbon balances – forest GHG emissions and removals are directly associated with changes in vegetation and soil carbon stocks on land. Net emissions or removals may thus be estimated by quantifying (i.e. modelling) net changes in vegetation and soil carbon stocks. This approach has been adopted extensively in the discussion in this section and in general in the methodology developed in this project.

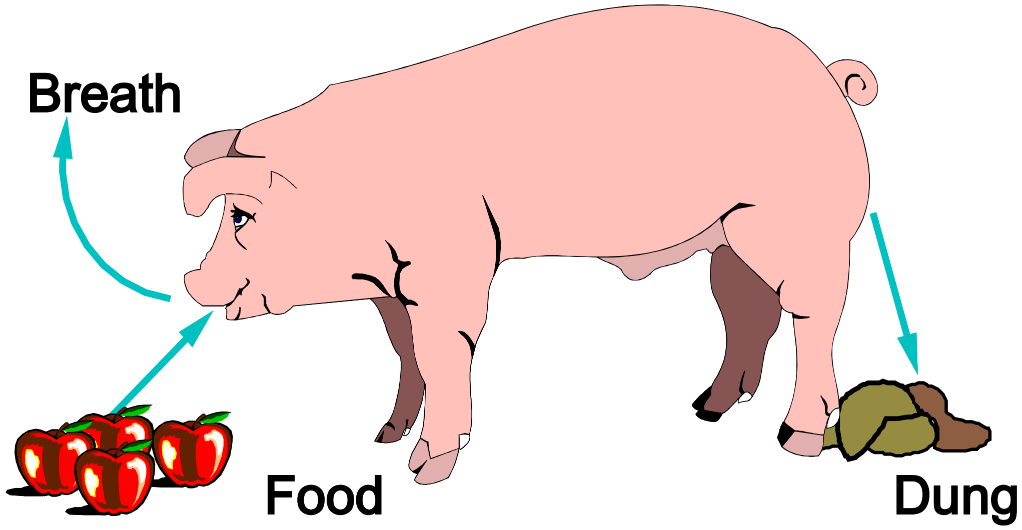


Figure 3.2. The carbon balance of a pig can be worked out by estimating all the flows of carbon into and out of the pig, or by working out how the weight of the pig (its carbon stock) is changing. After Maclaren (2000).

3.2 Carbon dynamics in individual stands

Figure 3.3 illustrates how carbon stocks in vegetation on an area of land (such as arable land, grassland or scrubland) can change if the land is established with a new stand of trees, by planting or by encouraging natural regeneration. Before the trees are established, the existing vegetation carbon stocks might typically comprise no more than 20 tonnes carbon per hectare (tC ha^{-1}). The small initial loss of carbon stocks due to removal of existing vegetation is not shown in Figure 3.3. The results in Figure 3.3 were produced using the Forest Research CARBINE forest carbon accounting and large-scale scenario analysis model (Thompson and Matthews, 1989; Matthews, 1994, 1996; Matthews and Broadmeadow, 2009) and represent the carbon stock changes due to planting a 1 hectare stand of Sitka spruce with a mean growth rate (over about 50 to 60 years) of 12 cubic metres stem volume per hectare per year (m^3 ha^{-1} yr^{-1}), as commonly observed for Sitka spruce stands in the UK. The stand is assumed to be managed without any harvesting (either through thinning or clearfelling), effectively being allowed to develop into a 'wilderness forest'.

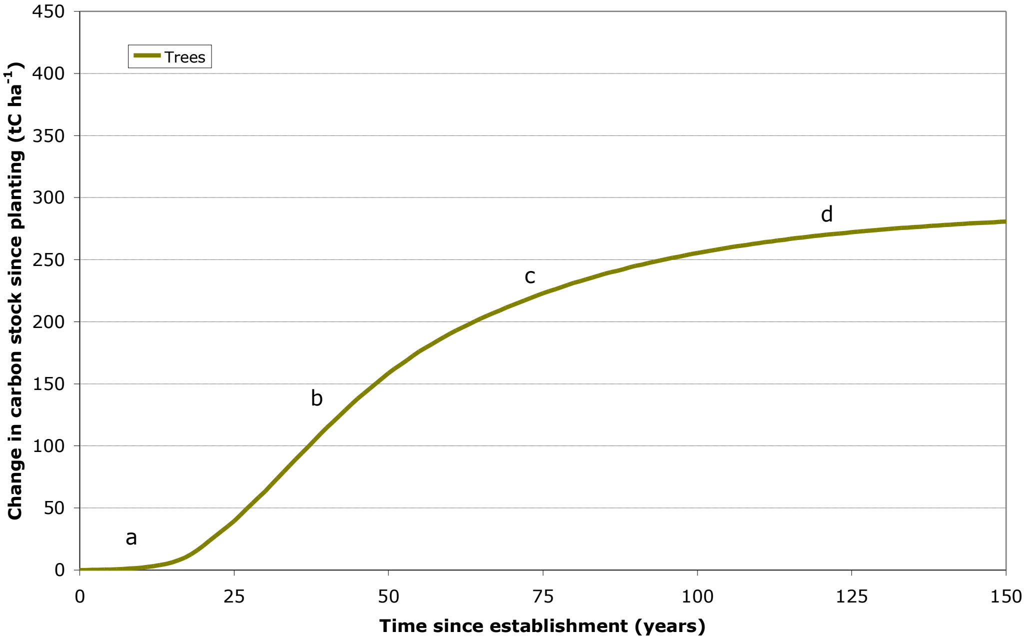


Figure 3.3. An illustration of the change in vegetation (tree) carbon stocks that can occur on an area of land by planting a stand of conifer trees. a: establishment phase; b: full-vigour phase; c: mature phase; d: long-term equilibrium phase.

As discussed in Matthews and Robertson (2006), four phases can be identified in the development of tree carbon stocks over time:

1. The establishment phase (denoted 'a' in Figure 3.3)
2. The full-vigour phase (denoted 'b' in Figure 3.3)
3. The mature phase (denoted 'c' in Figure 3.3) and
4. The long-term equilibrium phase (denoted 'd' in Figure 3.3).

The rate of carbon sequestration in the biomass of trees (the slope of the curve in Figure 3.3) can be significant in the full-vigour phase, for example a maximum rate of about 5 tonnes carbon per hectare per year (tC ha^{-1} yr^{-1}) is observed in Figure 3.3. However, after about a century, rates of carbon sequestration have declined to less than 1 tC ha^{-1} yr^{-1}, due to the phenomenon of 'saturation' as discussed in Matthews and Robertson (2006), Matthews *et al*. (2012) and Morison *et al*. (2012). As is clear from Figure 3.3, the ultimate result of planting 1 hectare of land with trees is not the continuous sequestration of carbon in trees, rather there is a one-off change (increase) in vegetation carbon stocks of between 250 and 300 tC ha^{-1}, which takes place over a number of decades. It is this property of forest stand carbon dynamics that has led to the conclusion that planting trees to sequester carbon and 'offset' GHG emissions due to other activities (such as burning fossil fuels) only 'buys time', (i.e. the sequestration eventually stops at some point in the future and it is then necessary to address the challenge of reducing the GHG emissions occurring due to other activities directly).

Influence of disturbance events on tree carbon stocks

It is very important to note that the relatively large carbon stock accumulated in the forest stand after about 100 years, as indicated in the example in Figure 3.3, involves the assumption that the stand is not subject to significant incidents of natural disturbance such as due to fire, storms or disease. Such disturbance events disrupt forest carbon stocks with the result that the long-term levels of carbon stock actually observed will be smaller than suggested by Figure 3.3 (see for example Figure 2 in Matthews and Robertson, 2006). In case where major disturbance occurs regularly, the long-term equilibrium carbon stock may be less than half of the level that would be achieved in the absence of disturbance.

Generally there will be greater risks of natural disturbance associated with higher carbon stocks – large carbon stocks represent more of a fuel source for fire than small carbon stocks, big trees are more prone to storm damage than small trees, ,whilst older trees may be more susceptible to attack by certain diseases.

Contributions to carbon stocks due to litter and soil

Creating a stand of trees on an area of land, by planting or by encouraging natural regeneration, will have an effect on carbon stocks in litter (dead vegetation) and soil as well as vegetation. Carbon stocks in litter are generally quite small, but soil carbon stocks can typically vary between 15 and 350 tC ha^{-1} (and considerably greater when considering peatlands), depending on the soil type but also critically on how the land has been managed before tree establishment. Small soil carbon stocks are generally associated with arable land due to regular soil cultivation, whilst large carbon stocks are generally associated with grassland and scrubland where soil disturbance is less frequent or less intensive.

As discussed in West (2011), soils in the UK have different thicknesses of organic matter overlying a mineral layer or rock. The upper organic layer, containing plant and animal residues at various stages of decomposition, contains a high proportion of the carbon in the soil while there can be appreciable quantities of organic matter associated with surface and sub-surface mineral layers.

Forests as a land use tend to have high levels of soil organic carbon which increase over time, with high inputs of decomposable material from large woody material, foliage and fine roots. However, disturbance of the soil, such as can occur when preparing ground for forest creation, managing the forest for timber or during a windthrow event, can lead to greenhouse gas emissions (Read *et al*., 2009). This is also true of soil drainage. Research suggests that following initial carbon losses from site preparation, the soil carbon will continue to accumulate over the next few decades at least (Read *et al*., 2009). Site preparation techniques vary widely in the amount of soil disturbed and associated emissions of soil carbon.

Typically, therefore, when changes are introduced to land use or to management within an existing land use, there will be associated changes in the equilibrium levels of soil carbon stocks. These changes occur with an exponential time constant of about 30 years (A. Hastings, Aberdeen University, personal communication) although accumulation of carbon in soil may continue at a much lower rate over longer timescales. Each combination of soil type, land use type, vegetation cover and vegetation management regime will have an associated characteristic equilibrium carbon stock. The loss or accumulation of soil carbon in response to changes in land use or land management is thus ultimately determined by the initial soil carbon stock and the final equilibrium soil carbon stock.

Figures 3.4 and 3.5 show examples of contrasting examples of the contributions due to litter and primarily soil to the development of carbon stocks over time on an area of land following the establishment of a stand of trees. The results in Figures 3.4 and 3.5 were produced using the Forest Research CARBINE forest carbon accounting and large-scale scenario analysis model based on the same example Sitka spruce stand as considered in Figure 3.3. The examples in Figures 3.4 and 3.5 are both based on the establishment of trees on a ‘gley’ soil type, which has a clay texture and is typical of upland soils found in Britain (where conifer trees have tended to be planted over the last century). Previous land management has been assumed to be as rough pasture, unmanaged grassland or heathland.

Rough pasture or unmanaged grassland will have an equilibrium soil organic matter content of between 100 and 150 tC ha^{-1}, whereas the equilibrium soil carbon stock under a typical conifer forest will be in the range 150 to possibly as much as 300 tC ha^{-1} under UK conditions, the details depending on rainfall, temperature and soil texture. (A.

Hastings, Aberdeen University, personal communication). Gley soils have relatively fine soil texture and are poorly drained and will tend to accumulate large amounts of carbon quite quickly. However if a gley soil is drained as part of tree establishment the rate of soil carbon accumulation will be slower, thus there is a trade off between accumulation of soil carbon and the accumulation of carbon in forest biomass as part of tree growth.

Many soils in the UK have a relatively high organic matter content (sometimes in the form of a 'histic' layer of peat typically less than 50 cm in depth), and Figures 3.4 and 3.5 illustrate tree establishment on gley soils with low and high initial organic matter content respectively. (These roughly equate to the soil classes of 'mineral' and 'organo-mineral' as referred to in West, 2011.) As in Figure 3.3, the results in Figure 3.4 and 3.5 express the *change* in carbon stocks (relative to the pre-existing levels) as a result of tree establishment, so that initial carbon stocks in soil and any dead vegetation are not shown (instead, the values in the graph start at zero). This is to avoid the possibility of 'overstating' the magnitude of carbon stocks (or carbon sequestration) attributable to the action of forest creation[6]. As illustrated in Figures 3.4 and 3.5, the contributions to carbon sequestration and carbon stocks due to forest litter are notable but generally relatively modest in magnitude. Conversely, soil carbon makes a large contribution to overall forest carbon stocks, sometimes greater than that due to trees. When establishing new forest stands, soil carbon can make a significant contribution to carbon sequestration in some circumstances (Figure 3.4), whilst in other circumstances there may be GHG emissions from soil as a consequence of tree establishment which can counteract the sequestration in trees and litter (Figure 3.5).

As discussed above, many factors determine whether soil carbon stocks go up or down initially following tree establishment and as already noted one important factor is the initial level of soil carbon stocks before tree establishment (high initial stocks tending to be reduced on tree establishment). Another important factor is the intensity with which land is cultivated as part of tree establishment (more intense cultivation tending to involve greater soil disturbance and consequent emissions). Emissions due to losses from soil carbon stocks can be so large that they can exceed sequestration in trees and litter for a number of years following tree establishment. In the example in Figure 3.5, it takes about 20 years for the cumulative sequestration due to the growth of trees to overtake losses of carbon in the soil. Subsequently, as trees become more established, soil carbon stocks can recover and even exceed the stocks that were present before tree establishment (as is the case in Figure 3.5).

---

[6] For completeness it may be noted that the initial soil carbon stocks estimated by the CARBINE model are about 85 tC ha^{-1} for the simulation in Figure 3.4 and about 200 tC ha^{-1} for the simulation in Figure 3.5.

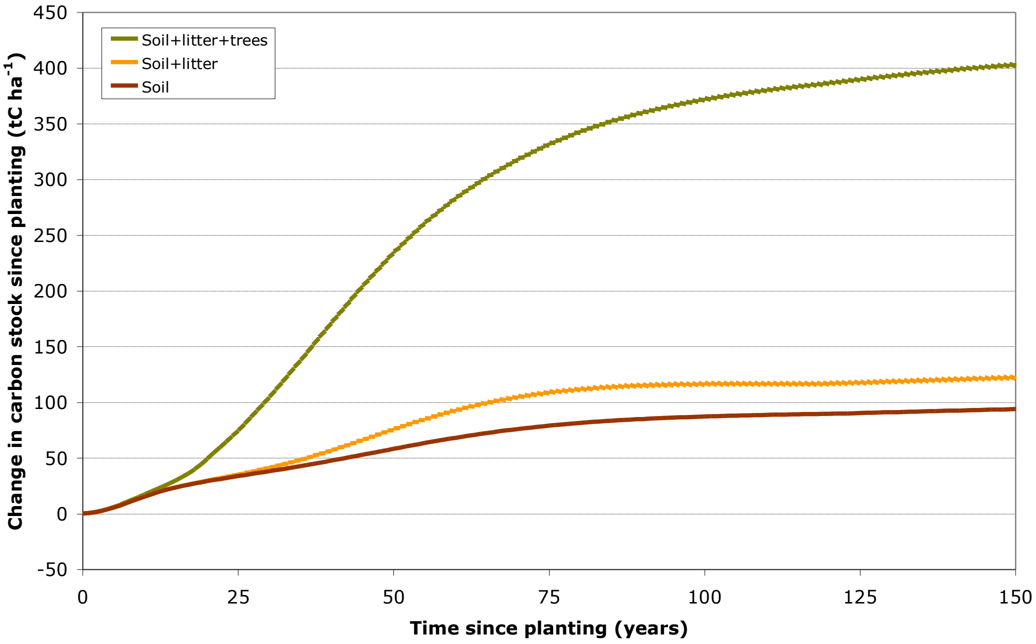


Figure 3.4. An illustration of the change in tree, litter and soil carbon stocks that can occur on an area of land by planting a stand of conifer trees. The example is for a 'typical' upland soil type such as a 'gley', with relatively low levels of soil organic matter before tree establishment.

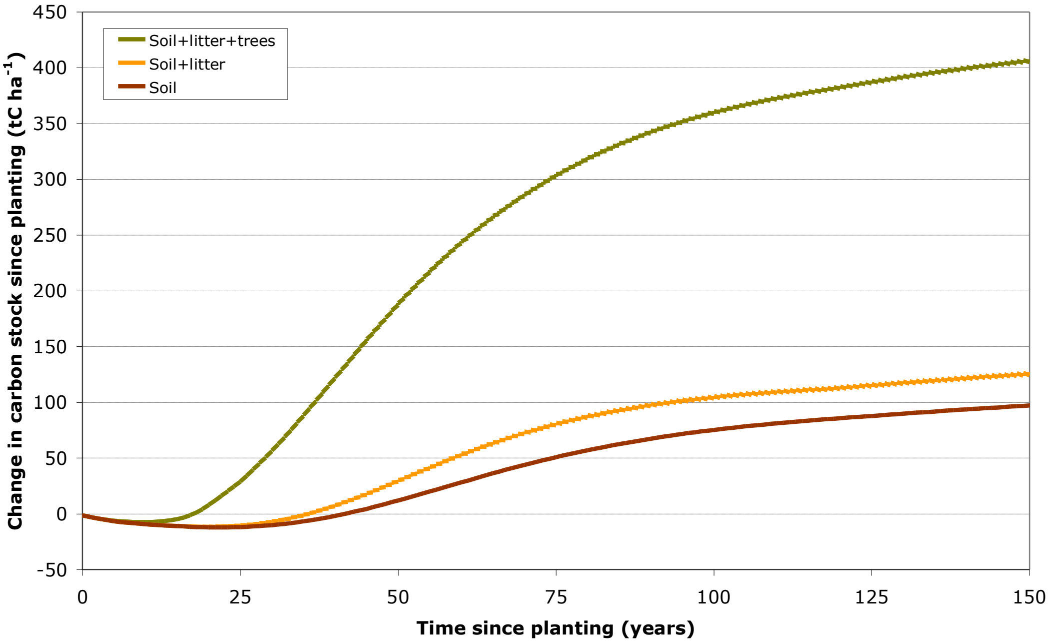


Figure 3.5. An illustration of the change in tree, litter and soil carbon stocks that can occur on an area of land by planting a stand of conifer trees. The example is for a 'typical' upland soil type such as a 'gley', with relatively high levels of soil organic matter before tree establishment.

However, in some cases where initial soil carbon stocks are very high (such as on peatlands where soil carbon stocks can easily be in excess of 500 tC ha^{-1}), there will never be a complete recovery of the initial level of soil carbon. (For this reason, the Forestry Commission's Woodland Carbon Code supports tree planting on 'mineral' and 'organo-mineral' soils, but not on 'organic' soils, see West, 2011).

Regardless of the specific contribution due to soil carbon, and the smaller contribution due to litter, Figures 3.4 and 3.5 show how the impact of tree establishment on overall stocks in trees, litter and soil is similar to that observed whether considering just tree carbon stocks (Figure 3.3), i.e. there is a one-off change (usually an increase) in the combined carbon stocks in vegetation, litter and soil which occurs over a number of decades. The long-term equilibrium carbon stock ultimately attained depends primarily on:

- The species of tree grown on the land
- The initial carbon stock in the soil
- The soil type (particularly in terms of texture – sand, loam or clay)
- Climatic conditions (particularly temperature and rainfall which will affect for example tree growth and respiration processes in the soil)
- How the trees are managed (e.g. for conservation of carbon stocks, as described above, or for production of timber or biomass, as discussed below).

Impacts of harvesting on stand carbon stocks

Figure 3.6 illustrates an example of the impact of harvesting on tree carbon stocks. The results in Figure 3.6 were produced using the CARBINE model and are based on the same type of forest stand as shown in Figure 3.3, except that the stand is assumed to be clearfelled every 56 years. (In other words, the stand is being managed according to a management regime involving no thinning and with clearfelling and replanting on a rotation of 56 years.) The curve in Figure 3.6 shows how carbon stocks in trees accumulate from time of planting up to the end of the rotation, when clearfelling effectively reduces carbon stocks (in living trees) to zero. The carbon stocks then accumulate again following replanting with the result that, over repeated rotations, carbon stocks in living trees effectively 'cycle' between zero and nearly 180 tC ha^{-1} every 56 years.

Figure 3.7 shows an equivalent result to Figure 3.6 but including the contributions due to litter and soil carbon. (Assumptions about litter and soil carbon are the same as in Figure 3.4, except that account has been taken of periodic clearfelling when producing the results in Figure 3.7.) As in previous figures, the results in Figure 3.7 express the *change* in carbon stocks as a result of tree establishment, so that initial carbon stocks in soil and any dead vegetation are not shown and values in the graph start at zero.

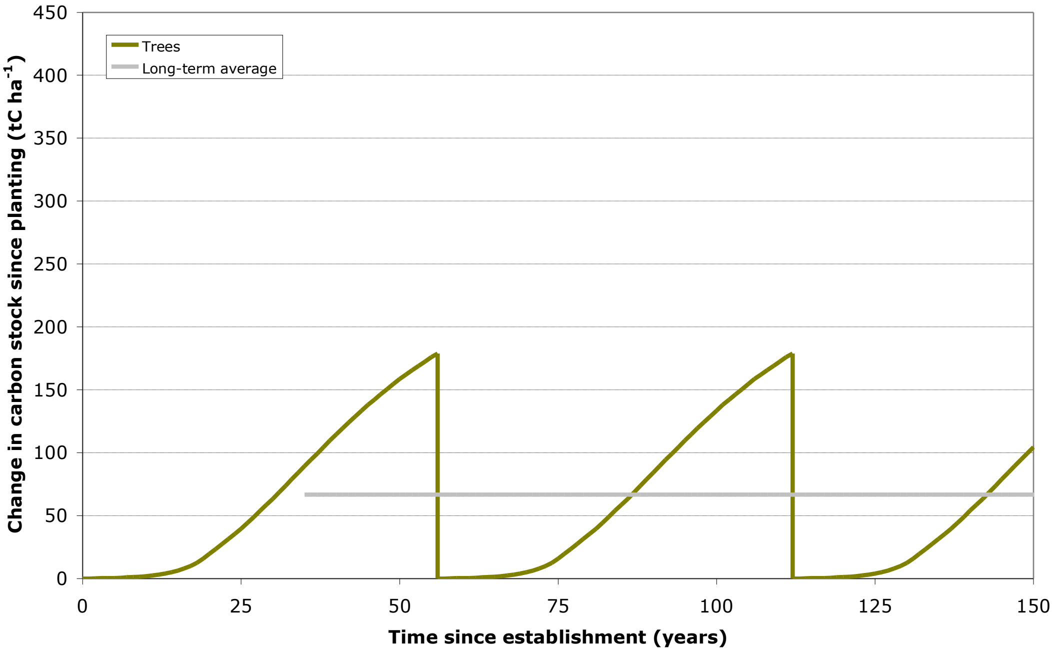


Figure 3.6. An illustration of the change in tree carbon stocks that can occur on an area of land by planting a stand of conifer trees, managed for production by clearfelling every 56 years. The grey line indicates the long-term average carbon stock (i.e. the mean carbon stock in trees over a 56 year rotation).

In the example in Figure 3.7, clearfelling is observed to result in a short-term reduction in soil carbon stocks, followed by a lower rate of carbon sequestration in soil compared to the case involving no clearfelling (Figure 3.4). Figure 3.7 also illustrates how carbon stocks in litter can be greatly increased by tree harvesting (when material from felled trees is left on site), but the litter decays relatively quickly, making only a short-term contribution to overall carbon stocks. As demonstrated by Figures 3.6 and 3.7, the impact of stand clearfelling on the development of carbon stocks, and on the development of combined carbon stocks in trees, litter and soil, is similar, but with the biggest single impact clearly on tree carbon stocks, with secondary impacts on litter and soil carbon.

The results in Figures 3.6 and 3.7 have two interpretations. On the one hand, it may be observed that harvesting clearly leads to significant reductions in tree carbon stocks (sometimes referred to as a 'carbon debt'); furthermore, it may take 50 years or more for tree carbon stocks to recover following harvesting. On the other hand, it may be observed that, if long-term average carbon stocks are considered (e.g. as marked by the grey line in Figure 3.6), it is still the case that carbon stocks have increased when compared with the levels observed before the stand of trees was established. The second interpretation is particularly pertinent when considering carbon stocks at a larger scale, such as in a forest made up of many stands of different tree ages, as discussed in Section 3.3.

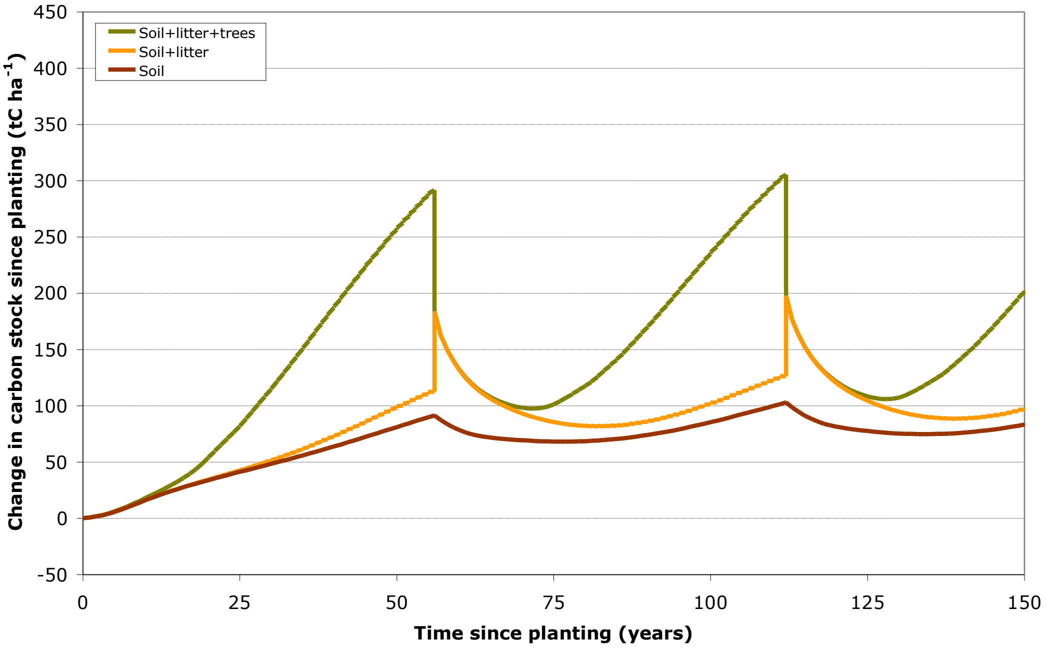


Figure 3.7. An illustration of the change in tree, litter and soil carbon stocks that can occur on an area of land by planting a stand of conifer trees, managed for production by clearfelling every 56 years.

3.3 Carbon dynamics in populations of stands

Although harvesting the trees forming an individual stand must lead to a loss of carbon stocks, not all stands forming a forest are felled at the same time. Hence, at the scale of a forest or landscape, losses of carbon stocks due to harvesting may be counterbalanced by sequestration in the remaining stands which are still growing, as is the case if the complete forest is managed on the basis of sustainable yield. (Sustainable yield is one of the fundamental principles underlying sustainable forest management.) Figures 3.8-3.12 illustrate how a forest might be created and then harvested according to sustainable yield principles, also showing the overall consequences for forest carbon stocks and carbon sequestration. (These are based heavily on earlier illustrations presented by Piers Maclaren, see for example Maclaren, 1996, 2000.) Figures 3.8-3.12 describe how a 5,600 hectare forest might be created by establishing a collection of even aged stands at a rate of 100 hectares per year over a period of 56 years. The stands are assumed to be formed of Sitka spruce trees with a mean growth rate (over about 50 to 60 years) of 12 m^3 stem volume ha^{-1} yr^{-1}. Harvesting is assumed to involve clearfelling of stands on a rotation of 56 years (i.e. after 56 years of growth). For the sake of simplicity, the stands are assumed to be managed according to a regime that does not involve any thinning prior to clearfelling. Whilst this example is theoretical, the strong parallel with the real-world conifer forest estate in the UK (and the manner in which much of it has been created) should be noted. Again, for simplicity, the results quoted in Figures 3.8-3.12

are for carbon stocks in trees only, i.e. no account is taken of carbon stocks in litter and soil.

Figure 3.8 shows the situation after 1 year. Just one hundred hectares of new Sitka spruces stands have been established and, after just one year of growth, levels of carbon stocks and carbon sequestration are negligible. After 10 years (Figure 3.9), 1,000 hectares of new Sitka spruce stands have been established, ranging in age from 1 to 10 years. These are still relatively young stands and both carbon stocks (0.7 thousand tonnes, or 0.7 ktC) and carbon sequestration (0.2 thousand tonnes per year, or 0.2 ktC yr^{-1}) are modest. After 25 years (Figure 3.10), 2,500 hectares of new Sitka spruce stands have been established, ranging in age from 1 to 25 years. The oldest stands are now in the full-vigour phase of tree growth. Carbon stocks have reached 25 ktC and the rate of carbon sequestration has risen to 3.9 ktC yr^{-1}. After 50 years (Figure 3.11), 5,000 hectares of new Sitka spruce stands have been established, ranging in age from 1 to 50 years. Many stands are now in the full-vigour phase of tree growth, with the oldest in the mature phase. Carbon stocks have reached 283 ktC and the rate of carbon sequestration has risen to 15.9 ktC yr^{-1}.

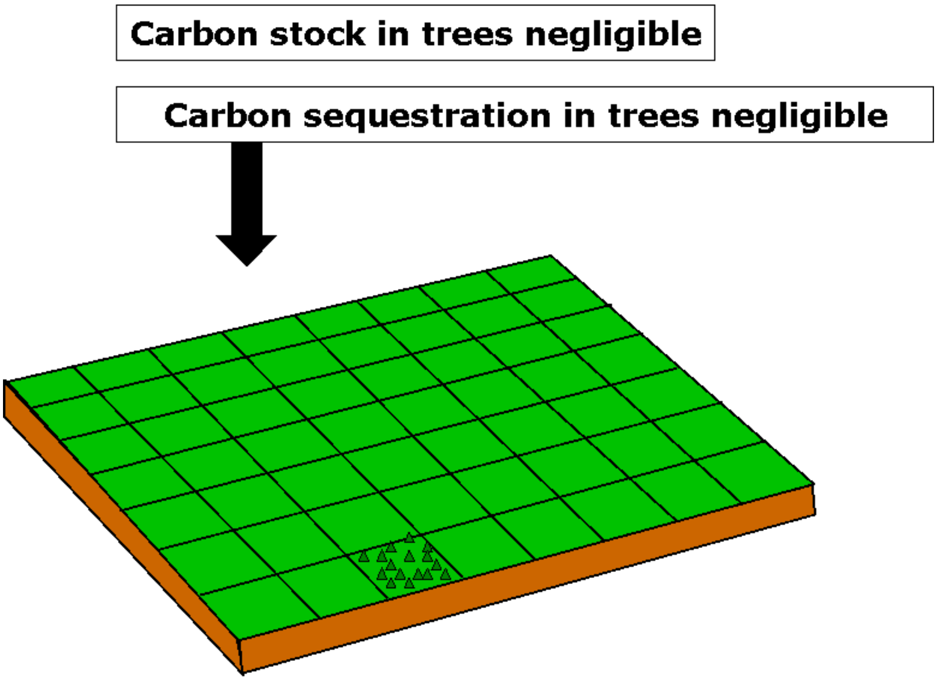


Figure 3.8. Creating a 5,600 hectare forest from even aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 1 year. (Figure based on the ideas of Piers Maclaren, see Maclaren, 1996, 2000.)

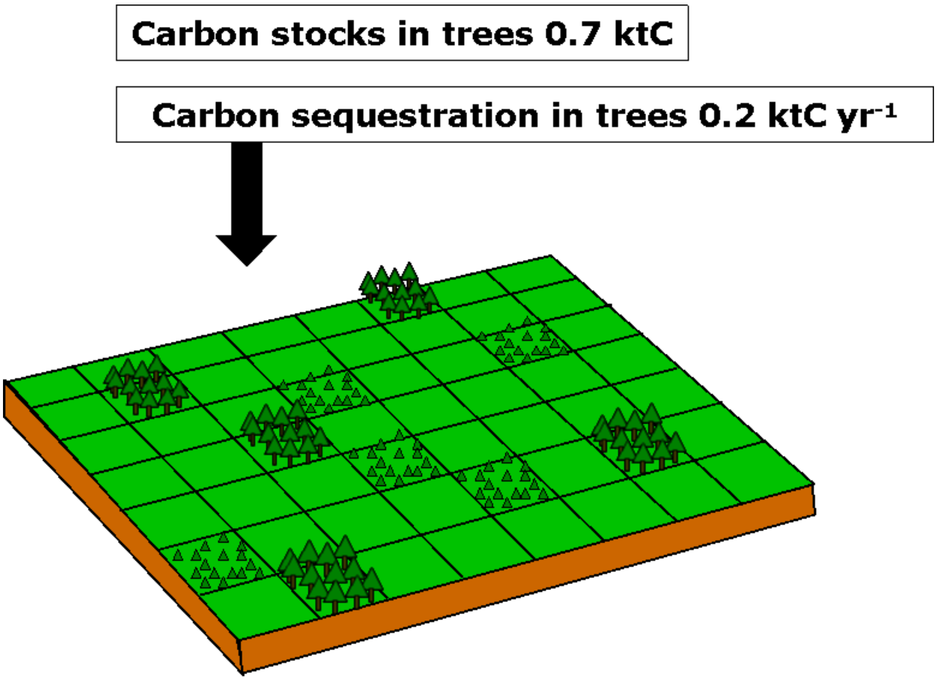


Figure 3.9. Creating a 5,600 hectare forest from even aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 10 years. (Figure based on the ideas of Piers Maclaren, see Maclaren, 1996, 2000.)

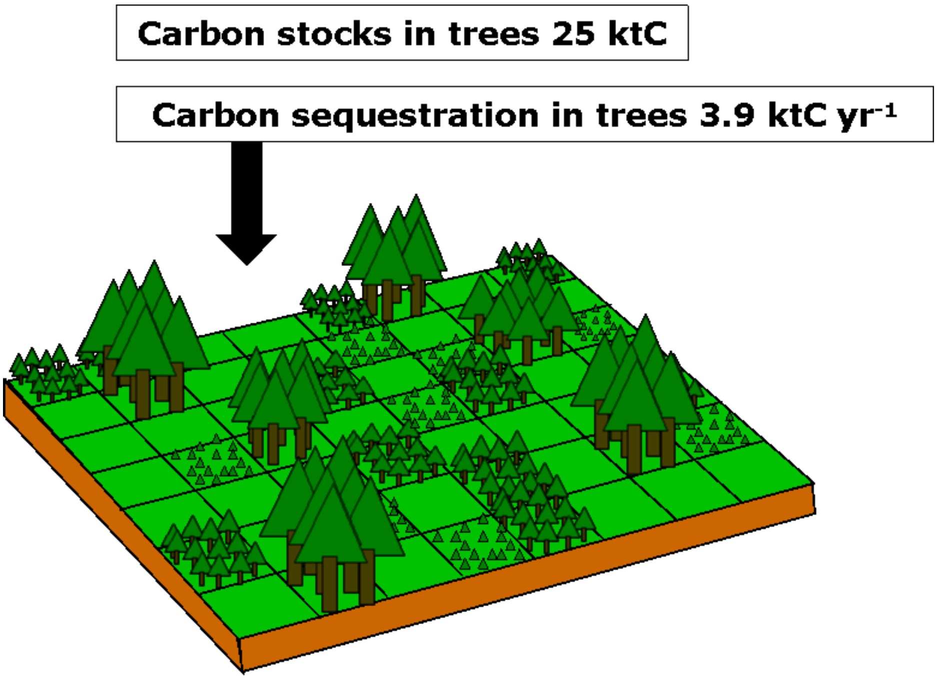


Figure 3.10. Creating a 5,600 hectare forest from even aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 25 years. (Figure based on the ideas of Piers Maclaren, see Maclaren, 1996, 2000.)

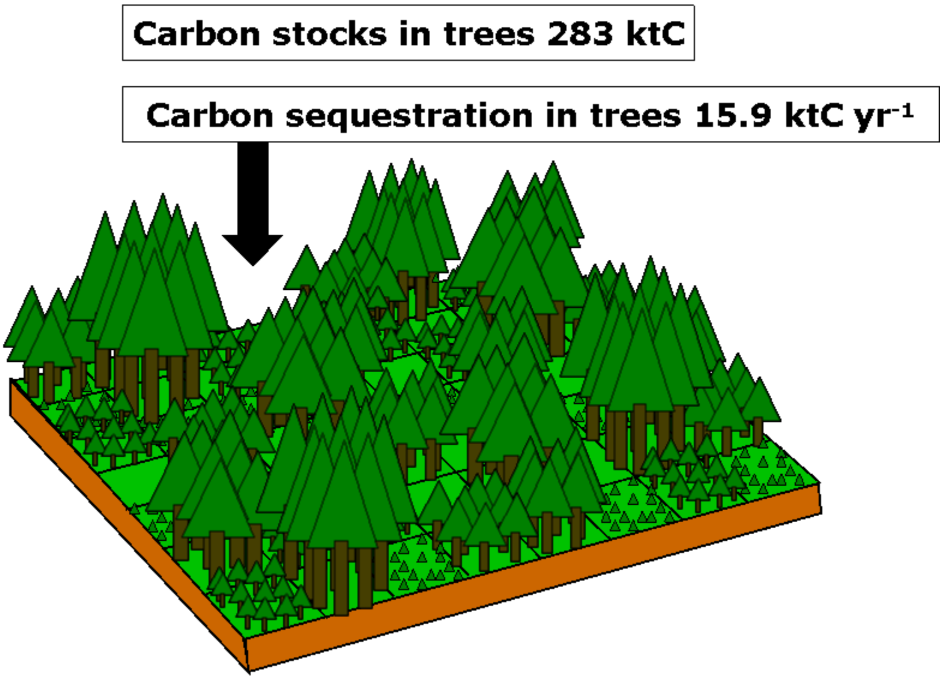


Figure 3.11. Creating a 5,600 hectare forest from even aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 50 years. (Figure based on the ideas of Piers Maclaren, see Maclaren, 1996, 2000.)

Figure 3.12 shows the situation after 56 years. By this stage, the complete area of 5,600 hectares has been established with Sitka spruce stands, ranging in age from 1 to 56 years. Carbon stocks have reached 368 ktC and the rate of carbon sequestration has risen to 17.9 ktC yr^{-1}. However, the oldest stands, planted 56 years previously, have now reached the age of rotation and are clearfelled. Most of the forest biomass (11.4 ktC) is harvested and transported to be processed into useful products, with the remainder, formed of offcuts, some branchwood, stumps and roots (6.5 ktC) left to decay and oxidise in the forest. Crucially, the losses of carbon from the forest due to the harvesting of the stands (11.4 + 6.5 = 17.9 ktC) are exactly matched by the sequestration of carbon across the entire forest. If the clearfelled stands are re-established in the same year (by planting or natural regeneration), a forest is created in which there are equal areas of stands of each age class over 56 year rotation. This property of the forest (i.e. equal areas of stands of each age class) ensures that removals of carbon stocks during harvesting of stands continue to be compensated for carbon sequestration across the forest. (This is further illustrated by the very simple example in Box 3.1)

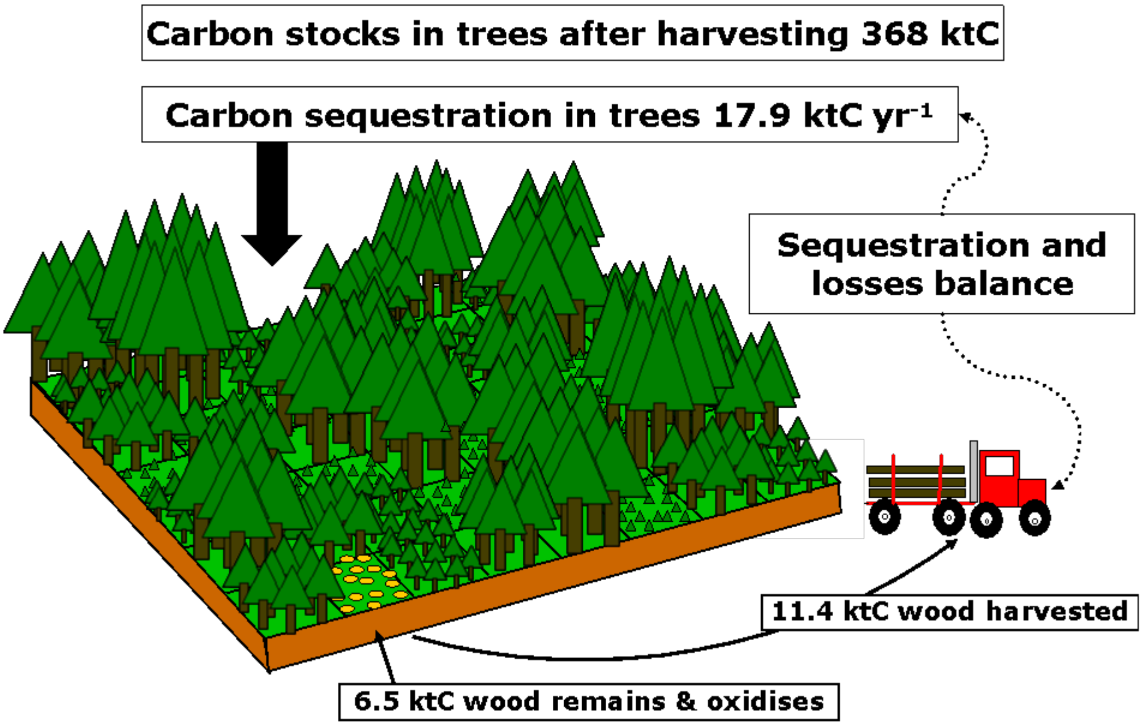


Figure 3.12. Creating a 5,600 hectare forest from even aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 56 years. (Figure based on the ideas of Piers Maclaren.)

The development over time of the carbon stocks in the trees comprising the stands described in Figures 3.8-3.12 is shown in Figure 3.13. The accumulation of carbon stocks becomes more rapid over a 40 year period, as more forest areas establish and older stands enter the full-vigour phase of growth. The accumulation of carbon stocks is then sustained up to year 56, at which point the first stands to be established (and therefore the oldest stands) are clearfelled. At this point there is a modest reduction in carbon stocks relative to the overall level in the forest, which is recovered within one year by the continued growth of the remaining forest stands. In year 57 another cohort of stands is clearfelled but the growth of the remaining forest stands continues to counterbalance losses of carbon stocks within one year. Provided forest stands are re-established as soon as they are clearfelled, *overall carbon stocks in the forest are not reduced (i.e. no 'carbon debt' is incurred)*, rather *a constant carbon stock is maintained* over time.

Creating a 5,600 ha forest as described in the preceding example will of course also have impacts on litter and soil carbon stocks, and an example of such impacts is illustrated in Figure 3.14. (Assumptions about litter and soil carbon are based on the same scenario as in Figure 3.7.) In this example, carbon stocks continue to accumulate in the soil after the constant carbon stock in trees observed in Figure 3.14 has been reached (i.e. during the second and subsequent rotations of forest stands), however, comments made in Section 3.2 concerning the potential variability of soil carbon responses to tree establishment also apply here.

Box 3.1 How losses of carbon stocks due to harvesting of stands can be counterbalanced exactly by forest sequestration

The purpose of this example is to illustrate how losses of carbon stocks due to harvesting of stands can be counterbalanced exactly by forest sequestration, when a forest is created consisting of equal areas of even aged stands for each age class up to the stand rotation age.

Consider an extremely simple forest system, consisting of just two stands of one hectare each, denoted Stand A and Stand B. These two stands are planted in successive years and are managed on a rotation of just two years. There are thus equal areas of forest stands in each age class up to the rotation age (when the stands are clearfelled).

Suppose a particular type of tree, when grown in a stand, sequesters 4 tonnes of carbon per hectare (4 tC ha^{-1}) in the first year of growth and a further 3 tC ha^{-1} in the second year of growth. At the end of one year of growth, carbon stocks in the stand will be equal to the carbon sequestered in that year, i.e. 4 tC ha^{-1}. At the end of two years of growth, carbon stocks in the stand will be equal to the sum of the carbon sequester in the first and second years, i.e. 4 + 3 = 7 tC ha^{-1}.

At the beginning of year 1, Stand A is established with trees of the type described above. Carbon stocks are negligible.

At the end of year 1 (beginning of year 2), Stand A has sequestered 4 tC and carbon stocks are also 4 tC. At this time, Stand B is established with trees of the type described earlier. Carbon stocks are negligible, so total carbon stocks in the forest (due to Stand A) are 4 tC.

At the end of year 2 (beginning of year 3), Stand A has sequestered a further 3 tC and carbon stocks rise to 7 tC. Stand B has sequestered 4 tC and carbon stocks are also 4 tC. Total carbon sequestration for the forest is thus 3 + 4 = 7 tC and total carbon stocks in the forest are 7 + 4 = 11 tC. Stand A is now felled, causing a loss of carbon stocks of 7 tC, equal to the sequestration for the whole forest for that year. Stand A is immediately re-established (by planting or natural regeneration).

At the end of year 3 (beginning of year 4), Stand B has sequestered a further 3 tC and carbon stocks rise to 7 tC. Stand A (re-established) has sequestered 4 tC and carbon stocks are also 4 tC. Total carbon sequestration for the forest is thus 3 + 4 = 7 tC and total carbon stocks in the forest are 7 + 4 = 11 tC. Stand B is now felled, causing a loss of carbon stocks of 7 tC, equal to the sequestration for the whole forest for that year. Stand B is immediately re-established (by planting or natural regeneration).

At the end of year 3 (beginning of year 4), Stand A (re-established) has sequestered a further 3 tC and carbon stocks rise to 7 tC. Stand B (re-established) has sequestered 4 tC and carbon stocks are also 4 tC. Total carbon sequestration for the forest is thus 3 + 4 = 7 tC and total carbon stocks in the forest are 7 + 4 = 11 tC. Stand A is now felled, causing a loss of carbon stocks of 7 tC, equal to the sequestration for the whole forest for that year. Stand A is immediately re-established (by planting or natural regeneration).

At the end of year 4 (beginning of year 5), Stand B (re-established) has sequestered a further 3 tC and carbon stocks rise to 7 tC. Stand A (re-established) has sequestered 4 tC and carbon stocks are also 4 tC. Total carbon sequestration for the forest is thus 3 + 4 = 7 tC and total carbon stocks in the forest are 7 + 4 = 11 tC. Stand B is now felled, causing a loss of carbon stocks of 7 tC, equal to the sequestration for the whole forest for that year. Stand B is immediately re-established (by planting or natural regeneration).

In principle, the preceding two steps can be repeated indefinitely (subject to the maintenance of site productivity).

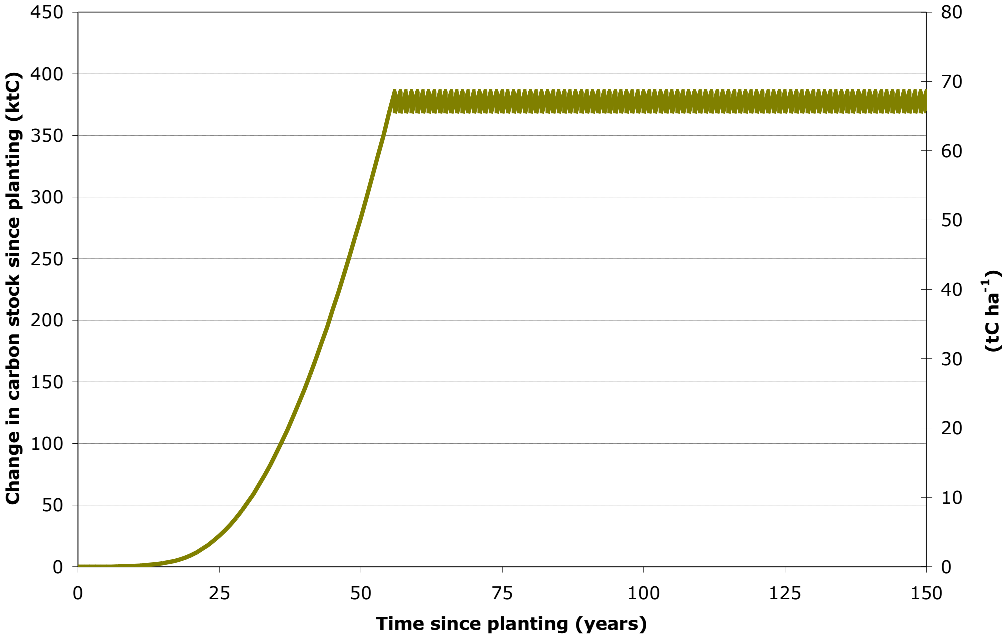


Figure 3.13. Development of carbon stocks over time in trees forming the stands of the 5,600 hectare forest created from even aged Sitka spruce stands over 56 years, as illustrated in Figures 3.8-3.12. The left-hand y-axis shows the change in total carbon stocks for the 5,600 ha area, the right-hand y-axis shows the change in carbon stocks for the area expressed in tC ha^{-1}.

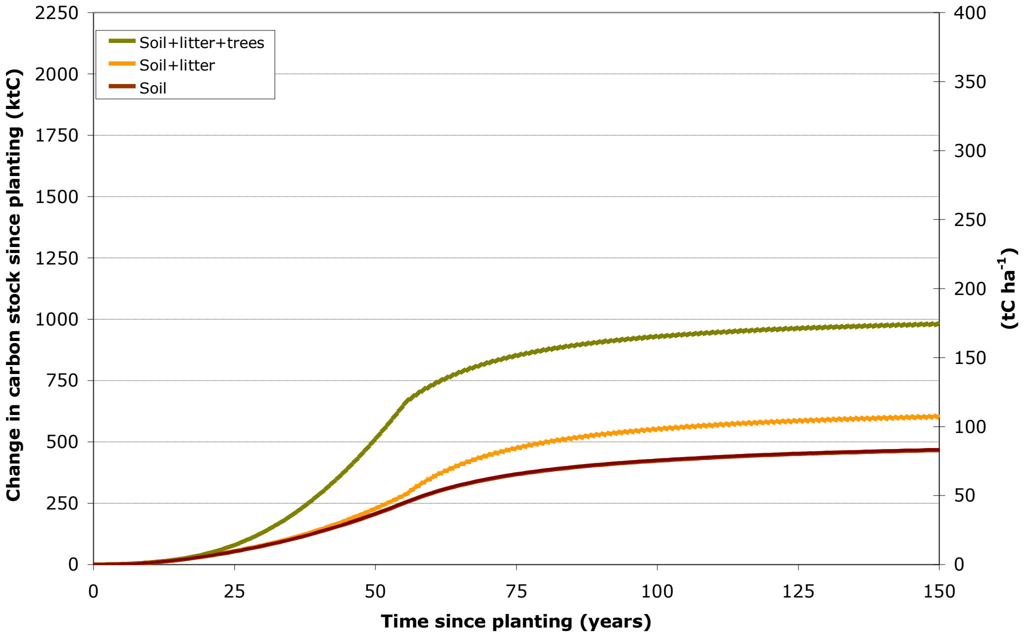


Figure 3.14. Development of carbon stocks over time in trees, litter and soil forming the stands of the 5,600 hectare forest created from even aged Sitka spruce stands over 56 years, as illustrated in Figures 3.8-3.12. The left-hand y-axis shows the change in total carbon stocks for the 5,600 ha area, the right-hand y-axis shows the change in carbon stocks for the area expressed in tC ha^{-1}.

It remains the case that managing a newly created forest for timber and biomass production through harvesting will result in lower carbon stocks and lower levels of carbon sequestration, when compared to the option of establishing the trees but not harvesting them, i.e. leaving the trees undisturbed to accumulate carbon on site, as illustrated in Figure 3.15. Carbon stocks in the undisturbed case (Figure 3.15) are about twice those in the case involving harvesting (Figure 3.14). However, comments made in Section 3.2 about the influence of natural disturbance events on forest carbon stocks also apply here.

It may be noted that carbon stocks removed from the forest during harvesting are not necessarily lost to the atmosphere immediately, but may be retained in harvested wood products for some time, in some cases many decades. The CARBINE model can be used to estimate the carbon stocks retained in wood products harvested from the stands forming the 5,600 hectare forest illustrated in Figures 3.8-3.14. The estimated additional contribution due to carbon in harvested wood products, shown in Figure 3.16, is significant but not enough to match the carbon stocks in the undisturbed case (Figure 3.15).

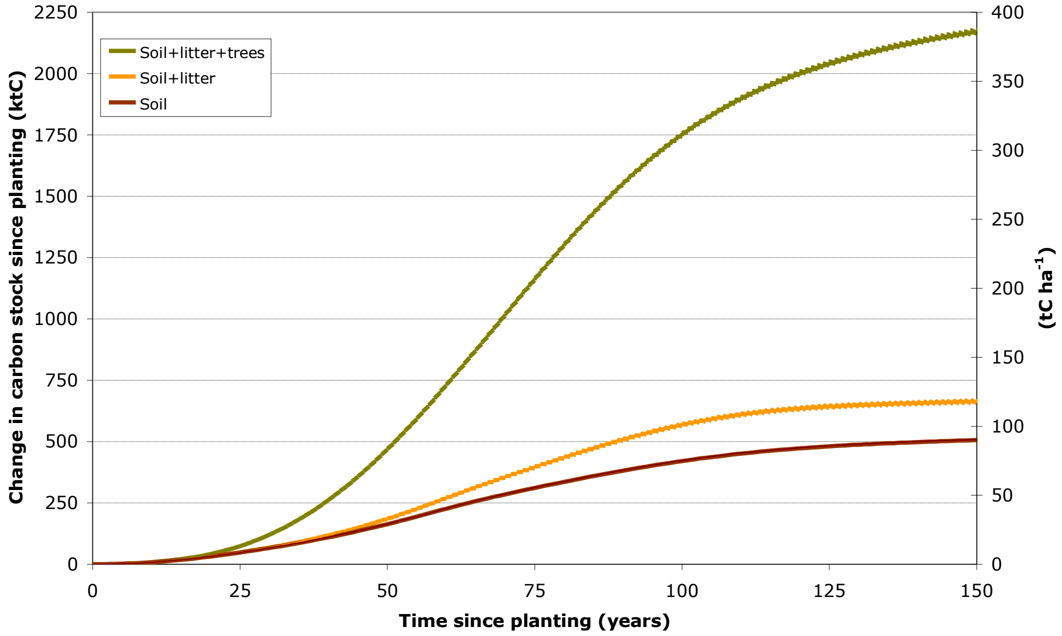


Figure 3.15. Development of carbon stocks over time in trees, litter and soil forming the stands of the 5,600 hectare forest created from even aged Sitka spruce stands over 56 years, managed without thinning or clearfelling in order to accumulate carbon. The left-hand y-axis shows the change in total carbon stocks for the 5,600 ha area, the right-hand y-axis shows the change in carbon stocks for the area expressed in tC ha^{-1}.

Higher carbon stocks and levels of carbon sequestration will often be observed in 'undisturbed' forests when compared with forests managed for production of timber and biomass, although at the same time management for conservation of forest carbon obviously denies access to harvested wood for use as a material or source of energy. As already stated in Section 3.2, it is also important to recognise that the management of forest stands to accumulate large carbon stocks will often greatly increase the risks of natural disturbance events occurring, effectively limiting the accumulation of forest carbon. (This would mean, for example, that full realisation of the large carbon stocks ultimately accumulated in the example in Figure 3.15 could probably never be achieved.)

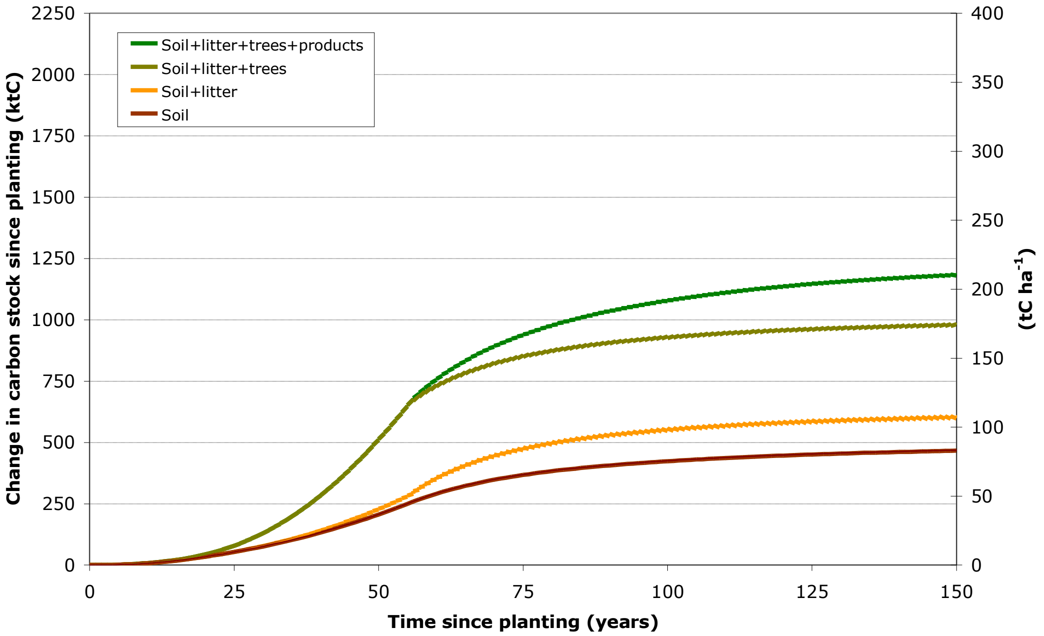


Figure 3.16. Development of carbon stocks over time in trees, litter and soil forming the stands of the 5,600 hectare forest created from even aged Sitka spruce stands over 56 years, as illustrated in Figures 3.8-3.12. The contribution due to carbon stocks retained in harvested wood products is also shown. The left-hand y-axis shows the change in total carbon stocks for the 5,600 ha area, the right-hand y-axis shows the change in carbon stocks for the area expressed in tC ha^{-1}.

Finally, the discussion presented in this section is based largely on the example of a forest formed of Sitka spruce stands, all with the same growth rate and with equal areas of stands in each age class up to the intended rotation of 56 years. This is an entirely theoretical case, as real world forests rarely have such perfectly uniform structures. For example, the uneven distribution of stand areas by age class generally results in peaks and troughs in rates of forest growth and in rates of harvesting and, in response, the carbon stock in the stands of trees forming a forest will fluctuate around a mean level, rather than following the mean level precisely as illustrated in Figure 3.13. Despite the simplifications inherent in the theoretical example presented here, it represents the essential general features observed in the development of carbon stocks in populations of forest stands, in particular the interplay between growth and sequestration on the one hand, and harvesting and removals of carbon on the other hand.

3.4 Influence of species and growth rate

Tree species and growth rate obviously have an impact on the development of tree carbon stocks and rates of sequestration, however, the importance of these factors is often overemphasised or misunderstood. The claim is sometimes made that conifer tree species are 'best' for sequestering carbon and, equally, the same claim is sometimes made for broadleaf tree species.

Clearly many factors will affect the rate of carbon sequestration, starting with the rate of photosynthesis of the trees, which depends on incident radiation from the sun. All trees are 'C3 plants' and, as such, might be expected to achieve similar rates of photosynthesis at a given geographical location, provided that the species of tree is well matched to the site and general environment (A. Hastings, Aberdeen University, personal communication). Soil carbon dynamics will depend on the input of organic carbon arising from fine roots (including fine root turnover) and dead woody biomass. In turn these processes will depend on the climate, soil type and in particular on the environmental conditions in the layer of soil directly affected by tree and plant roots and associated micro-organisms (A. Hastings, Aberdeen University, personal communication). The equilibrium soil carbon stock will depend on the interaction of these various processes.

Generally in the UK, conifer tree species are faster growing than broadleaf tree species in terms of stem volume production. However, broadleaf tree species tend to have more branchwood than conifers and their wood tends to be higher density. Thus, in terms of simple rate of carbon sequestration by trees, the choice between conifer and broadleaf species will often be marginal; rather, effective sequestration will be achieved by matching tree species to site and climate on conventional silvicultural grounds. The intended long-term objective of forest management does influence the selection of tree species, but generally in very broad terms:

- If the aim is to manage forests to create an enduring carbon stock that is relatively large in magnitude, then 'climax' broadleaf tree species will be most appropriate, at leas as a long-term aim for forming the bulk of stands and forests.
- If the aim is to manage forests for high levels of timber and biomass production (e.g. to achieve mitigation in the construction and energy sectors), then rapidly growing 'pioneer' conifer and broadleaf species, or moderately productive species producing enduring timber, will be more appropriate.

In both of the above cases, ensuring a reasonable level of species diversity may be important as a precaution against disturbance events such as attacks by pests and pathogens or catastrophic windthrow, and also against long-term changes in site conditions due to climatic change.

Figure 3.17 illustrates just one example of how carbon stocks can vary with site type, tree species and growth rate, whilst also showing how ultimate outcomes in terms of carbon sequestration and carbon stocks can display some similar characteristics, despite involving contrasting forestry systems. Figure 3.17 describes the accumulation of carbon stocks in a 5,600 hectare forest, created by establishing a collection of individual even aged stands of oak over a period of 120 years. The oak stands are assumed to have a mean stem volume growth rate of 6 m^3 ha^{-1} yr^{-1} over about 90 years. Harvesting is assumed to involve thinning of stands every 5 years from about age 25 years onwards, with clearfelling on a rotation of 120 years. The area of forest created is the same as for the example for Sitka spruce considered in Figures 3.8 to 3.16, but:

- The species in this example is oak.
- The growth rate (in terms of stem volume) is much lower than for the spruce.
- The rotation is more than twice as long as for the spruce (with the consequence that it takes longer to create a forest composed on stands with equal areas up to the rotation age).
- Harvesting involves regular thinning (i.e. the selective felling and harvesting of some trees) during the rotation as well as clearfelling.

In addition, the example in Figure 3.17 is based on establishment of trees on a 'brown earth' soil type (more typical of English lowlands), which has a loam texture, whilst previous land management has been assumed to be as rough pasture, unmanaged grassland or heathland[7].

Comparison of Figures 3.16 and 3.17 reveals that these two contrasting example of forest creation involve similar changes in vegetation (i.e. trees) carbon stocks over 150 years (about 65 and 50 tC ha^{-1} respectively), although the overall changes in carbon stocks are markedly different when contributions due to soil, litter and harvested wood products are also taken into account (about 200 and 75 tC ha^{-1} respectively). Carbon stocks also take longer to accumulate in the broadleaf example (Figure 3.17). This is a reflection of the slower rate of stand establishment in terms of areas created, but this is related to the slower (stem volume) growth rate and much longer rotation needed for growing oak, when compared to Sitka spruce.

There is a particularly marked difference in the response of soil carbon in the examples in Figures 3.16 and 3.17. This illustrates the greater potential variability of soil carbon stock changes in soil compared with trees, although the overall outcome for combined forest carbon stocks (soil plus litter plus trees) is the same (i.e. a net accumulation). As already noted in Section 3.2, the Forestry Commission's Woodland Carbon Code supports tree planting on 'mineral' and 'organo-mineral' soils, but not on 'organic' soils, see West, 2011).

---

[7] The initial equilibrium soil carbon stock (not shown in the figure – see discussion in Section 3.2) is about 75 tC ha^{-1}.

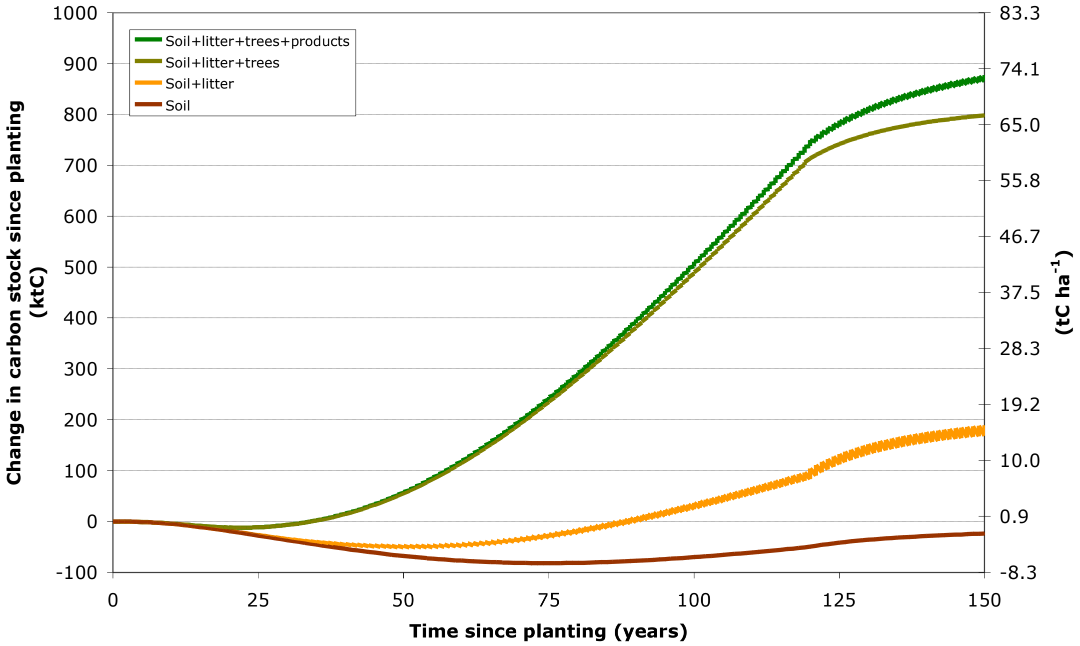


Figure 3.17. Development of carbon stocks over time in trees, litter, soil and harvested wood products forming the stands of the 5,600 hectare forest created from even aged oak stands over 120 years, similar in principle to the example of Sitka spruce over 56 years as illustrated in Figures 3.8-3.12. The left-hand y-axis shows the change in total carbon stocks for the 5,600 ha area, the right-hand y-axis shows the change in carbon stocks for the area expressed in tC ha^{-1}.

3.5 Impacts of changes to forest management

So far the discussion in this section has considered the GHG dynamics associated with creating new forests and with the ongoing management of forests either to conserve carbon stocks or for production of timber and biomass. It is also important to consider the potential impacts of changes to existing forest management on forest GHG dynamics, particularly where this involves changes to existing levels of harvesting. The main options of relevance to this report are scenarios involving:

- 'Leaving carbon in the forest' in order to conserve and potentially enhance forest carbon stocks, i.e. stopping harvesting in forests already under management for production.
- 'Restoring management in neglected forests', i.e. re-introducing harvesting in forest stands that were created with the intention of producing timber and biomass, but which were subsequently abandoned and have fallen into neglect.

Leaving carbon in the forest

This type of change to management has already been considered implicitly in Sections 3.2 and 3.3. Various results have been presented in Figures 3.3 to 3.7 and 3.13 to 3.17, illustrating the long-term carbon stocks that can be accumulated in stands of trees and whole forests, depending on whether they are managed for production of timber and biomass or managed for conservation of carbon. Generally, estimates of long-term carbon stocks are greater in stands and forests where no harvesting occurs (Figures 3.3 to 3.5 and Figure 3.15 compared with Figures 3.6, 3.7 and Figures 3.13, 3.14 and 3.17). Accordingly, the suspension of harvesting in forests should result in a one-off increase in the levels of carbon stocks, with associated sequestration, although, as previously, constraints on the accumulation of forest carbon stocks due to incidents of natural disturbance must be stressed.

The accumulation of additional carbon in forest stands where production is suspended is likely to take place over a number of decades. Further discussion of management options aimed at conserving forest carbon stocks, and estimates of their potential, are presented in Matthews *et al*. (2012) and Annex 3 of Lesschen *et al*. (2012).

The LCA calculations carried out for this study take account of the accumulation of additional forest carbon stocks that would occur if harvesting of forest areas was to be stopped (see Section 5.2).

Restoring management in neglected forests

The potential impacts of this type of change to management have already been discussed in Bates *et al*. (2011), Matthews *et al*. (2012) and Annex 3 of Lesschen *et al*. (2012). In principle the long-term impacts on forest carbon stocks due to re-introducing harvesting in stands will effectively be the reverse of the case involving suspension of harvesting, i.e. there will be a one-off decrease in levels of carbon stocks, with associated GHG emissions. The time over which these carbon stock changes take place could be relatively rapid (e.g. if existing stands are progressively clearfelled and replaced) or gradual (e.g. involving progressive thinning). Matthews *et al*. (2011) have considered how harvesting might be introduced in 'neglected' stands through carefully controlled thinning operations aimed at ensuring the retention of target levels of growing stock. Figure 3.18 illustrates how carbon stocks might develop over time if this type of management was to be introduced in a 'neglected' stand of mixed broadleaf trees with relatively low growth rates. These results were produced using the Forest Research CSORT model (Morison *et al.*, 2012). CSORT is a 'second generation' forest carbon accounting model, which works at the per-hectare scale. Compared to CARBINE, CSORT is capable of representing a wider range of forest types and more complex management regimes, such as in this example. The stand is assumed to be composed of mixed sycamore, ash and birch trees with a growth rate over about 50 years of 4 m^3 ha^{-1} yr^{-1}. Prior to 'year zero' in Figure 3.18, the stand has been allowed to develop from establishment up to maturity with only one early thinning, after which management has been suspended. Management based on progressive thinning according to the systems described in Matthews *et al.* (2011) is assumed to start at 'year zero'.

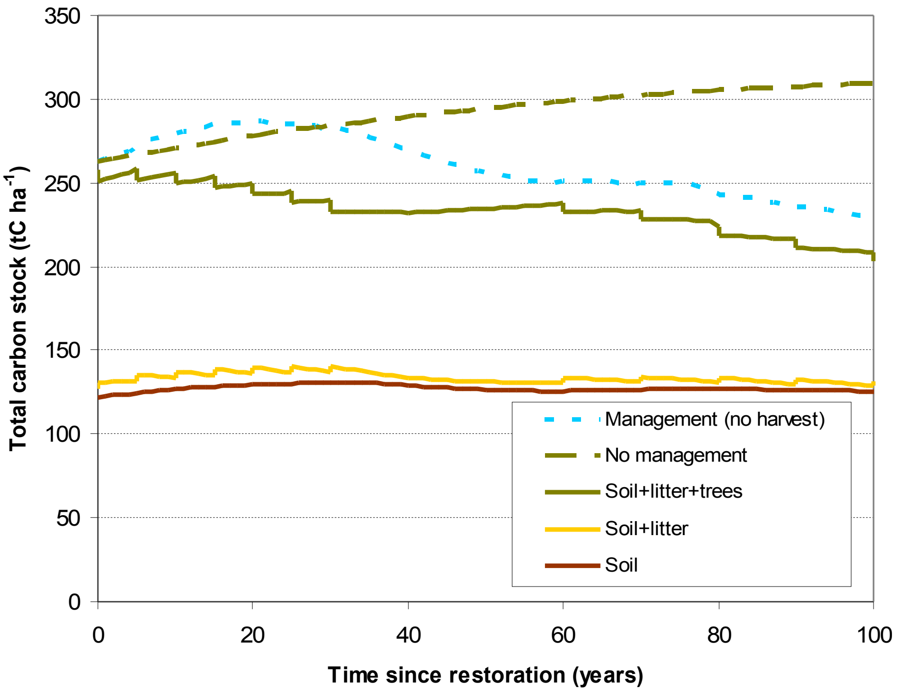


Figure 3.18. Development of carbon stocks over time in trees, litter, soil in a 'neglected' stand of mixed broadleaf trees, where management involving harvesting for timber and biomass production is re-introduced. The results are for a stand of mixed sycamore, ash and birch. The dashed green line shows how carbon stocks in the forest would be expected to continue to accumulate if management was not introduced, in the absence of natural disturbance events. The dashed blue line shows how forest carbon stocks would develop if management was to be introduced involving selective felling of trees and retention of dead wood in the forest to meet environmental and amenity (i.e. non-timber) objectives.

The results in Figure 3.18 are presented slightly differently to those in previous figures in this section, in that absolute carbon stocks are displayed, rather than changes relative to pre-existing levels. The progressive reduction of carbon stocks in trees (and also for trees, litter and soil combined) due to periodic thinning operations is apparent in Figure 3.18. Such reductions are an inevitable and necessary by-product of introducing production and are also essential as part of managing the stand to achieve regeneration and growth of new and younger trees. Nevertheless, tree carbon stocks are reduced by around 40% over a period of a century. The carbon stocks in the trees should stabilise and even recover to some extent as new and young trees regenerate. Lessons are still being learned about the best ways to restore management in 'neglected' forests – it is possible, for example, that more intensive initial thinning than assumed in the example in Figure 3.18 may enable faster stand regeneration and consequent recovery of carbon stocks. Consequently there is uncertainty over how big the short-term and long-term reductions carbon stocks would be when restoring management in 'neglected' forests, as well as the period over which these reductions would take place and with what pattern.

If harvesting was not introduced in 'neglected' forest areas, the carbon stocks might be expected to continue to accumulate, as illustrated by the dashed green line Figure 3.18. However, the extent to which this might occur is uncertain as it depends on a number of factors, notably the ages of the trees comprising the forest areas and the potential impacts of natural disturbance events. The rate and level of accumulation shown in Figurer 3.18 represents a 'best case scenario' for the type of forest considered (i.e. mixed broadleaf trees with a typical growth rate for the UK at the onset of the mature phase of growth).

The LCA calculations carried out for this project take account not only of the reductions in carbon stocks likely to be observed when restoring management in 'neglected' forests but also of the potential for continue accumulation of carbon stocks in the absence of the introduction of management (see Section 5.2). In the case of restored management in 'neglected' forests the estimates referred to for continued accumulation of carbon stocks (in the absence of management) are on the high side of the possible range.

As an alternative scenario, the dashed blue line in Figure 3.18 shows how carbon stocks might develop if management involving thinning (the selective felling of some trees) was to be introduced in 'neglected' broadleaf forests but the felled wood was retained and stacked within the forest, rather than being harvested and utilised for timber or fuel. Superficially, such a scenario may seem unrealistic. However, the thinning of 'neglected' broadleaf forests for non-timber objectives is already under consideration. The purpose of the management would be to open the canopy of the forests to encourage ground flora and the regeneration of young trees, thereby supporting the species and structural diversity of the forests. Furthermore, for example, Forestry Commission forest management guidelines already require the retention of target amounts of dead wood on forest sites in order to provide habitats for small mammals, birds, insects, fungi and so on. A management regime involving thinning of forests and retention of stacks of felled wood on site thus represents a potentially real scenario. The comparison of this scenario with the strict 'no management' scenario illustrates the potential uncertainties in the development of carbon stocks in 'neglected' broadleaf forests if management involving harvesting of timber and/or fuel was not introduced. As shown in Figure 3.18 (dashed blue line), the thinning of forests and retention of felled wood on site actually results in enhanced carbon stocks in the short term (20 to 30 years), because the felled trees are retained and take time to degrade and decay, whilst the growth of the remaining standing trees responds to release from competition with neighbouring trees that have been felled. However, in the longer term, forest carbon stocks are reduced and reach levels that approach those estimated for forests managed for production.

The LCA calculations carried out for this study consider the option of management (thinning) without production as an alternative scenario to either no management or restoring management with production (see Section 5.2).

3.6 Carbon sequestration due to suspension of harvesting in forests

In recent years a number of research papers have focussed on the fact that, whilst ongoing, long-term management of forests for wood production through harvesting does not necessarily involve reductions in forest carbon stocks (see Section 3.3), nevertheless the effect of continued harvesting is generally to maintain forest carbon stocks at relatively modest levels. As a corollary, it is noted that, potentially, carbon stocks in forests would be larger if there was no harvesting. The question has thus arisen, would the suspension of harvesting in forests already under management for production lead to benefits in terms of forest carbon sequestration that exceed the benefits, in terms of low emissions, that are associated with the use of harvested wood for bioenergy or wood-based materials?

In this study, the option of suspending harvesting in forests previously under long-term management, involving harvesting in order to achieve forest carbon sequestration, represents a distinct scenario for forest management and non-wood use, labelled as Scenario 00.00 (see Sections 4.5 and 4.6), in recognition of the particular interest in this option. The results for Scenario 00.00 may be compared explicitly and transparently with results for other scenarios involving wood production (see, for example, Figures 5.12 to 5.14 in Section 5). It should be noted that some researchers argue that estimates of impacts in terms of GHG emissions for scenarios involving harvesting and wood production should always be calculated relative to the option of no harvesting represented by Scenario 00.00, such that comparison with this scenario is always implicitly made. However this is an aspect of forest carbon assessment and LCA methodology that is still a subject of debate (see Section 6). Results for scenarios involving wood production relative to results for no production can be easily inferred and understood through direct comparison such as facilitated in Figures 5.12 to 5.14 presented in Section 5.5 of this report.

The idea that harvesting can be suspended in forests to allow additional forest carbon to be sequestered is receiving considerable attention. However there is limited acknowledgement of the very high uncertainty that should be attached to projections of future forest carbon sequestration under these types of scenario. Whilst ongoing carbon sequestration is a likely outcome in the short term, it is important to note high uncertainty attached to estimates of medium- and long-term carbon dynamics and also the increasing risks of natural disturbance, and, consequently, the high uncertainty that should be attached to carbon sequestration achieved by low- or no-management forestry options.

3.7 Key conclusions on forest GHG dynamics

It is hoped that the discussion in this section has demonstrated that, whilst not simple, the GHG (primarily carbon) dynamics of forest systems can be understood in terms of the interactions between a few factors, i.e. soil type, tree species, growth rate and how the trees are managed. When creating new forests, it is also important to take account of the level of carbon stocks pre-existing in vegetation and soil on the land to be forested. Tree species and growth rate are important factors but their main relevance is through their influence on decisions about the management of stands and forests (e.g. management for production is likely to be favoured where growth rates are relatively high). Concomitantly, decisions about management objectives may influence the selection of tree species.

In situations where new forests are created, or existing forests have been under long-term management for production of timber and/or biomass, harvesting of wood *does not incur* a 'carbon debt'. Higher levels of carbon stocks may be achieved by avoiding harvesting and protecting forest stands, however, the potential for this may be constrained by the impacts of natural disturbance events. A 'carbon debt' *is incurred* when management involving harvesting is introduced or restored in (generally unmanaged) forest stands with existing high levels of carbon stocks. The negative impacts of harvesting on carbon forest stocks can be minimised by adopting appropriate silvicultural systems (e.g. involving thinning or patch felling rather than clearfelling), but cannot be avoided completely.

The stands forming conifer forests in the UK are typically the result of afforestation and are in their second or even third rotation of production, thus they are approaching or have reached the more 'constant' region of the development of carbon stocks, such as illustrated for later years in Figures 3.11, 3.12 and 3.14 in Section 3.3. Broadleaf forests in the UK that are already under management for production have generally been so for at least a century, therefore the development of carbon stocks should also be in the more 'constant' region shown for later years in Figure 3.15. It follows that the major impacts on overall life cycle emissions when considering conifer and broadleaf forests already in production are likely to be associated with decisions on how harvested wood is used, rather than related to GHG dynamics within the forest. The option of ceasing harvesting in these forests, with the aim of conserving and potentially enhancing forest carbon stocks must also be acknowledged. However, as already noted, the potential for accumulating carbon stocks in forests is finite and likely to involved increased risks of natural disturbance events, which may limit the levels of forest carbon stocks.

The restoration of management (involving harvesting) in broadleaf forests that have been 'neglected' is likely to lead to a marked reduction in long-term forest carbon stocks, which will make a significant contribution to life cycle emissions of relevant forest management and wood utilisation scenarios. However, it must be stressed that the magnitude and pattern of development over time of these carbon stock changes is uncertain and highly dependent on the silvicultural approaches adopted. There is a case for further research to identify optimal silvicultural regimes specifically in support of restoring management in ‘neglected’ forests.

4. Approach to GHG balance estimation

As described in detail in this section, the estimation of GHG emissions balances for specific wood products and associated forestry sources involved four main steps:

1. Definition and modelling of characteristic forest types
2. Definition and modelling of characteristic wood use types and associated 'counterfactuals'.
3. Modelling of potential production of wood products from characteristic forest types, and any associated forest carbon stock changes and GHG emissions due to forest management.
4. Detailed LCA calculations for complete wood production and consumption chains.

4.1 Characteristic forest types

As explained in Section 1.3 of the introduction to this report, Task A of this project involved identifying sources of wood and the range of energy and material end use applications to be analysed. Three characteristic forest types were defined as relevant within the scope of this project:

1. Coniferous forests already under management for production of timber and/or woodfuel.
2. Broadleaf forests already under management for production of timber and/or woodfuel.
3. Broadleaf forests formed of stands established within the last 50 to 100 years. The initial intention was to manage these stands for production of timber and/or woodfuel but, due to unfavourable socioeconomic circumstances, the stands fell into 'neglect'. The intention is now to restore these forests to active management to meet a range of environmental and socioeconomic objectives but, crucially, involving harvesting of trees as part of management for production.

These three forest types were identified as broadly representative of the majority of forest areas in the UK (see Section 2 of this report). In turn, three forest types were represented in model simulations and LCA calculations by particular forest stand types in terms of species composition, growth rate and management regime. Details are given in Table 4.1.

The methodology used to model forest stands (in order to estimate levels of production and carbon stock changes) is described in Section 4.3.

Table 4.1 'Model' stands used to represent characteristic forest types

Characteristic forest type	'Model' stand type comprising forests			
	Tree species	Growth rate (as yield class[a])	Management regime	Rotation (years)
Coniferous, managed for production	Sitka spruce	12	Thinning[a] every five years from stand age 25 years, periodic clearfell[a] on rotation, with fallow period of 2 years between felling and re-establishment..	60
Broadleaf, managed for production	Oak	6	Thinning[a] every five years from stand age 30 years, periodic clearfell[a] on rotation, with fallow period of 2 years between felling and re-establishment..	120
Broadleaf, neglected then restore to management for production	Mixed sycamore, ash and birch	4	Thinning[a] every five years, with the aim of balancing production, maintenance of growing stock levels and encouraging regeneration of young trees. No clearfell[a], so no rotation; management as continuous cover[a] instead.	

a. See Glossary for definitions of terms.

4.2 Characteristic wood use options and counterfactuals

As already noted, Task A of this project involved identifying a range of energy and material end use applications to be analysed. For each type of wood end use, it was also necessary to identify relevant 'counterfactuals' which would fulfil specific energy or material end uses if UK-grown wood were not to be consumed. It was recognised that, for most existing applications, there were two fundamental ways of meeting needs for energy or materials, should consumption of UK-grown wood for a specific application be reduced or cease entirely:

1. Consumption of UK-grown wood could be substituted for by non-wood options. In the case of wood used for bioenergy, fossil fuels could serve as a substitute. For wood-based materials, there may be a wide range of possible non-wood substitutes based on plastics, metals, concrete etc., obviously highly dependent on the specific end use.
2. Consumption of UK-grown wood could be substituted for by importing wood from other (i.e. non-UK) sources.

Consequently, as described below, wherever possible and meaningful two possible counterfactuals were identified for each wood end use option considered within the scope of this project – one involving use of a non-wood substitute and one involving use of imported wood.

The various options actually identified for using forest products, as woodfuel or wood products, were established within this project so that representative cases could be considered, realistic counterfactuals could be identified and their total GHG emissions could be determined. In some respects, the task of identifying suitable end uses for harvested wood as fuel and material products was straightforward; the aim was to identify examples of wood utilisation that constituted 'high volume' applications that could be regarded as 'typical' for a given type of processed wood. The selection of cases for wood utilisation also needed to involve potential non-wood and imported-wood counterfactuals that could be regarded as 'typical', such that estimates of impacts on GHG emissions due switching between different wood utilisation options could be regarded as robust. However, there were also some significant practical constraints on the selection of wood applications and counterfactuals, imposed in quite large degree by the scope and timescale for this project. Specifically, as the project was specified to rely on existing research and available studies, consideration of options for the utilisation of wood involving extensive new LCA research was precluded. Similarly, it was necessary, as far as possible to consider 'simple' cases of wood utilisation, e.g. avoiding options for the end use of wood that involved complex processing and conversion routes and, in particular, complex applications involving the use of different types of wood in combination. This issue was particularly relevant for applications of wood as a material, for example where particleboard and sawn timber are frequently used to make composite wood structures. Although such applications of wood materials may represent some important and even 'typical' cases for wood utilisation, these could not be considered within the scope of this project due to the extensive new LCA calculations that would have been required to estimate GHG impacts for specific wood components.

The system diagram in Figure 4.1 illustrates the overall approach to representing the harvesting of wood, its utilisation for specific products and relationships to relevant non-wood counterfactuals.

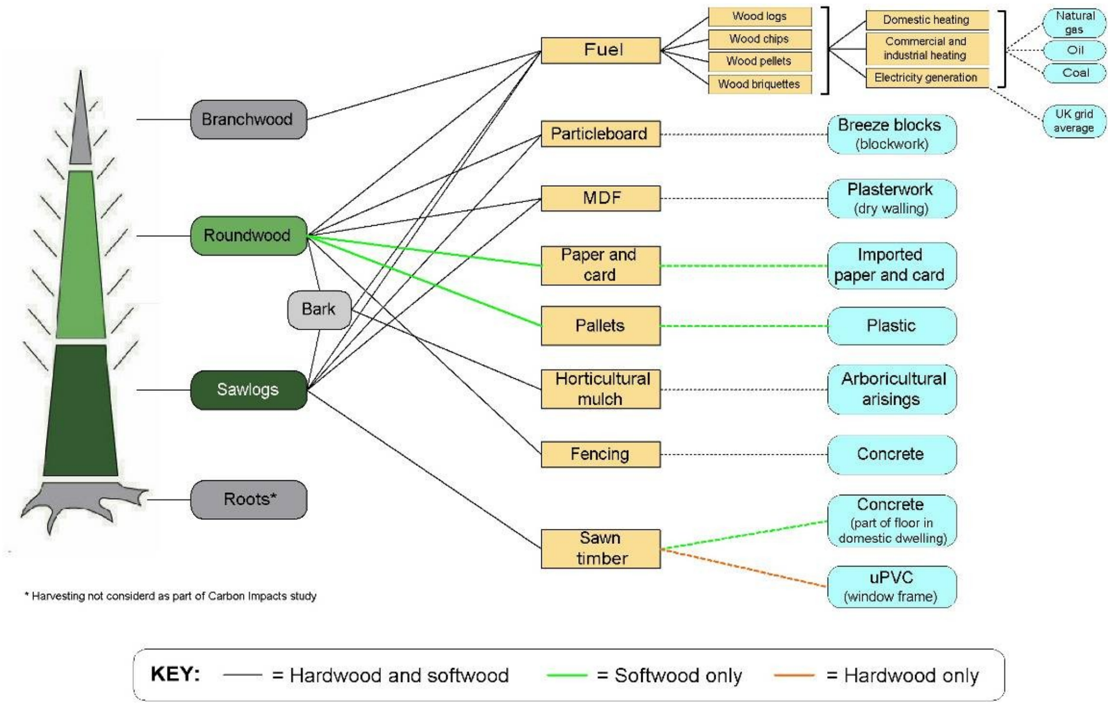


Figure 4.1. Representation of wood harvesting, processing and utilisation chains within this project, including relationships to non-wood counterfactuals. (Note that alternative counterfactuals involving imported wood were also identified and modelled, see Table 4.4.)

The modelling of wood processing chains and allocation of harvested wood as a material or fuel to specific end uses recognised that wood production and consumption generally involves three distinct stages:

1. The conversion of felled trees into primary wood raw materials, i.e. sawlogs, roundwood, bark and branchwood.
2. The processing of primary wood raw materials into final wood products (e.g. sawn timber, particleboard, wood chips).
3. The consumption and utilisation of final wood products for specific end-use applications (e.g. as part of exterior walls or floor of a house, for a window frame, for fencing, or as fuel to generate domestic heat).

Primary wood raw materials

The first stage in the harvesting and utilisation of wood products entails the conversion of harvested trees into the primary wood raw materials of:

- (Large-diameter) sawlogs
- Small roundwood
- Bark
- Branchwood.

It should be noted that significant elements of this conversion stage generally take place as an integral part of tree felling and extraction of harvested wood from the forest.

For all practical purposes, the quantities of primary wood raw materials produced in harvesting operations are determined not by choice but by the physical dimensions and characteristics of harvested trees (e.g. only stem wood of sufficiently large diameter will be suitable for conversion into sawlogs, whilst there will be a fixed amount of bark on the stem of any tree). To some extent these quantities are influenced by decisions about the detailed management of stands (e.g. extent of thinning, rotation period) but the major determinants are tree species and growth rate (see for example Edwards and Christie, 1981).

The main factors that can be controlled during harvesting concern the detailed specification of sawlogs and small roundwood (in terms of minimum diameter and length) and whether (or not) to harvest part or all of the branchwood produced during tree felling, or leave branchwood on site. The specifications assumed in this study for roundwood and sawlog material are given in Table 4.2. It should be noted that these specifications are consistent with those already used in the estimation of GHG balances for a range of bioenergy options involving UK and international forestry, as incorporated in the Environment Agency's $BEAT_2$ software tool and reported by Bates *et al*. (2011). Decisions about branchwood harvesting will be influenced by environmental constraints associated with site conditions (see for example Moffat *et al.*, 2006). The modelling methodology developed in this project has allowed for the possibility that branchwood may be left on site, or some or all may be harvested. When calculating 'standard' results, a default assumption was made that 50% of branchwood would be retained on site whilst 50% would be harvested.

As discussed in Section 4.3 below, the CSORT forest carbon accounting model was used to estimate potential production of sawlogs, roundwood, bark and branchwood for each of the characteristic forest/stand types described in Section 4.1.

Table 4.2 Specifications assumed for small roundwood and sawlogs in terms of minimum diameter and length

Product type	Minimum diameter (over bark, cm)	Length	
		Fixed or random	(m)
Roundwood	7	Fixed	3
Sawlogs	18 (conifer) 25 (broadleaf)	Random but with minimum length	3

Final wood products

A total of 5 fuel and 7 material final wood products were identified as relevant to the UK forest sector. Fuel products consisted of:

1. Primary raw wood materials (specifically for supply direct to power stations)
2. Wood logs
3. Wood chips
4. Wood pellets
5. Wood briquettes.

Material products consisted of:

1. Sawn timber
2. Particleboard
3. Medium Density Fibreboard (MDF)
4. Fencing
5. Palletwood
6. Paper and card
7. Horticultural mulch.

A further possible material wood product relevant to the UK forest sector, Oriented Strand Board (OSB) was not covered within the scope of the project. Estimates of GHG impacts for OSB are likely to be similar to those for (more generic) particleboard, but with the critical qualification that levels of recycled wood used as input to production to OSB would be zero.

There are practical constraints on the potential to convert primary raw wood material into final products, most obviously (for all practical purposes) only sawlogs are suitable for processing into sawn timber, and even then not with 100% efficiency. Conversely, there are some final wood products which can be derived from almost any type of primary wood raw material, the clearest example being wood chips for consumption as fuel. The conversion routes from primary wood raw material to final wood products considered within the scope of this project are summarised in Table 4.3.

Assumptions about inputs of recycled wood into the manufacture of board products have a significant influence on estimated GHG emissions. Inputs of recycled wood to the manufacture of particleboard are significant, ranging from 40% to 95% in the UK with an average of about 70% (A. Kerr, Wood Panel Industries Federation, personal communication). For the purpose of LCA calculations in this project, the effect of inputs of recycled wood to particleboard manufacture were represented by making a percentage reduction to the amount of fresh wood required to produce a given quantity of particleboard, and making a commensurate reduction to the outputs of waste wood from particleboard at end-of-life. (This effectively treats the contribution of recycled wood as a ‘closed loop’ or ‘static stock’ within the particleboard industry.) The percentage of recycled wood assumed as input to particleboard production could be varied in LCA calculations; a default value of 70% was assumed[8].

Table 4.3 Summary of routes for conversion of primary wood raw materials into final wood products

Primary material	Final wood product
Sawlogs	Sawn timber (fraction dependent on potential for conversion of sawlogs), particleboard, MDF, woodfuel (raw wood, logs, chips, pellets or briquettes).
Roundwood	Fencing, pallets (fractions dependent on potential for conversion of sawlogs), particleboard, MDF, paper and card, woodfuel (raw wood, logs, chips, pellets or briquettes).
Bark	Horticultural mulch, woodfuel (raw wood or chips).
Branchwood	Leave in forest, or harvest for woodfuel (as raw wood or chips). Fractions of branchwood may be allocated for retention in the forest or harvest for woodfuel (default 50:50 allocation).

Consumption and utilisation of final wood products

The final stage in the harvesting and utilisation of wood products involves the consumption and utilisation of the final wood products described above in specific applications and end uses. Four principal conversion routes were considered for the consumption of woodfuel:

- Domestic heating
- Commercial and industrial heating
- Commercial and industrial CHP
- Electricity generation only.

It should be noted that the scenario for the consumption of woodfuel for power only generation, as modelled in this study, represents power generation in a dedicated biomass-fired power station. It should be stressed that this scenario is not the same as the consumption of woodfuel for electricity generation through co-firing with coal – this scenario was not included in the scope of the study.

Some of the final material wood products listed earlier in this section are eponymous with their end uses (i.e. fencing, palletwood); others, most obviously sawn timber, particleboard and MDF, may be utilised in a diverse range of specific applications. As already discussed in Section 4.2, choices made about specific applications of wood (as a fuel or material) constitute a critical step in determining the results reported in this project. These assumptions are summarised in Table 4.4.

---

[8] It should be noted that 'small' variations in this assumed default value (e.g. between 65% and 85% would not affect the patterns in the results as presented in Section 5 of this report.)

Table 4.4 Representative cases adopted in this project for utilisation of final wood products in specific applications and end uses

Wood product	End-use application	Counterfactuals	
		Imported wood	Non-wood
Fuel	Domestic, commercial and industrial heating Commercial and industrial CHP Electricity generation	Imported woodfuel from Canada	Domestic, commercial or industrial heating: natural gas-fired, oil-fired or coal-fired heating. Electricity generation: natural gas (CCGT), oil-fired or coal-fired electricity generation; also UK average grid electricity (2004).
Horticultural mulch (from bark)	Horticultural mulch	None	Horticultural mulch from arboricultural arisings
Particleboard	Internal component of external wall construction for domestic building	Imported particleboard from Eire	Blockwork (breeze blocks)
MDF	Interior work in domestic buildings e.g. dry walling	Imported MDF from Eire	Plasterboard from gypsum recovered from power station flues; surface coat of plaster.
Sawn timber (softwood)	Component of floor construction for domestic building	Imported sawn timber from Baltic states	Concrete screed
Sawn timber (hardwood)	Window frame	Imported sawn timber from USA	uPVC window frame
Fencing	Fencing	Imported fencing from Baltic states	Reinforced concrete fencing
Palletwood	Pallets	Imported pallets from Eire	Recycled plastic pallets
Paper and card	Paper and card (e.g. for packaging)	Imported paper and card from Baltic states	None
Plywood and veneer	Not currently produced from UK/GB resource (included for information only; the product option is out of scope for this study)		

Note: see Figure 4.1 for a pictorial description of wood products and non-wood counterfactuals.

Different wood products have different characteristic working lifetimes, varying from quite short, such as in the case of (most) paper, card and pallets to very long, such as in the case of structural timber in buildings. As discussed in some detail in Section 4.5, the conventions adopted in LCA calculations required assumptions to be made about the working lifetimes of different wood products, i.e. the period after which a specific wood product would come to the end of its useful life and would need to be disposed of. Assumptions about working lifetimes made in this study are summarised in Table 4.5 in terms of the three time horizons adopted for LCA calculations in this study (20, 40 and 100 years, see Section 4.4) and whether particular wood products would reach the end of their working lives within a specified time horizon.

Table 4.5 Assumptions about working lifetimes of final wood products with respect to time horizons considered in LCA calculations

Wood product	Time to end-of-life		
	Within 20 years	Within 40 years	Within 100 years
Fuel	×	×	×
Horticultural mulch	×	×	×
Particleboard			×
MDF			×
Sawn timber			×
Fencing	×	×	×
Palletwood	×	×	×
Paper and card	×	×	×

Note: '×' indicates that a wood product is assumed to have reached the end of its useful life during the specified time horizon (20, 40 or 100 years).

Disposal of material wood products

The disposal of material wood products at end-of-life can have very large impacts on GHG emissions balances and it was recognised that different options for disposal of wood products needed to be represented within the scope of the project. A total of 7 disposal options were identified:

1. Dry landfill
2. Wet landfill without energy recovery
3. Wet landfill with energy recovery
4. Waste incineration without energy recovery
5. Waste incineration with energy recovery
6. Waste Incineration Directive (WID) compliant power only generation
7. Waste Incineration Directive (WID) compliant CHP generation.

This particular list of disposal options was chosen to ensure that all possibilities and their consequences, in terms of total GHG emissions, would be covered in this study. However, it is necessary to qualify this choice. It is known that low GHG emissions will arise from disposal to dry landfill since any wood is expected to remain intact over a very long period of time. Unfortunately, such an option is unlikely to be available in the UK. In contrast, disposal to wet landfill has been and still is a possibility in the UK. Without energy recovery, wood product disposal to wet landfill results in very substantial total GHG emissions due to decay to CO_2 and CH_4, and subsequent leakage of these GHGs to the atmosphere. Energy recovery, assumed to consist of power only generation, reduces these emissions considerably due to conversion of CH_4 to CO_2 during landfill gas combustion and the possibility of displacing electricity generated from fossil fuels. In the context of disposal to wet landfill without or with energy recovery, it is appreciated that such options may not be available in the long-term future. Disposal to waste incineration is a current alternative to landfill. Without energy recovery, waste incineration simply releases carbon sequestered in wood products via combustion into the atmosphere. The magnitude of these GHG emissions can be reduced with energy recovery, assumed to consist of power only generation, by the potential displacement of fossil fuels used in electricity production. It is expected that disposal to waste incineration with energy recovery may be a prominent option in the medium-term future in the UK. Whereas the waste incineration options specified here are intended to reflect principal means for disposing of municipal solid waste, two further options were included to cover possible longer-term possibilities in which dedicated WID compliant power only and CHP plants are constructed specifically to burn waste wood products. Evaluation of total GHG emissions for such plants includes the potential displacement of fossil fuels for heat production and electricity generation.

Conventional combustion technology, with typical thermal efficiencies for energy recovery, has been assumed for all relevant options. It is possible that new technologies, such as gasification, with higher thermal efficiencies, might be introduced in the medium- to long-term future. It is possible to modify the details of the workbooks, at the level of embedded cell formulae, to address this. However, a more significant effect on total GHG emissions would result from the application of carbon capture and storage (CCS) to the stack emissions of all disposal options which include energy recovery. Consequently, the workbooks incorporate options for applying CCS, with assumed significant decreases in CO_2 emissions (88%), reductions in thermal efficiencies (18%) and increases GHG emissions due to CCS equipment installation and operation (0.05 $kgCO_2/kWhe$ generated), to wood waste disposal to wet landfill, waste incineration, and WID compliant power only and CHP generation, all with energy recovery (Viebahn *et al*., 2007). These same assumptions about CCS are also incorporated in the evaluation of wood-fired commercial and industrial CHP generation, and power only generation in the workbooks. These are currently consider to provide suitable large-scale opportunities for the cost-effective application of CCS in the longer-term future, if such technology becomes technically- and economically-proven in a realistic timescale. It was assumed that CCS technology is unlikely to be available for smaller-scale applications such as domestic wood-fired heating, and the majority of commercial and industrial wood-fired heating.

Counterfactuals: imported wood

For each final wood product and end-use application listed in Table 4.4, an option was identified for supplying the required wood product through production outside the UK. These assumptions about wood non-UK sources are also listed in Table 4.4. Assumptions were based broadly on the analysis presented in Section 2 of this report, and involve production of softwood from coniferous forests in the Baltic States, Canada or Eire and hardwood production from broadleaf forests in the USA. Assumptions about the types of stands in these countries that would be involved in providing this wood (should UK production be replaced) are given in Table 4.6. Many of the assumptions (where relevant) are consistent with those made in previous work on GHG impacts of international forestry (Bates *et al*., 2011).

It was necessary to give careful consideration to assumptions about how forest areas outside the UK would be managed in order to meet additional requirements for wood imports to the UK. The possibility that such requirements might be met from ongoing management of forest areas already in production was explored, but finally discounted on both a pure theoretical basis and in the light of evidence on likely changes to patterns for wood demand (see for example Mantau *et al*., 2010). Instead it was concluded that a significant increase in requirement for imported wood in the UK would entail intensification of the management of forests in other countries, similar in some respects to restoration of management in neglected forests, as already discussed in Section 3.5 of this report. Table 4.6 includes a summary description of the management regime assumed in modelling work.

Table 4.6 'Model' stands used to represent characteristic forest types for imported wood counterfactuals

Characteristic forest type	**'Model' stand type comprising forests**			
	Tree species	**Growth rate (as yield class[a])**	**Management regime**	**Rotation (years)**
Coniferous, Baltic states	Scots pine	4	Initial clearfelling[a] or heavy felling retaining 'seed trees', then active re-establishment of successor stand. Successor stand(s) managed with periodic thinning[a] and clearfell[a] on a rotation, with fallow period of 2 years between felling and re-establishment.	110
Coniferous, Canada	Norway spruce	8		120
Coniferous, Eire	Sitka spruce	14		50
Broadleaf, USA	Oak	4		160

a. See Glossary for definitions of terms.

Counterfactuals: fuel (energy) products

In the case of wood energy products, the basis of the comparison was the delivered energy provided wood-fired heating, CHP or electricity plants and the alternative means of providing this delivered energy. The units adopted for this comparison were 1 MWh of delivered heat or 1 MWh of delivered electricity. A number of different sources, mainly in the form of published or internal MS Excel workbooks, were used to obtain estimates of total GHG emissions per MWh for chosen counterfactuals. For consistency, all estimates of total GHG emissions for the counterfactuals included the emissions associated with the manufacture and maintenance of relevant plant and equipment.

Each of these conversion routes required specification of representative counterfactuals. For domestic heating, the counterfactuals were based on systems with a typical output rating of 10 kW and consisted of a natural gas-fired condensing boiler an average thermal efficiency of 90%, an oil-fired condensing boiler with an average thermal efficiency of 93%, and a coal-fired boiler with an average thermal efficiency of 70%. For both the oil- and coal-fired boilers, it was assumed that the round trip distance for delivering the fuel was 200 km. The same assumptions have been adopted for commercial and industrial heating based on systems with a typical output rating of 10 MW. Four different counterfactuals were adopted for electricity. These consisted of a 505 MW output rating combined cycle gas turbine power plant with a thermal efficiency of 45%, a load factor of 80% and a life of 30 years; a 450 MW output rating oil-fired power plant with a thermal efficiency of 33%, a load factor of 80% and a life of 25 years; a 1,296 MW output rating coal-fired power plant with flue gas desulphurisation, a thermal efficiency of 36%, a load factor of 80% and a plant life of 40 years; and UK average grid electricity for 2004 (with total GHG emissions derived from input-output analysis).

Assumptions about wood non-wood energy counterfactuals are summarised in Table 4.4.

Counterfactuals: material products

As discussed earlier, the counterfactuals for wood products were based on assumptions about the most likely displacement options and, although these are open to further discussion and debate, and contingent upon practical constraints and available data. Unfortunately, the identification of wood product counterfactuals is a far from simple process and there is no uniquely defined and agreed set of options. In order to estimate subsequent total GHG emissions, it is also necessary to establish a reasonable basis of comparison. In terms of constructional wood products, suitable information is available from the Edinburgh Centre for Carbon Management Update of Carbon Benefits which provides a basis for comparing the application of sawn timber and particleboard with possible counterfactuals.

In the case of softwood sawn timber, the chosen application was timber flooring which can be compared with concrete screed flooring. It is necessary to take into account design and component details for both types of flooring. However, these types of flooring share some common components, such as concrete slab, hardcore and particleboard which are used in the same quantities per unit area of flooring. There is a small difference in the amount of polystyrene insulation which can be easily estimated in terms of GHG emissions. Hence, the main difference is between the amounts of sawn timber and concrete screed, and their related total GHG emissions. The relevant counterfactual for hardwood sawn timber was assumed to be a uPVC window frame.

The chosen basis for particleboard and its counterfactual was assumed to be external walls. This involves the comparison of a wall with external and internal particleboard on timber stud work against a wall constructed with blockwork. Both walls have insulation but this is assumed to be the same in each case. The main problem with the comparison would seem to be the timber stud work which would, of course, be derived from forest products (sawn timber from sawlogs). However, examination of the basic data shows that the amount required per unit area of wall is not large and its contribution to total GHG emissions, relative to that of the particleboard, is negligible.

In the case of MDF, the counterfactual was assumed to be plasterboard used for internal walls. In both instances, the same quantities of sawn timber stud work are required so that the GHG emissions implications of this shared component are cancelled out in the calculations. For wooden pallets, the chosen counterfactual was recycled plastic pallets. Whilst such pallets could be compared directly, the difference in their weights was taken into account in the evaluation of total GHG emissions. However, it was assumed that their lifetime would be the same. The counterfactual for timber fencing was taken to be concrete fencing and the basis for comparison was a unit area of fencing.

In terms of paper and card, it was necessary to assume that the most likely counterfactual would be equivalent products imported into the UK from the Baltic States. Since no further information was available from published sources, it was assumed that the total GHG emissions associated with the production of paper and card are the same in both the UK and the Baltic States, and that the only significant difference in total GHG emissions would be due to shipping with a round trip distance of 2,000 km assuming a full outward journey and an empty return journey. Finally, the counterfactual for bark used as horticultural mulch was taken to be the same product derived from arboricultural arisings.

Assumptions about wood non-wood counterfactuals for materials are summarised in Table 4.4.

Wood products and counterfactuals: LCA data and calculations

Work carried out for this project needed to rely on data and results from existing LCA studies. However, in general, existing data and results still required reworking in order to be used in the specific LCA calculations needed to deliver the project outputs. Since the focus of this project is on the GHG impacts of utilising woody biomass, detailed and extensive calculations were made for relevant wood product chains, based on a set of workbooks, as discussed in Section 4.4 of this report. Bespoke LCA calculations were also made for non-wood counterfactuals but a detailed approach as employed with wood products was not possible, rather it was necessary to rely more heavily on published LCA results and specific emissions factors. Table 4.7 gives details of the main research studies and publications referred to in estimating GHG emissions factors for non-wood counterfactuals relevant to this project. Bespoke calculations were always needed at some level, for example to ensure that GHG emissions estimated for non-wood counterfactuals could be related to (and compared with) GHG emissions for the equivalent wood product.

Table 4.7 Key research studies and publications used in deriving GHG emissions factors for wood products and non-wood counterfactuals

Wood end-use or counterfactual	Data sources
Wood-fired energy end uses	Data taken from $BEAT_2$ workbooks (DEFRA, 2007 and 2008), updated with timber transport data (ConFor, 2010) and augmented, where necessary, with bespoke calculations (e.g. wood-fired kiln drying of wood).
Fossil fuels (various) and electricity (various sources); displaced by wood-fired energy	Bespoke calculations using internal workbooks from previous projects (SDC, 2005, and NATURALHY, 2008), and publicly-accessible workbook for total GHG emissions of UK fuel and electricity supply in 2004 (NNFCC, 2009)
Imported woodfuels (chips and pellets from Canada)	Data taken from $BEAT_2$ workbooks (DEFRA, 2007 and 2008), updated with timber transport data (ConFor, 2010) and augmented, where necessary, with bespoke calculations (e.g. wood-fired kiln drying of wood).
Concrete screed floor component (displaced by softwood timber floor components)	Data taken from another study (ECCM, 2006) augmented by bespoke calculations.
uPVC window frame (displaced by hardwood window frame)	Data taken from another study (ECCM, 2006) augmented by bespoke calculations.
Horticultural mulch from arboricultural arising (displaced by bark mulch)	Bespoke calculations using an internal workbook from a previous project (NNFCC, 2010)
Blockwork external wall component (displaced by particleboard)	Data taken from other studies (ECCM, 2006 and Wilson, 2009a) augmented by bespoke calculations
Plasterboard dry walling (displaced by MDF)	Data taken from another study (Wilson, 2009b) augmented by bespoke calculations
Concrete fencing (displaced by wooden fencing)	Bespoke calculations using basic information on fence specifications
Recycled plastic pallets (displaced by wooden pallets)	Bespoke calculations based on industry data (Bertrand and Simon, 2007).
Paper and card	Bespoke calculations based on statistical data for the UK paper and board sector augmented, where necessary, with CSORT results to reflect current production in the Baltic States.

4.3 Application of CSORT model

The main LCA calculations needed for this project were carried out based on a set of workbooks, as discussed in Section 4.4 of this report. However, the Forest Research CSORT model was applied to provide key input estimates to these workbooks representing:

- Relevant changes in forest carbon stocks
- Levels of production of primary wood raw materials (see Section 4.2)
- GHG emissions associated with forest operations (i.e. forest establishment, forest maintenance, tree harvesting and extraction of wood products to forest roadside).

As discussed in some detail in Bates *et al*. (2011) and Morison *et al*. (2012), the CSORT model is a 'second generation' forest carbon accounting model under development by Forest Research, constituting a step-upgrade to the long-established CARBINE model. CARBINE was used to produce the majority of the results presented in figures in Section 3 of this report because it is simpler and quicker to use. CSORT was used to produce the much more detailed results needed for the LCA calculations forming the core of this study. The outputs produced by the CARBINE and CSORT model are very similar. However, compared with CARBINE, CSORT can represent a much greater range of forestry systems (in terms of patterns of management and harvesting) and can produce much more detailed results for GHG emissions associated with specific forestry operations (e.g. use of machinery during ground preparation, herbicide application, tree harvesting and timber extraction, production of tree seedlings and the use of fences or tree shelters for tree protection.) The methodology employed in applying CSORT to provide the results needed for the workbooks was very similar to that adopted by Bates *et al*. (2011) for the development of forestry profiles for inclusion in the Environment Agency's BEAT$_2$ software tool. As with the approach used for BEAT$_2$, two variants of the methodology were applied, the first being used to represent forest areas already under management for production and the second being used to represent the restoration of management for production in 'neglected' forests. Reference should be made to Bates *et al*. (2011) for a full description of these methodologies. Crucially, the methodology for forests already under management for production recognised that, in reality under current conditions, biomass supplied from UK conifer forests comes from stands across a distribution of ages across the rotation period (i.e. some stands will be young and in the process of becoming established, some will be in the middle of their rotations and undergoing thinning, while some will be close to or at the point of clearfelling at the end of their rotations).

As already discussed in detail in Section 3.3 of this report, if a forest consists of a large collection of stands, with ages distributed evenly over the rotation then, in any particular year, over the whole population of stands, the total carbon stock would remain the same (as some stands get thinned or felled but others grow). Consequently the total forest area neither sequesters nor emits carbon as a result of stock changes in the individual stands of trees. In general forestry practice, the creation and maintenance of such an even distribution of age classes is often a fundamental management objective, because this ensures that:

- Forest stocks are continuously being replenished as trees grow, are thinned or felled.
- The level of production of biomass and timber remains smooth from year to year, rather than going through peaks and troughs.
- The achievement of such an outcome is a fundamental criterion for sustainable forest management.

Where production of biomass is from existing forests (i.e. not newly-created) under sustainable management as 'business as usual', the assumption of an even distribution of age classes and, therefore, zero carbon stock changes (in trees) is a good model, certainly more appropriate than assuming that all stands are established at the beginning of the time horizon. Thus, in the modelling of cases involving forests already under management for production, an even age class distribution has been assumed. One consequence off adopting this approach for such cases is that estimates of annualised carbon stock changes do not depend on the selected time horizon. However, where appropriate in these cases, account was taken of long-term changes in soil carbon stocks. Results were thus generated allowing for annualised soil carbon stock changes in forests formed of stands typically in their first, second and third rotations. These results may be referred to as optional cases within the workbooks; in selecting default values for standard results, the estimates for the second rotation were assumed for conifer forests in the UK already under management for production, whilst estimates for the third rotation were assumed for broadleaf forests in the UK already under management for production. These selections for defaults reflect the respective historical status and development of coniferous and broadleaf forest areas in the UK as discussed in Sections 2 and 3 of this report (see in particular Section 3.6). Related annualised estimates of biomass production (for each primary wood raw material) and GHG emissions due to forest operations, were also estimated based on CSORT results.

For 'neglected' forest areas, restored to management for production, and for forest areas where management is intensified to increase production, interventions to produce timber and biomass constitute a clear change from business as usual management, introduced in 'year 0' and consequent forest carbon stock changes must be accounted for over an appropriate time horizon (i.e. 20 years, 40 years or 100 years, as adopted in this project). These carbon stock changes needed to be calculated relative to a 'business as usual' or reference case. The development of carbon stocks under the reference case was assumed to involve continued carbon sequestration but at modest rates. Time-dependent levels of biomass production, and GHG emissions due to forest operations, also needed to be accounted for when processing the results from CSORT.

4.4 Detailed LCA calculations for wood chains

For the purposes of this project, detailed GHG emission calculations were performed in MS Excel workbooks representing, individually, conifer forests managed for production, broadleaf forests managed for production and neglected broadleaf forests restored to management and production in the UK (see Section 4.1). These workbooks have identical structures although they assemble data from a variety of different sources in order to meet the aims and objectives of the technical specification. The general workbook structure consists of:

- A *Version Notes* worksheet which documents the particular version of the workbook and all modifications involved in its development.
- An *Input Parameters* worksheet which lays out the main analytical parameters, such as the chosen number of the forest rotation (if relevant), the choice of time horizon (20, 40 or 100 years), the choice of end-of-life disposal options for wood products, and the choice of counterfactuals, that can be selected for subsequent analysis of total GHG emissions for scenarios of forest product usage.
- A *Scenario Results* worksheet which records results for total GHG emissions (in $kgCO_2\ ha^{-1}\ yr^{-1}$) for each scenario of forest product usage broken down by contribution and set up for subsequent ranking of results.
- A *Forest Profile* worksheet which assembles results from the CSORT model representing the forest carbon stock balance, the wood product stock balance, GHG emissions for forest establishment and maintenance, GHG emissions for harvesting and extraction and the production of forest products (sawlogs, roundwood, bark and branchwood).
- An *End-of-Life Summary* worksheet for the GHG emissions associated with the disposal options for wood products and their selected counterfactuals.
- Seven individual *Disposal Option* worksheets with details of the GHG emissions associated with the disposal of products to dry landfill, to wet landfill without and with energy recovery, to incineration without and with energy recovery, and to Waste Incineration Directive (WID) compliant power only and CHP generation.
- A *Counterfactuals* worksheet with a summary of equivalent products and services to woodfuel and wood products and details of their avoided GHG emissions broken down by provision and end-of-life disposal, where relevant.
- A *Global Warming Potentials* worksheet for methane ($kgCO_2/kgCH_4$) and nitrous oxide ($kgCO_2/kgN_2O$).
- Thirty three individual *Biomass Chain* worksheets representing, visually by flow charts, each specified chain for the generation of bioenergy or the provision of wood products from sawlogs, roundwood, bark and branchwood giving the stages in each chain, the key chain parameters that can be varied, the quantities of wood involved, the amounts of bioenergy or wood products available from each chain, the calculation of GHG emissions at each stage in the chain with details of the

sources of all essential data, and summaries of total GHG emissions for each chain.

This structure enables the workbooks to take into account variations in biomass chain parameters, via relevant parts of the individual *Biomass Chain* worksheets, and variations in the analytical parameters, via the *Input Parameters* worksheet. Biomass chain parameters, indicated by the pale green cells in the flow charts of the individual *Biomass Chain* worksheets, can be varied separately. These parameters include modes of wood transport and their round trip distances, wood losses for each relevant stage in the biomass chain, and specifications for bioenergy applications (ash content of the woodfuel, and net output rating, thermal efficiency and load factor of the bioenergy plant). It is particular important to note that all GHG emission calculations in the individual *Biomass Chain* worksheets are organised in terms of annualised production from hectare of forest as the LCA functional unit so that results are expressed in terms of total GHG emissions per annualised hectare of forest (kgCO_2 ha^{-1} yr^{-1}).

Consequential LCA has been applied throughout the calculations in the workbooks. This means that the results represent the global carbon impact of specified scenarios of forest management and forest product usage. Specifically, calculations include all sources of GHG emissions. In addition to carbon stock changes in the forests, and the temporary sequestration of carbon in woodfuel and wood products and its eventual release as CO_2 and CH_4 during combustion and degradation in landfill sites, GHG emissions associated with manufacture and maintenance of all plant, machinery and equipment are incorporated into these calculations. In many instances, these contributions to GHG emissions are comparatively small, although in some cases, such as the use of capital intensive plant or the use of equipment with short operating lives, contributions can be significant.

Prominent assumptions in the calculations are summarised in notes at relevant points in the workbooks, especially in connection with the individual *Disposal Option* worksheets, the *Counterfactuals* worksheet and the individual *Biomass Chain* worksheets. In most instances, further information can be found in the specific referenced sources. One particular general assumption is that any incidental wood losses in the biomass chains are assumed to result in the burning of wood, usually in quite small quantities, without any energy recovery. Since the calculations account for carbon sequestered temporarily in both woodfuel (over quite short periods of time) and wood products (over potentially longer periods of time), it is necessary to ensure that all carbon, including that released as CO_2 from the burning of wood losses has been fully accounted. Hence, the individual *Biomass Chains* for bioenergy generation include carbon balance calculations which check that the overall balance is zero.

The main sources of data used in the workbooks are CSORT model results provided by Forest Research, timber transport GHG emissions from a study prepared by North Energy Associates Ltd and Forest Research for the Timber Transport Forum via the Confederation of Forest Industries (UK) Ltd, other transport GHG emissions produced by North Energy Associates Ltd for the National Non-Food Crops Centre and biomass chain GHG emissions from relevant $BEAT_2$ workbooks produced by AEA Technology plc and North Energy Associates Ltd for the Environment Agency and the Department for Environment, Food and Rural Affairs. Where necessary, data were modified for current purposes. For example, this involved modifying wood drying calculations to reflect the use of woodfuel, which is increasingly becoming current practice, instead of using fossil fuels which was more prevalent previously and, hence, incorporated into earlier $BEAT_2$ workbooks.

4.5 Important conventions in LCA calculations

The interpretation of results presented in this study requires a clear understanding of certain key conventions adopted in carrying out underlying LCA calculations. It is particularly important to understand that calculations:

- Aim to evaluate the impacts on GHG emissions balances of decisions *'taken now'* to harvest wood (or not to harvest wood) and choices *'taken now'* about the utilisation of harvested wood for specific end uses.
- Are principally relevant to decisions about the management of large populations of stands of trees (i.e. forests, see Sections 3.3 and 3.5) and involve the averaging and annualising of GHG removals and emissions over time as appropriate for the type of forest being considered.

Evaluation of decisions 'taken now': forest carbon stocks

If a decision is taken now to stop harvesting and 'leave carbon in the forest', then carbon stocks might be expected to rise from an initial (average) equilibrium carbon stock to a new, higher (average) equilibrium carbon stock (see discussion in Section 3 and in particular Section 3.5 and Figures 3.14 and 3.15). This change in carbon stocks would follow a roughly exponential trajectory and would take place over a period of several decades, perhaps as long as a century, depending on the tree species, growth rate and the rotation(s) on which forest stands have previously been managed. Such changes in forest carbon stocks associated with the option of stopping harvesting have been considered as a specific scenario in this study (scenario 00.00 in Tables 4.8 and 4.9, Section 4.6). Relevant results are discussed in Section 5.2.

If a decision is taken now to continue harvesting trees from forests already under management for sustainable wood production, then carbon stocks in the trees making up the forest should neither increase nor decrease (see discussion in Section 3 and in particular Section 3.3). However, there may be some ongoing changes in soil carbon stocks, although these will also eventually reach equilibrium (see for example discussion of figures 3.14, 3.16 and 3.17 in Section 3). Such changes in carbon stocks have been considered as part of the modelling of scenarios involving continued management of forest areas for wood production. Relevant results are illustrated in Section 5.2.

If a decision is taken now to restore management in 'neglected' broadleaf forests (either involving harvesting of wood products or felling of trees without harvesting to meet environmental and amenity objectives), then carbon stocks might be expected to drop from an initial average equilibrium carbon stock to a new, lower average equilibrium carbon stock (see discussion in Section 3 and in particular Section 3.5 and Figure 3.18). The time taken and the pattern over time by which this carbon stock change takes place will be strongly dependent on the specific approach taken to restoring management (e.g. involving either introduction of significant harvesting through heavy thinning or management of changes in growing stock levels through progressive but gradual thinning), but in all cases a lower average equilibrium carbon stock will ultimately be reached, after which there should be no further long term changes in forest carbon stocks. Conversely, as discussed in Section 3.5, if a decision is taken now *not to* restore management in areas of 'neglected' broadleaf forest, then forest carbon stocks might be expected to continue to increase until an equilibrium level is reached. The magnitude of this increase and the time taken will depend on a number of factors, such as the mean age of the trees comprising the 'neglected' forest areas and the extent of the previous 'neglect' (e.g. whether harvesting of trees never took place, or harvesting was practiced for a period and then halted). Nevertheless the change in carbon stocks would follow a roughly exponential trajectory and would most likely take place over a period of several decades. All such changes in carbon stocks associated with restoring management in 'neglected' broadleaf forest areas (realised and counterfactual) have been considered in the modelling of relevant scenarios, as illustrated by the example results in Section 5.2.

Evaluation of decisions 'taken now': harvested wood products

To reiterate, this study is concerned with evaluating the impacts of decisions taken now about whether to harvest wood and how to utilise harvested wood. As a very important consequence, it is not necessary (indeed it would be incorrect) for this study to take account of existing 'legacy' carbon stocks in harvested wood products that have already been harvested and are in use or have already been disposed of, as well as other impacts on GHG emissions associated with the utilisation of *existing* wood products and their disposal. By the same token, it has been necessary for this study to model the carbon stock changes associated with any harvested wood products manufactured as a result of decisions *taken now* as well as any subsequent impacts on GHG emissions, notably when wood products come to the end of their useful lives and are disposed of. Certain important wood products have working lifetimes lasting many decades. Thus, the impacts on GHG emissions due to the disposal at end-of-life of wood products manufactured now will often not become apparent in LCA results for shorter time horizons (i.e. 20 and 40 years). However, some wood products such as paper and card have relatively short working lifetimes and the impacts of disposal at end-of-life will be registered over shorter time horizons. The full impacts on GHG emissions arising from disposal at end-of-life of all wood products considered in this study are registered over a 100 year time horizon because all wood products have been assigned notional working lifetimes of no more than 100 years. Assumptions made about the working lifetimes for different wood products have already been reported in Table 4.5, Section 4.2.

Evaluation of decisions 'taken now': imported wood

If a decision is taken now to stop harvesting and 'leave carbon in the forest', then one option (counterfactual) is to import harvested wood instead. As already discussed in Section 4.2, in this study it has been assumed that a significant increase in requirement for imported wood in the UK would entail intensification of the management of forests in other countries. This assumption has important implications for the estimation of GHG balances for imported wood, with much of the preceding discussion concerning restoration of management in neglected forests applying. The sensitivity of results to this assumption is briefly explored in Section 5.2.

Averaging and annualising: forest carbon stocks

Many of the points concerning the treatment of forest carbon stocks on the basis of populations of stands have already been discussed immediately above and in Sections 3.3 to 3.5. It is also important to understand the implications of the annualisation of GHG removals and emissions over specified time horizons, as already referred to in Section 4.3. For example, consider the modelled reduction in forest carbon stocks over time due to the restoration of management in 'neglected' forests, as illustrated in Figure 4.2 (note that this is based directly on the example already presented in Figure 3.18, Section 3.5). The example calculations in Figure 4.2 demonstrate how the estimated emissions depend on the selected time horizon. As already noted in the preceding discussion, the time taken and the pattern over time by which this carbon stock change takes place will be strongly dependent on the specific approach taken to restoring management and this will influence the estimation of annualised emissions over different time horizons. However, in all cases a lower average equilibrium carbon stock will ultimately be reached, with the result that annualised emissions will tend to become smaller over longer time horizons. More generally, as discussed above, the trajectory with which many changes in forest carbon stocks develop will be roughly exponential, with the result that annualised emissions will be largest over a 20 year time horizon and smallest over a 100 year time horizon.

Averaging and annualising: harvested wood products

The production of wood from an individual stand of trees is discontinuous over time. Typically under UK conditions, there will be no production from a stand for the first 20 years following establishment (because the trees are too young and small to produce useful quantities of wood). Initial harvesting takes place around age 20 years as a thinning operation. The process of thinning is then repeated generally every 5 years until the time of clearfell (i.e. the rotation period) is approached, clearfelling constituting the main production event for the stand. Consequently, annualised levels of production from an individual stand can be very sensitive to the selected time horizon. However, if a population of stands with ages distributed evenly over the rotation period is considered, such as discussed in Section 3.3, per-hectare production will be maintained at a constant level representing the time-averaged level of production over a rotation for an individual stand. The estimation of annualised production for a population of stands has been illustrated in detail by Bates *et al.* (2011) and Matthews *et al.* (2012).

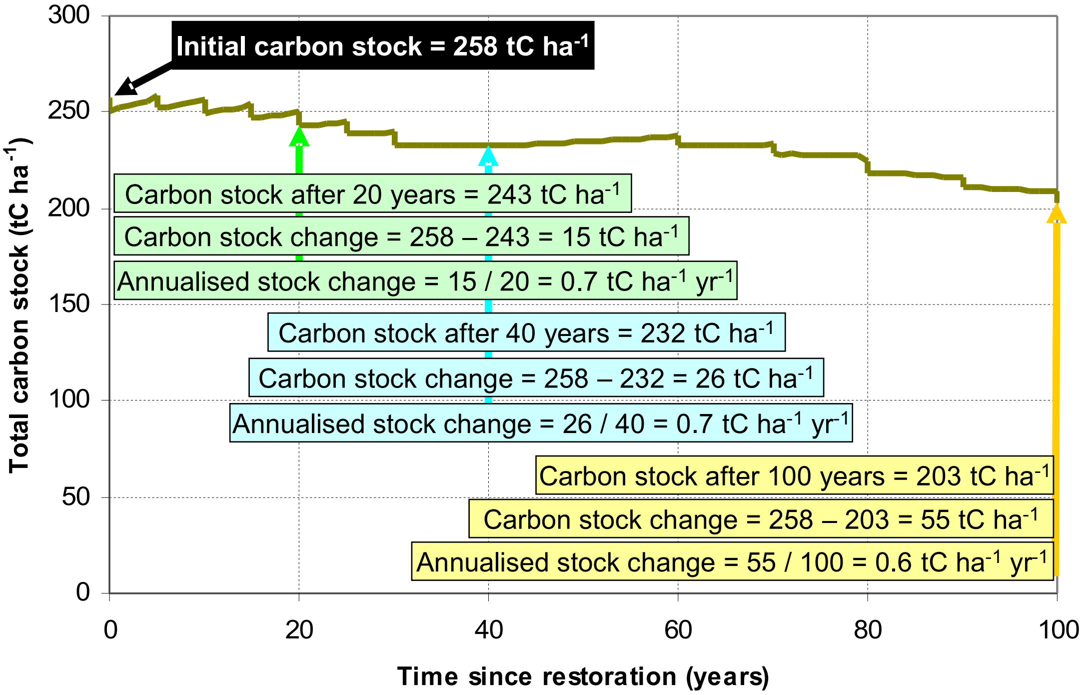


Figure 4.2. Illustration of the calculation of annualised carbon stock changes due to restoration of forest management in 'neglected' broadleaf forests.

In this study, scenarios involving continued production from existing areas of forest have involved the assumption that production is from a population of stands evenly distributed over rotations, with the result that levels of production are constant and do not depend on the time horizon. The situation is different when considering production from 'neglected' broadleaf forest areas which have been restored to management. Levels of production (and the quantities of raw wood products harvested) will depend strongly on the composition of 'neglected' forest areas before the re-introduction of management, and on the particular management regime applied. As a result, annualised production will vary with the selected time horizon in terms of the total quantity of wood produced and in terms of the relative mix of raw wood products. The dependence of levels and types of production on time horizon when considering the introduction of management in previously unmanaged forest areas has been illustrated by Bates *et al.* (2011).

4.6 Results for standard scenarios

A key element of this project involved the reporting of GHG emissions for a range of 'standard' scenarios for the management of forest areas and the utilisation of wood (if harvested) for different final products. As already explained (see Section 4.2 and in particular Figure 4.1) harvested wood can be converted into a diverse range of (combinations of) products, subject to certain physical and mechanical constraints. Results for standard scenarios permitted the analysis of the range of possible impacts on GHG emissions due to the use of wood as a material and/or fuel and the sensitivity of results to decisions made about the harvesting of wood and its utilisation for specific end products. Slightly different sets of scenarios were defined for coniferous and broadleaf forest types as given in Tables 4.8 and 4.9 respectively.

Each scenario was given a 4 digit code with the form 'XX.YY', where XX is the 'main scenario number' (as shown in tables 4.8 and 4.9) and YY denotes a 'sub-scenario' related to the utilisation of woodfuel for different energy conversion routes (see Tables 4.10 and 4.11). It should be noted that the same format of four digit codes is used sequentially for the managed conifer and broadleaf forests, and the restoration of neglected forests. However, because of differences in the composition of scenarios for conifer and broadleaf forests, these codes do not necessarily coincide across these two types of forest.

Table 4.8 List of standard scenarios for forest management/wood utilisation: coniferous forests

Main scenario number	**Sawlogs**		**Small roundwood**		**Bark**	**Branch wood (50%)**
	Main	**Offcut**	**Main**	**Offcut**		
00.00	Leave in forest (no harvesting)					
01	All stemwood for fuel				Fuel	Fuel
02	Sawn timber	Fuel	Fuel		Fuel	Fuel
03	Sawn timber	Fuel	Particleboard		Fuel	Fuel
04	Sawn timber	Particleboard	Particleboard		Fuel	Fuel
05	Sawn timber	Particleboard	Fuel		Fuel	Fuel
06	Sawn timber	Fuel	MDF		Fuel	Fuel
07	Sawn timber	MDF	MDF		Fuel	Fuel
08	Sawn timber	MDF	Fuel		Fuel	Fuel
09	Sawn timber	Fuel	Pallets	Fuel	Fuel	Fuel
10	Sawn timber	Particleboard	Pallets	Particleboard	Fuel	Fuel

Table 4.8 (continued) List of standard scenarios for forest management/wood utilisation: coniferous forests

Main scenario number	Sawlogs		Small roundwood		Bark	Branch wood (50%)
	Main	Offcut	Main	Offcut		
11	Sawn timber	MDF	Pallets	MDF	Fuel	Fuel
12	Sawn timber	Fuel	Fencing	Fuel	Fuel	Fuel
13	Sawn timber	Fuel	Fencing	Particleboard	Fuel	Fuel
14	Sawn timber	Fuel	Fencing	MDF	Fuel	Fuel
15	Sawn timber	Particleboard	Fencing	Fuel	Fuel	Fuel
16	Sawn timber	Particleboard	Fencing	Particleboard	Fuel	Fuel
17	Sawn timber	Particleboard	Fencing	MDF	Fuel	Fuel
18	Sawn timber	MDF	Fencing	Fuel	Fuel	Fuel
19	Sawn timber	MDF	Fencing	Particleboard	Fuel	Fuel
20	Sawn timber	MDF	Fencing	MDF	Fuel	Fuel
21	Sawn timber	Fuel	Paper and card		Fuel	Fuel
22	Sawn timber	Particleboard	Paper and card		Fuel	Fuel
23	Sawn timber	MDF	Paper and card		Fuel	Fuel
24	All stemwood for fuel				Mulch	Fuel
25	Sawn timber	Fuel	Fuel		Mulch	Fuel
26	Sawn timber	Fuel	Particleboard		Mulch	Fuel
27	Sawn timber	Particleboard	Particleboard		Mulch	Fuel
28	Sawn timber	Particleboard	Fuel		Mulch	Fuel
29	Sawn timber	Fuel	MDF		Mulch	Fuel
30	Sawn timber	MDF	MDF		Mulch	Fuel
31	Sawn timber	MDF	Fuel		Mulch	Fuel
32	Sawn timber	Fuel	Pallets	Fuel	Mulch	Fuel
33	Sawn timber	Particleboard	Pallets	Particleboard	Mulch	Fuel
34	Sawn timber	MDF	Pallets	MDF	Mulch	Fuel
35	Sawn timber	Fuel	Fencing	Fuel	Mulch	Fuel
36	Sawn timber	Fuel	Fencing	Particleboard	Mulch	Fuel
37	Sawn timber	Fuel	Fencing	MDF	Mulch	Fuel
38	Sawn timber	Particleboard	Fencing	Fuel	Mulch	Fuel
39	Sawn timber	Particleboard	Fencing	Particleboard	Mulch	Fuel
40	Sawn timber	Particleboard	Fencing	MDF	Mulch	Fuel
41	Sawn timber	MDF	Fencing	Fuel	Mulch	Fuel
42	Sawn timber	MDF	Fencing	Particleboard	Mulch	Fuel
43	Sawn timber	MDF	Fencing	MDF	Mulch	Fuel
44	Sawn timber	Fuel	Paper and card		Mulch	Fuel
45	Sawn timber	Particleboard	Paper and card		Mulch	Fuel
46	Sawn timber	MDF	Paper and card		Mulch	Fuel

Table 4.9 List of standard scenarios for forest management/wood utilisation: broadleaf forests

Main scenario number	Sawlogs		Small roundwood		Bark	Branch wood (50%)
	Main	Offcut	Main	Offcut		
00.00	Leave in forest (no harvesting)					
00.01*	Management for environment and amenity objectives (no harvesting)*					
01	All stemwood for fuel				Fuel	Fuel
02	Sawn timber	Fuel	Fuel		Fuel	Fuel
03	Sawn timber	Fuel	Particleboard		Fuel	Fuel
04	Sawn timber	Particleboard	Particleboard		Fuel	Fuel
05	Sawn timber	Particleboard	Fuel		Fuel	Fuel
06	Sawn timber	Fuel	MDF		Fuel	Fuel
07	Sawn timber	MDF	MDF		Fuel	Fuel
08	Sawn timber	MDF	Fuel		Fuel	Fuel
09	Sawn timber	Fuel	Fencing	Fuel	Fuel	Fuel
10	Sawn timber	Fuel	Fencing	Particleboard	Fuel	Fuel
11	Sawn timber	Fuel	Fencing	MDF	Fuel	Fuel
12	Sawn timber	Particleboard	Fencing	Fuel	Fuel	Fuel
13	Sawn timber	Particleboard	Fencing	Particleboard	Fuel	Fuel
14	Sawn timber	Particleboard	Fencing	MDF	Fuel	Fuel
15	Sawn timber	MDF	Fencing	Fuel	Fuel	Fuel
16	Sawn timber	MDF	Fencing	Particleboard	Fuel	Fuel
17	Sawn timber	MDF	Fencing	MDF	Fuel	Fuel
18	All stemwood for fuel				Mulch	Fuel
19	Sawn timber	Fuel	Fuel		Mulch	Fuel
20	Sawn timber	Fuel	Particleboard		Mulch	Fuel
21	Sawn timber	Particleboard	Particleboard		Mulch	Fuel
22	Sawn timber	Particleboard	Fuel		Mulch	Fuel
23	Sawn timber	Fuel	MDF		Mulch	Fuel
24	Sawn timber	MDF	MDF		Mulch	Fuel
25	Sawn timber	MDF	Fuel		Mulch	Fuel
26	Sawn timber	Fuel	Fencing	Fuel	Mulch	Fuel
27	Sawn timber	Fuel	Fencing	Particleboard	Mulch	Fuel
28	Sawn timber	Fuel	Fencing	MDF	Mulch	Fuel
29	Sawn timber	Particleboard	Fencing	Fuel	Mulch	Fuel
30	Sawn timber	Particleboard	Fencing	Particleboard	Mulch	Fuel
31	Sawn timber	Particleboard	Fencing	MDF	Mulch	Fuel
32	Sawn timber	MDF	Fencing	Fuel	Mulch	Fuel
33	Sawn timber	MDF	Fencing	Particleboard	Mulch	Fuel
34	Sawn timber	MDF	Fencing	MDF	Mulch	Fuel

*Note: scenario 00.01 only relevant for restoration of management in neglected broadleaf forests.

Table 4.10 Significance of sub-scenario numbers for utilisation of wood as fuel*

Sub-scenario number	Energy conversion route
XX.01	Sawlogs and/or smalll roundwood used for domestic heating with logs Bark and branchwood used for domestic heating with wood pellets
XX.02	Sawlogs and/or smalll roundwood used for domestic heating with briquettes Bark and branchwood used for domestic heating with wood pellets
XX.03	Domestic heating with wood pellets
XX.04	Commercial and industrial heating with wood chips
XX.05	Commercial and industrial combined heat and power with wood chips
XX.06	Power only generation with raw wood (branchwood harvested and utilised as bales)
XX.07	Power only generation with wood pellets

*Note: this list applies to scenarios where sawlog and/or roundwood material is utilised for fuel.

Table 4.11 Significance of sub-scenario numbers for utilisation of wood as fuel*

Sub-scenario number	Energy conversion route
XX.01	Domestic heating with wood pellets
XX.02	Commercial and industrial heating with wood chips
XX.03	Commercial and industrial combined heat and power with wood chips
XX.04	Power only generation with raw wood (branchwood harvested and utilised as bales)
XX.05	Power only generation with wood pellets

*Note: this list applies to scenarios where neither sawlog nor roundwood material is utilised for fuel.

5. Results and interpretation

5.1 'Absolute' and 'relative' emissions

It is of course essential that the precise meaning of any reported value for GHG emissions is defined in a clearly understandable way. Unfortunately, there is no widely accepted and applied terminology for referring to types of GHG emissions (and/or removals) associated with forestry/bioenergy/wood products systems. For the purposes of this project, two types of GHG emissions may be defined:

1. Absolute (total) GHG emissions
2. Relative GHG emissions.

Absolute GHG emissions

In this report, absolute GHG emissions are calculated (on an annualised basis over a specified time horizon) as the sum of:

- The carbon stock change in forests, which can consist of a net 'removal' (negative value) or a net 'emission' (positive value)
- The quantity of harvested carbon utilised in wood products including fuel (always a negative value, denoting the sequestration of carbon in newly-harvested wood products, see Section 4.5 and inclusion of disposal at end of this list)
- The GHG emissions associated with forest operations including ground preparation, tree planting, herbicide application, tree protection (always an emission and therefore a positive value)
- The GHG emissions associated with wood harvesting and extraction (always an emission and therefore a positive value)
- The GHG emissions associated with wood transport (always an emission and therefore a positive value)
- The GHG emissions associated with wood processing (always an emission and therefore a positive value)
- The GHG emissions associated with disposal of harvested wood products at end-of-life, assuming this occurs within the specified time horizon (always an emission and therefore a positive value).

Calculations include the three major GHGs (CO_2, CH_4 and N_2O) and results are expressed in units of kilograms or tonnes of CO_2-equivalent. The contributions listed above are estimated as distinct components in the workbooks produced as part of this project (see Section 4.4) and then added together to produce the full result. However, there is one type of wood product which is treated according to a slightly different scheme, namely woodfuel. In this case, the 'processing' of woodfuel (to produce energy) involves actually burning the wood, with the result that the GHG emissions associated with 'wood processing' include the GHG emissions due to the combustion (i.e. the end use) of the wood.

Examples illustrating the calculation of absolute GHG emissions are given in Figures 5.1 to 5.4, Section 5.2.

Relative GHG emissions

In this report, relative GHG emissions are calculated as:

Relative GHG emissions = Absolute GHG emissions – Counterfactual GHG emissions.

Absolute GHG emissions have been defined above. The ‘counterfactual’ GHG emissions are the emissions that would occur if wood was not harvested (and utilised as specified for a particular scenario) and the services that would have been supplied by the harvested wood were provided by other means.

In the case of ‘non-wood’ counterfactuals, the counterfactual GHG emissions represent the estimated life cycle emissions for manufacturing an equivalent product from a non-wood alternative. For example, in a scenario involving the production of pallets, the counterfactual GHG emissions would be estimated based on an equivalent quantity of pallets manufactured from plastic[9].

In the case of (imported) wood counterfactuals, the counterfactual emissions represent the estimated life cycle emissions for manufacturing an equivalent product from imported wood sources. The calculations involved are similar to those for estimating absolute GHG emissions for UK-grown wood but are relevant to the growing and harvesting of wood in other countries and its importation (see Section 4.2).

It is important to emphasise and understand that the counterfactual GHG emissions used for the calculation of relative GHG emissions as defined for the purposes of this study do not include the continued sequestration of carbon in forests that would result if wood was not harvested. Rather, the possibility of not harvesting wood but rather ‘leaving it in the forest’ is modelled as an explicit scenario (Scenario 00.00, see Section 3.6 and Tables 4.8 and 4.9, Section 4.5), the continued sequestration of carbon in forests that would result if wood was not harvested are not included in the calculation of counterfactual GHG emissions. As such, explicit results for the sequestration of carbon in forests in which harvesting is suspended (i.e. Scenario 00.00) can be compared directly with results for scenarios involving harvesting and wood utilisation. The rationale for this approach is elaborated in Section 6 of this report and in particular in Section 6.2.

---

[9] It is important to note that ‘complete equivalence’ is required when comparing counterfactuals with wood products, and this is incorporated into the LCA workbooks. This means, for example, that the relative lifetimes of the products, as well as their physical functions, have to be taken into account. Pallets are a good example because it is necessary to assume that a wooden pallet has a lifetime of (typically) 2 years, compared with a plastic pallet for which a (typical) lifetime of 8 years is assumed. Hence, in order to substitute for 1 wooden pallet, 2/8 = 1/4 of a plastic pallet is required. This is accounted for in the LCA workbooks (mainly in the Counterfactuals worksheet along with differences in the weights of pallets.

If absolute GHG emissions from harvesting and utilising wood under a particular scenario are smaller than the counterfactual GHG emissions, then the result for relative GHG emissions will be a negative number. If absolute GHG emissions are larger than counterfactual GHG emissions, then the relative GHG emissions take a positive number. Hence, 'large' negative values for relative GHG emissions may be taken to suggest that the harvesting and utilisation of wood from UK forests (and according to the given scenario) should provide GHG emissions benefits overall. In this context, relative GHG emissions (specifically when taking negative values) may be referred to loosely as representing the potential '*emissions savings*' that may be achieved through the harvesting and utilisation of UK-grown wood. However, these results need to be understood in the context of estimating carbon impacts for different wood utilisation options, which is the focus of this project. This subject is discussed in detail in Section 6 of this report.

Examples illustrating the calculation of relative emissions are given in Figures 5.5 and 5.7, Section 5.3.

5.2 Absolute emissions for example scenarios

'No harvesting' scenarios

Figure 5.1 shows the results for arguably the simplest forest scenarios modelled as part of this study, involving no wood production (Scenarios 00.00 and 00.01).

As discussed in earlier sections of this report (see in particular Section 4.5), the suspension of management in forests involving harvesting of trees (Scenario 00.00) is likely to lead to an increase in forest carbon stocks and, hence to carbon sequestration in forests. As can be seen in Figure 5.1, results for conifer forests suggest quite high rates of carbon sequestration particularly over shorter time horizons (about −17, −14 and −8 tCO_2 ha^{-1} yr^{-1}, equivalent to about −5, −4, and −2 tC ha^{-1} yr^{-1} respectively for time horizons of 20, 40 and 100 years). These results reflect assumptions about the average age of forest stands at the point when harvesting is suspended. Specifically stands were assumed to be roughly around the point of 'mid-rotation', therefore, in the 'full-vigour' phase of growth with potential for high rates of carbon sequestration. This could be viewed as a pessimistic assumption (when comparing with no harvesting) but it is consistent with a related assumption that coniferous forest stands in the UK are generally already under management for wood production on the basis of sustainable and continuous yield (i.e. forest stands are managed on a characteristic rotation with the aim of achieving an even distribution of stand ages over the rotation, see Sections 3.3 and 4.5). As discussed in Section 4.5, the annualised rate of carbon sequestration diminishes as the time horizon becomes longer.

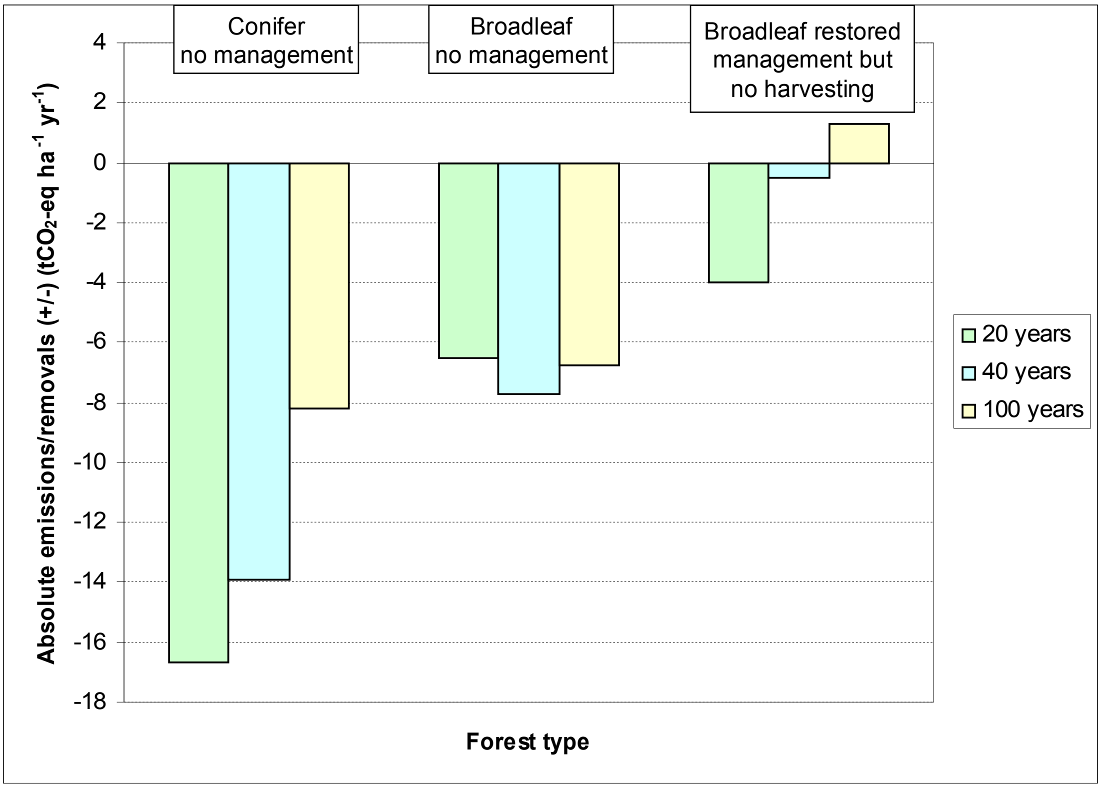


Figure 5.1. Rates of carbon sequestration (or emissions) estimated for characteristic UK forest types when management is suspended (Scenarios 00.00 and 00.01). Results are shown for time horizons of 20, 40 and 100 years.

Estimated annualised rates of carbon sequestration for broadleaf forests where management is suspended (or not introduced) are lower than those estimated for coniferous forests, although a reduction in rate with time horizon is not apparent. In fact an almost constant rate is estimated at about $-7tCO_2$ ha^{-1} yr^{-1} (about −2 tC ha^{-1} yr^{-1}), reflecting the particular pattern of growth predicted by the CSORT model for the assumed tree species and growth rate; it remains the case that the rate of carbon sequestration would diminish if longer time horizons were considered.

As discussed in Section 5.1, carbon sequestration estimates such as shown in Figure 5.1 for coniferous and broadleaf forests in which management is suspended can be used as 'reference lines' against which to compare estimates of relative GHG emissions for other scenarios involving harvesting and production of wood for fuel and/or materials. Ideally, relative GHG emissions for such scenarios need to match or preferably be less (more negative) than these reference lines.

It should be noted that the same rates of carbon sequestration are referred to as reference lines when considering either the continued management of broadleaf forests or the restoration of management in 'neglected' broadleaf forests. However, the overall results in terms of carbon stock changes for the two types of forest system will be different because the stock changes associated with 'continued management' and 'restored management' are modelled differently.

In the case of restored management in 'neglected' forest areas, an alternative set of carbon sequestration rates may be referred to, which are based on the scenario of restored management but without harvesting and production of wood (Scenario 00.01), as discussed in Section 3.5. Annualised results for this scenario are also shown in Figure 5.1. Estimated annualised rates of carbon sequestration over time horizons of 20 years and 40 years are low (about −4, −0.5 tCO_2 ha^{-1} yr^{-1}, equivalent to about −1, −0.1 tC ha^{-1} yr^{-1} respectively), reflecting the fact that trees are being felled as part of management to meet environmental and amenity objectives (but not involving wood production). Nevertheless, net sequestration is still observed because the wood from felled trees is assumed to be stacked and retained in the forest. However, over a 100 year time horizon, carbon stock changes due to the felling of trees and GHG emissions from the degradation and decay of felled wood exceed sequestration in growing trees, with the result that annualised sequestration is estimated to be positive, i.e. a small net emission (about 1 tCO_2 ha^{-1} yr^{-1}, equivalent to about 0.3 tC ha^{-1} yr^{-1}).

'Energy only' scenario example

Figure 5.2 shows an example of the calculated absolute GHG emissions for a scenario involving harvesting of wood from UK forests and using all of the wood for fuel (Scenario 01.06, without application of CCS). The scenario is based on the consumption of raw wood for power only generation. The figure shows the overall absolute GHG emissions for the three characteristic UK forest types and also contributions made to the total result by:

- Forest carbon stock changes (dark green bars in figure)
- Harvested carbon utilised as fuel (olive bars)
- Forest operations including harvesting (dark orange bars)
- Wood transport and processing (yellow-orange bars)

The overall absolute GHG emissions are shown as light green bars.

In the case of coniferous and broadleaf forests already under management for production, forest carbon stock changes register as modest levels of carbon sequestration (1 tCO_2 ha^{-1} yr^{-1} for conifer forests, for broadleaf forests the level is almost negligible). In the case of restoring management in 'neglected' broadleaf forests, forest carbon stock changes register as significant emissions (2 tCO_2 ha^{-1} yr^{-1}, equivalent to about 0.6 tC ha^{-1} yr^{-1}).

For all three forest types, the harvesting of wood leads to a transfer of carbon to wood products (sequestration – see related discussion in Sections 4.5 and 5.1). The magnitude of this transfer of carbon is different for the three forest types because they are directly related to levels of production which in turn depend on the productive potential of the different forest types. The carbon 'sequestered' in wood products is re-emitted to the atmosphere quickly when the wood is combusted (included as part of yellow-orange bar in Figure 5.2) and the emissions from the combusted wood exactly balance the inflow of carbon as harvested wood. Other emissions due to wood processing include (generally small) contributions due to wood transport, wood chipping as part of processing at the power station and the actual process of conversion to energy. GHG emissions due to forest operations (also generally small) are shown separately (dark orange bar). GHG emissions due to disposal of wood at end-of-life are always zero for scenarios where all wood is utilised for fuel for reasons explained in Section 5.1.

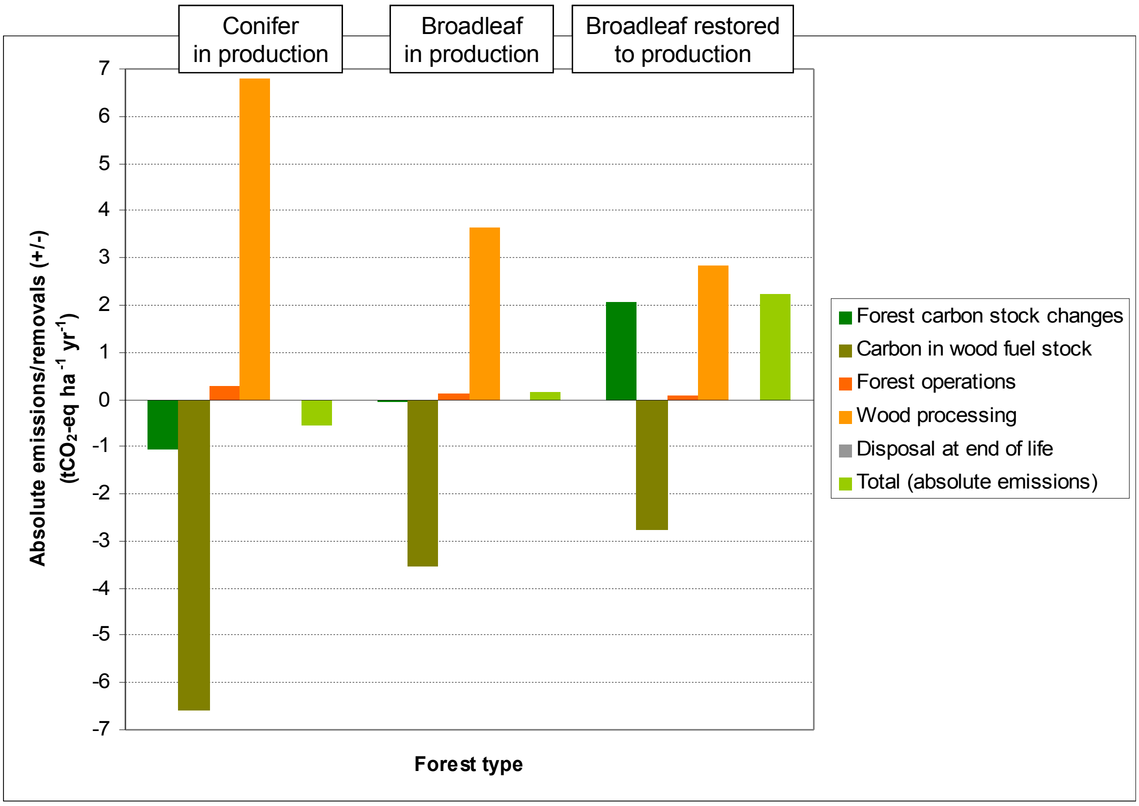


Figure 5.2. Absolute GHG emissions estimated for characteristic UK forest types for example scenarios involving management for production of wood for fuel only (Scenario 01.06, without application of CCS). Total emissions are shown as well as contributions to the total due to forest carbon stocks, carbon in harvested wood, forest operations and wood processing including combustion. Results are shown for 40 year time horizon.

The overall results for absolute GHG emissions for the scenario are shown by the light green bars in Figure 5.2. For coniferous and broadleaf forests already under management for production, absolute GHG emissions are close to zero (in fact there is slight net sequestration in the case of coniferous forests). However, significant absolute GHG emissions are registered for the case of restored management in 'neglected' broadleaf forests (2 tCO_2–equivalent ha^{-1} yr^{-1}, equivalent to about 0.6 tC-equivalent ha^{-1} yr^{-1}), almost entirely attributable to associated forest carbon stock changes.

It is worth noting that the results in Figure 5.2 illustrate contrasting examples in which woodfuel production from forests might be described as 'carbon neutral' in certain circumstances (in the case of continued management of coniferous and broadleaf forests) and might be described as incurring a 'carbon debt' in certain other circumstances (as in the case of restored management and harvesting in 'neglected' broadleaf forests).

'Material products' scenario example

Figure 5.3 illustrates the calculated absolute GHG emissions for example scenarios involving the harvesting of wood and the production of a mix of materials and fuel. The example selected for managed coniferous forests involves production of a combination of sawn timber, MDF, paper and card and woodfuel, the latter used for commercial and industrial CHP generation with wood chips (Scenario 23.05, without application of CCS). Generally paper and card are not produced from hardwoods in the UK. Therefore, the equivalent scenarios for broadleaf forests are slightly simpler, involving the production of sawn timber, MDF and woodfuel for CHP with wood chips (Scenario 07.05, without application of CCS). The figure shows the overall absolute GHG emissions for the three characteristic UK forest types and also contributions made to the total result by:

- Forest carbon stock changes (dark green bars in figure)
- Harvested carbon utilised as products fuel (olive bars)
- Forest operations including harvesting (dark orange bars)
- Wood transport and processing (yellow-orange bars)
- Disposal of wood products at end-of-life (assumed to be through combustion in a WID-compliant power-only plant, grey bars).

The overall absolute GHG emissions are shown as light green bars.

The results in Figure 5.3 have been calculated in the same way as for Figure 5.2 and can be directly compared, revealing some important features. The carbon stock change in forests and the quantities of carbon in wood products are the same in each scenario when comparing Figure 5.3 with Figure 5.2. The GHG emissions from forest operations are very similar. There are marked differences in the GHG emissions from wood processing, with greater GHG emissions arising when using all the wood for fuel only. Conversely, when considering the scenario for a mix of wood products, there are notable although relatively small GHG emissions associated with disposal of wood at end-of-life for the example based on coniferous forests (this is due to the disposal over relative short timescales of paper and card products), whereas such GHG emissions are zero for the fuel-only scenario (see earlier discussion). Overall, absolute GHG emissions are lower for the scenario involving mixed uses of wood compared with fuel only. The key difference is due to the carbon stock retained in some wood products which have lifetimes longer than the 40 year time horizon used in the calculation of the absolute GHG emissions.

The overall result is that absolute GHG emissions for these examples of production of a mix of materials and fuel are observed to be negative (i.e. net sequestration) when considering forest types already under management for production, whilst absolute GHG emissions for the case restoration of management in ‘neglected’ broadleaf forests are observed to be smaller than would be the case if all the harvested wood was used for fuel.

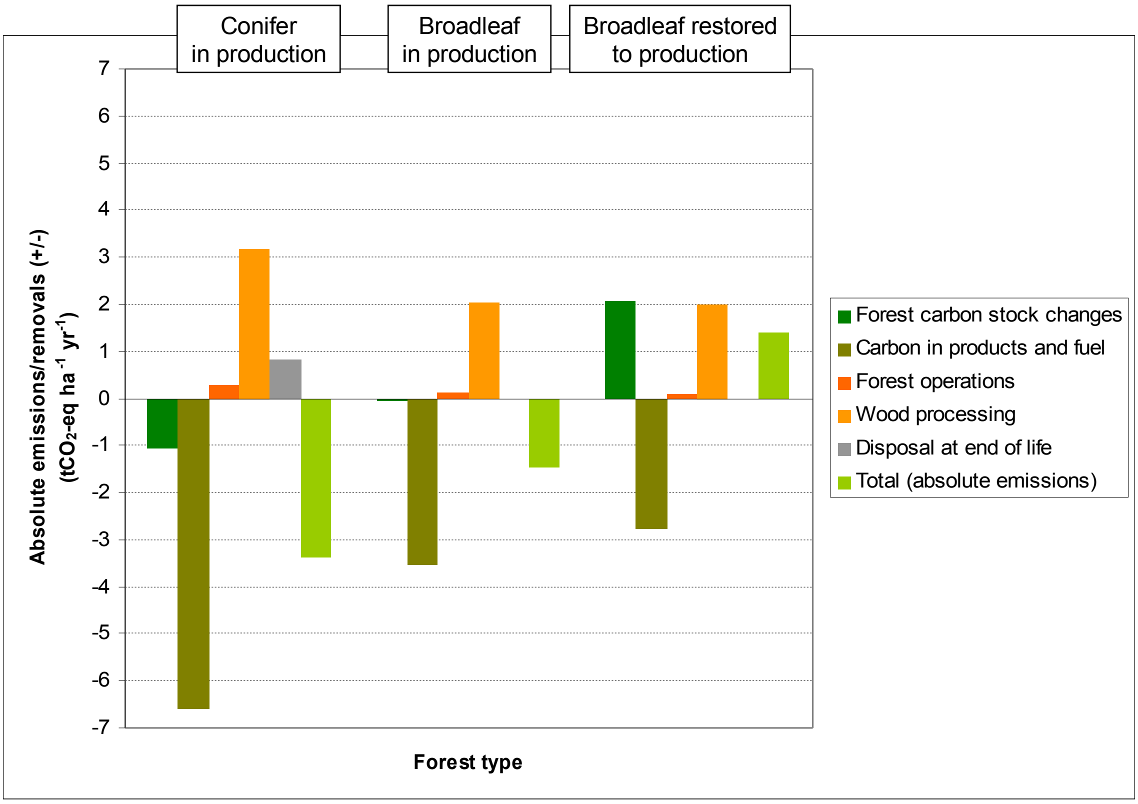


Figure 5.3. Absolute GHG emissions estimated for characteristic UK forest types for example scenarios involving management for production of wood for a range of materials and fuel (Scenario 23.05, for coniferous forest example, Scenario 05.07 for broadleaf forest examples, all without application of CCS). Total emissions are shown as well as contributions to the total due to forest carbon stocks, carbon in harvested wood, forest operations and wood processing including combustion. Results are shown for 40 year time horizon.

Sensitivity of absolute emissions to disposal options

Over longer time horizons, GHG emissions due to the disposal of material wood products become more significant and show strong dependence on the approach to disposal, as illustrated in Figure 5.4. The results in Figure 5.4 show the GHG emissions due to disposal of wood products at end-of-life over a 100 year time horizon for the example forest type of conifer forests already under management for production, and in which harvested stemwood is utilised for sawn timber and particleboard (Scenario 04.03, without application of CCS).

Disposal to dry landfill results in theoretically very low GHG emissions but this is also an unlikely scenario; there are few if any strictly dry landfill sites in the UK. Apart from dry landfill the lowest calculated absolute GHG emissions result from energy recovery in Waste Incineration Directive (WID) compliant plants, either for power only (about 6 tCO_2-equivalent ha^{-1} yr^{-1}) or for CHP generation (about 4 tCO_2-equivalent ha^{-1} yr^{-1}). The highest theoretical GHG emissions result from disposal of waste wood to wet landfill, particularly in the case when energy is not recovered (about 50 tCO_2-equivalent ha^{-1} yr^{-1}). Estimates of methane emissions from disposal of wood to landfill are highly uncertain. It is also be noted that energy recovery from landfill gas is frequently but not universally practiced.

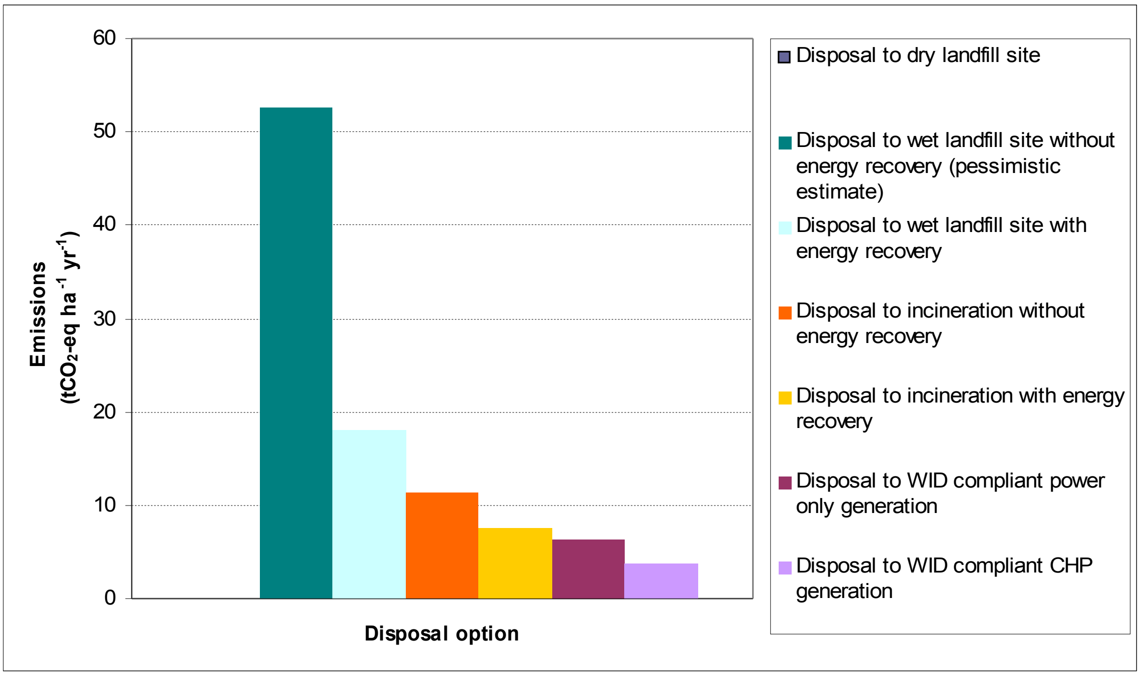


Figure 5.4. Examples of GHG emissions associated with disposal of solid wood products at end-of-life. The results are based on the same scenario as in Figure 5.3 for the example of conifer forests managed for production, but the time horizon considered is 100 years. Results are shown for different disposal options. Emissions due to disposal to dry landfill are small and do not register in the graph.

'Energy only' scenarios: absolute emissions per unit energy

Estimates of GHG emissions from bioenergy sources are frequently expressed in the form of absolute GHG emissions per unit of delivered energy, e.g. in units of $kgCO_2$–equivalent GJ^{-1} or $kgCO_2$–equivalent MWh^{-1}. Such 'GHG emissions factors' can be useful as one way of comparing different options for provision of energy (either as electricity or heat) and examples produced from the results of this study are shown in Table 5.1, for scenarios involving harvesting of wood from UK forests and using all of the wood for fuel. (The selected scenarios are 01.01-01.04, 01.06 and 01.07. Scenario 01.05 is omitted because it involves CHP generation. The calculation of an emissions factor is complicated when more than one form of energy is produced.)

In the case of coniferous and broadleaf forests already under management for production, the estimated GHG emissions factors are the same for all three time horizons (see discussions in Section 3.3 and particularly Section 4.3; note also that woodfuel is assumed to be consumed relatively quickly after harvesting so the impacts of fuel combustion will be the same regardless of the selected time horizon). However different results are obtained for different time horizons when considering restoration of management in 'neglected' broadleaf forests because of the time-dependent nature of carbon stock changes (see Sections 3.5, 4.3 and 4.5). The results in Table 5.1 for broadleaf forests with restored management are for a time horizon of 40 years.

When considering coniferous and broadleaf forests already under management to provide woodfuel either for domestic-scale or commercial and industrial heating, the estimated GHG emissions factors (in the range –31 to -11 kgCO_2-equivalent MWh^{-1} for conifer forests and 24 to 44 kgCO_2-equivalent MWh^{-1} for broadleaf forests) are very low compared with equivalent emissions factors for fossil fuels such as natural gas, oil and coal (typically in the range 235 to 525 kgCO_2-equivalent MWh^{-1}). A similar pattern is observed for power only production using woodfuel from conifer and broadleaf forests already under management, although the magnitudes of the GHG emissions factors are different (–121 kgCO_2-equivalent MWh^{-1} for conifer forests and 70 kgCO_2-equivalent MWh^{-1} for broadleaf forests compared with GHG emissions factors for power only production from fossil fuels ranging from 488 to 1,048 kgCO_2-equivalent MWh^{-1}). The picture is rather different for woodfuel-only production from 'neglected' broadleaf forests restored to management. Estimated GHG emissions factors for domestic-scale or commercial and industrial heat range from 347 to 378 kgCO_2-equivalent MWh^{-1} which is in the same range observed for fossil fuels. For electricity (power only) production the estimated GHG emissions factor is 1195 kgCO_2-equivalent MWh^{-1}, which is significantly higher than estimated for UK grid average electricity (588 kgCO_2-equivalent MWh^{-1}).

Table 5.1 Examples of estimates of GHG 'emissions factors' due to the production of woodfuel from characteristic UK forest types

Scenario number	Scenario description	Absolute emissions ($kgCO_2$–eq MWh^{-1})*		
		Managed conifer	Managed broadleaf	Broadleaf (restored management)**
01.01	Domestic heating with logs from 100% of sawlogs and roundwood, and wood pellets from 100% of bark and 50% of branchwood	-25	32	364
01.02	Domestic heating with briquettes from 100% of sawlogs and roundwood, and wood pellets from 100% of bark and 50% of branchwood	-11	44	378
01.03	Domestic heating with wood pellets from 100% of sawlogs, roundwood and bark, and 50% of branchwood	-21	37	375
01.04	Commercial and industrial heating with wood chips from 100% of sawlogs, roundwood and bark, and 50% of branchwood	-31	24	347
01.06	Power only generation from 100% of sawlogs, roundwood and bark, and 50% of branchwood (all wood supplied in raw form)	-121	70	1195
01.07	Power only generation with wood pellets from 100% of sawlogs, roundwood and bark, and 50% of branchwood	-107	109	1382

Notes: *1 $kgCO_2$-eq MWh^{-1} = 1 gCO_2 kWh^{-1}. **Time horizon of 40 years selected for broadleaf (restored management) forest type. Time horizon not relevant for other forest types.

It is difficult to compare GHG emissions factors estimated in this study with previously reported estimates because there may be significant variations in LCA methodology and conventions adopted in different studies The most relevant and comparable GHG emissions factors recently reported are due to Bates *et al.* (2011) and refer to electricity (power only) generation. Bates *et al.* (2011) quote estimates for power generation from wood harvested from forests already under management for production (based on roundwood) are –65 and 51 $kgCO_2$-equivalent MWh^{-1}, respectively, for coniferous and broadleaf forest types. These estimates bear reasonable comparison with the relevant estimates in Table 5.1 (–121 and 70 $kgCO_2$-equivalent MWh^{-1} respectively). For restored management in 'neglected' broadleaf forests, Bates *et al.* (2011) presented GHG emissions factors for time horizons 20 years and 100 years and only for power for power generation from wood chips. Estimates reported for the 20 year time horizon range from 122 to 2,923 $kgCO_2$-equivalent MWh^{-1}, this wide range illustrating the sensitivity of results to assumptions about the way in which management is restored. The nearest equivalent estimate in Table 5.1 (1195 $kgCO_2$-equivalent MWh^{-1} for a 40 year time horizon) falls within this range.

All of the GHG emissions factors considered so far have involved scenarios in which CCS technologies have not been applied. Estimates of GHG emissions factors produced by this study for relevant plants (power only generation[10]) with application of CCS are large and negative (i.e. in the region of –1,500 and –500 $kgCO_2$-equivalent MWh^{-1} for all forest types) suggesting significant net sequestration of carbon. However it should be noted that CCS technologies could equally be applied to fossil fuel-based power-only generation and this would be expected to lead to significant reductions in emissions factors for these cases, however, the estimation of such emissions factors was outside the scope of this study.

5.3 Relative emissions for example scenarios

'Energy only' scenario example

Figure 5.5 illustrates how relative GHG emissions have been estimated in this study for an example scenario involving all harvested wood being utilised in raw form for fuel to generate power only (Scenario 01.06, without application of CCS).

Results are presented for the three characteristic UK forest types over a time horizon of 40 years. The absolute GHG emissions for wood production from UK forests (light green bars in Figure 5.5) are exactly the same as already considered in Section 5.2, Figure 5.2. The dark yellow bars in Figure 5.5 show the GHG emissions that would occur if an equivalent amount of electricity (to that generated using the raw wood) were to be generated using 'UK grid average electricity' (see Section 4.2 and in particular Table 4.7). The rationale behind the definition of counterfactuals and detailed assumptions has already been discussed in Section 4.2. However, it is critical to understanding the results

---

[10] CCS can also be considered for application to CHP plants but evaluation of GHG emissions factors for such plants has been excluded from this particular analysis due to the complexity of addressing the generation of two forms of energy simultaneously, as indicated earlier.

of this study to appreciate the principle of identifying a counterfactual for wood production and estimating the GHG emissions for this alternative action, and the point is worth stressing here. Specifically, a decision not to harvest wood from UK forests implies that the services that would have been provided by the harvested wood (i.e. as a source of fuel or materials) would need to be met in some other way, specifically by importing the wood from other countries or using some alternative to wood, such as fossil fuels or non-wood materials. Sources based on imported wood or non-woodfuels and materials thus represent the 'counterfactuals' to UK wood as a source of fuel or materials. Hence, it is necessary to estimate the GHG emissions that would be associated with utilisation of these counterfactuals, and compare these with results involving production of wood from UK forests. Estimates of relative GHG emissions, as defined in Section 5.1 and illustrated by the violet bars in Figure 5.5, make such a comparison in quantitative form.

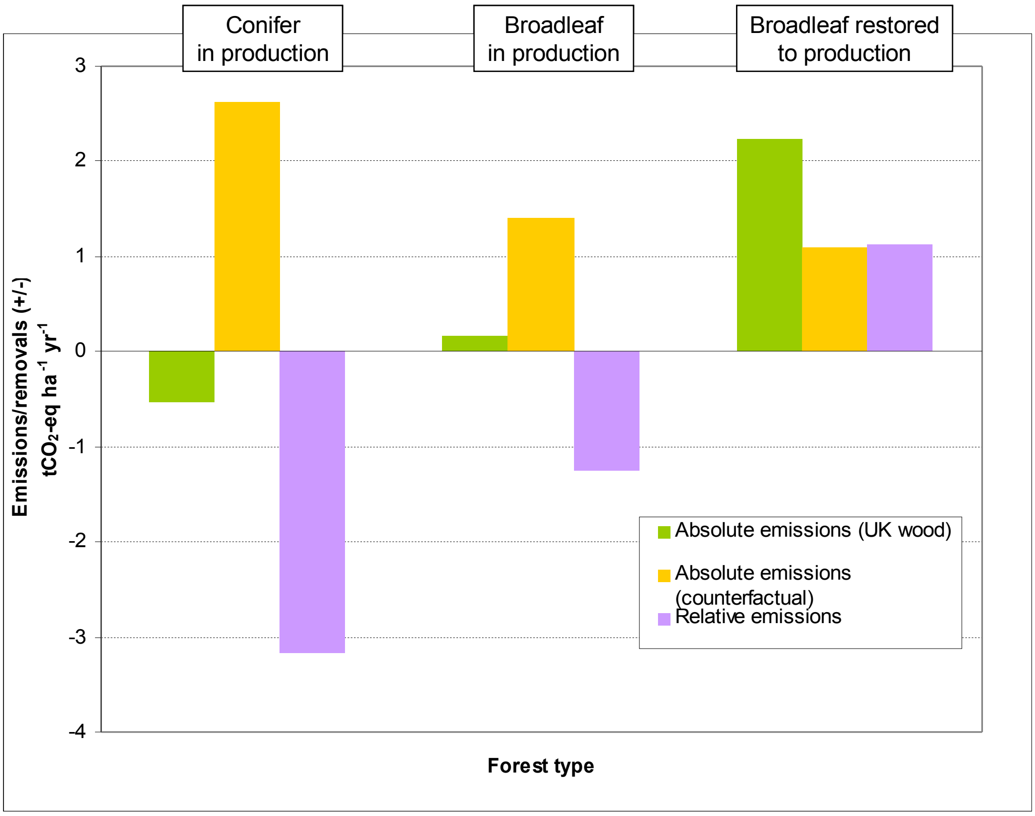


Figure 5.5. Estimation of relative GHG emissions estimated for characteristic UK forest types for example scenarios involving management for production of wood for fuel only (Scenario 01.06, without application of CCS). Absolute emissions are shown for production from UK forests, for a counterfactual scenario as well as the resultant relative emissions. Results are shown for 40 year time horizon.

Thus, taking the example of wood production from coniferous forests already under management as shown in Figure 5.5, relative GHG emissions may be calculated by subtracting the absolute GHG emissions for the counterfactual based on 'UK grid average' electricity (dark yellow bar, 2.6 tCO_2-equivalent ha^{-1} yr^{-1}) from the absolute

GHG emissions for the scenario based on UK wood production (light green bar, –0.5 tCO_2-equivalent ha^{-1} yr^{-1}), giving the result

Relative GHG emissions = –0.5 – 2.6 = –3.1 tCO_2-equivalent ha^{-1} yr^{-1} (violet bar).

This result implies that producing wood from UK forests and using all of the raw wood for power only generation would result in a reduction in GHG emissions of 3.1 tCO_2-equivalent ha^{-1} yr^{-1} when compared with (or relative to) the counterfactual of producing the electricity from a 'UK grid average' mix of fossil fuels and other energy sources.

Sensitivity to selected counterfactual

As already explained immediately above, the results in Figure 5.5 are based on a scenario involving production of wood from characteristic UK forest types and using all the raw wood for power only generation, and a counterfactual of producing the electricity from a 'UK grid average' mix of fossil fuels and other energy sources. Figure 5.6 shows examples of GHG emissions that would be associated with other possible counterfactual scenarios involving power only generation using:

- Natural gas, pale red bars
- Coal, bright yellow bars
- Imported wood instead of UK wood (also assuming that production from non-UK forests would need to be 'intensified' – i.e. higher levels of harvesting – in order to increase the supply of wood to the UK), medium blue bars.
- Imported wood instead of UK wood (also assuming that the supply of non-UK wood can be met from existing levels of production from forests in other countries, i.e. 'business as usual' management of non-UK forests), pale blue bars.

Results are shown for all three characteristic UK forest types and can be compared with the counterfactual GHG emissions for 'UK grid average' electricity as assumed in Figure 5.5 (dark yellow bars). The results in Figure 5.6 illustrate the sensitivity of estimated counterfactual GHG emissions to choices made concerning a relevant counterfactual. The basis for selecting counterfactual scenarios in this study has been discussed in Section 4.2.

It may be noted that GHG emissions associated with a 'business as usual' management are relatively small and, in certain cases, comparable with GHG emissions for scenarios involving UK wood. (In the case of restoring management in 'neglected' UK broadleaf forests, GHG emissions associated with the 'business as usual management' imported wood scenario are, in fact, lower.) However, in this study counterfactual scenarios involving imported wood have involved an assumption of intensified production in non-UK forest areas.

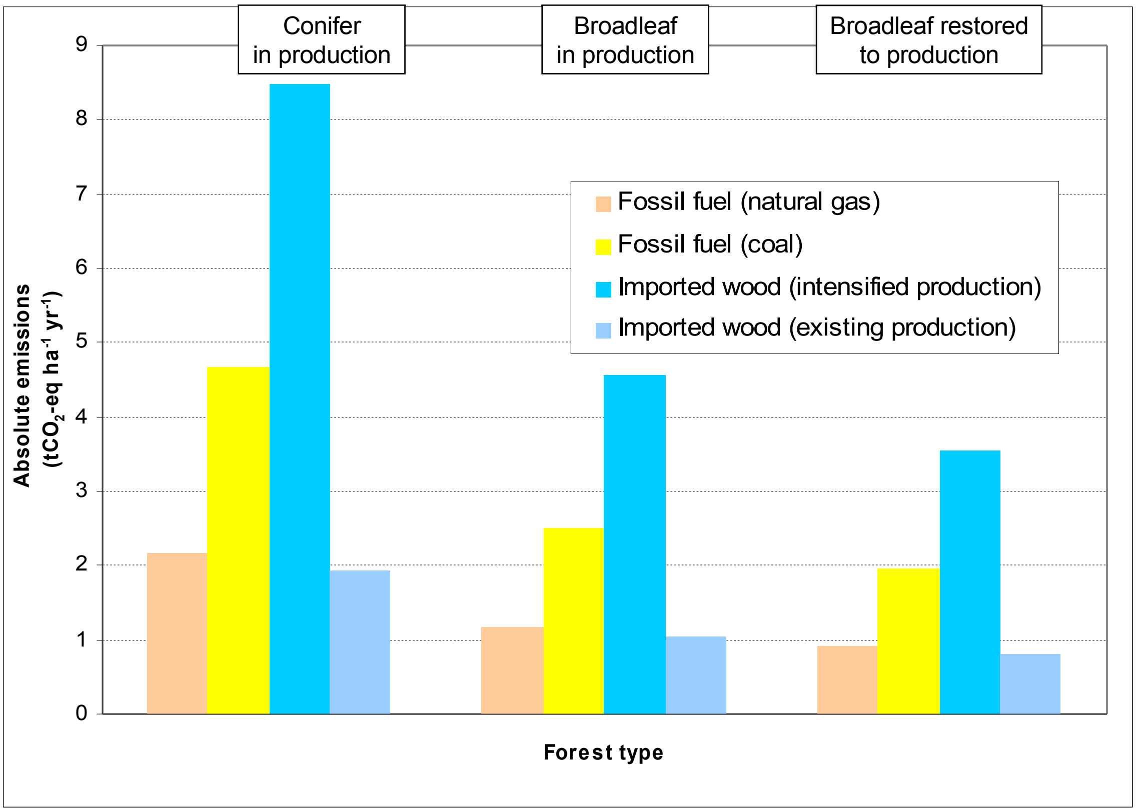


Figure 5.6. Examples of estimated GHG emissions for possible fossil fuel and imported wood counterfactuals for example scenarios involving management for production of wood for fuel only (Scenario 01.06, without application of CCS). These results may be compared with the emissions for the counterfactual assumed in Figure 5.5.

'Material products' scenario example

Figure 5.7 illustrates how relative GHG emissions have been estimated in this study for example scenarios involving the harvesting of wood and the production of a mix of materials and fuel. The example selected for managed coniferous forests involves production of a combination of sawn timber, MDF, paper and card and woodfuel, the latter used for commercial and industrial CHP generation with wood chips (Scenario 23.05, without application of CCS). Generally, paper and card are not produced from hardwoods in the UK. Therefore, the equivalent scenarios for broadleaf forests are slightly simpler, involving the production of sawn timber, MDF and woodfuel for CHP with wood chips (Scenario 07.05, without application of CCS). Results are presented for the three characteristic UK forest types over a time horizon of 40 years. The absolute GHG emissions for wood production from UK forests (light green bars in Figure 5.7) are exactly the same as already considered in Section 5.2, Figure 5.3.

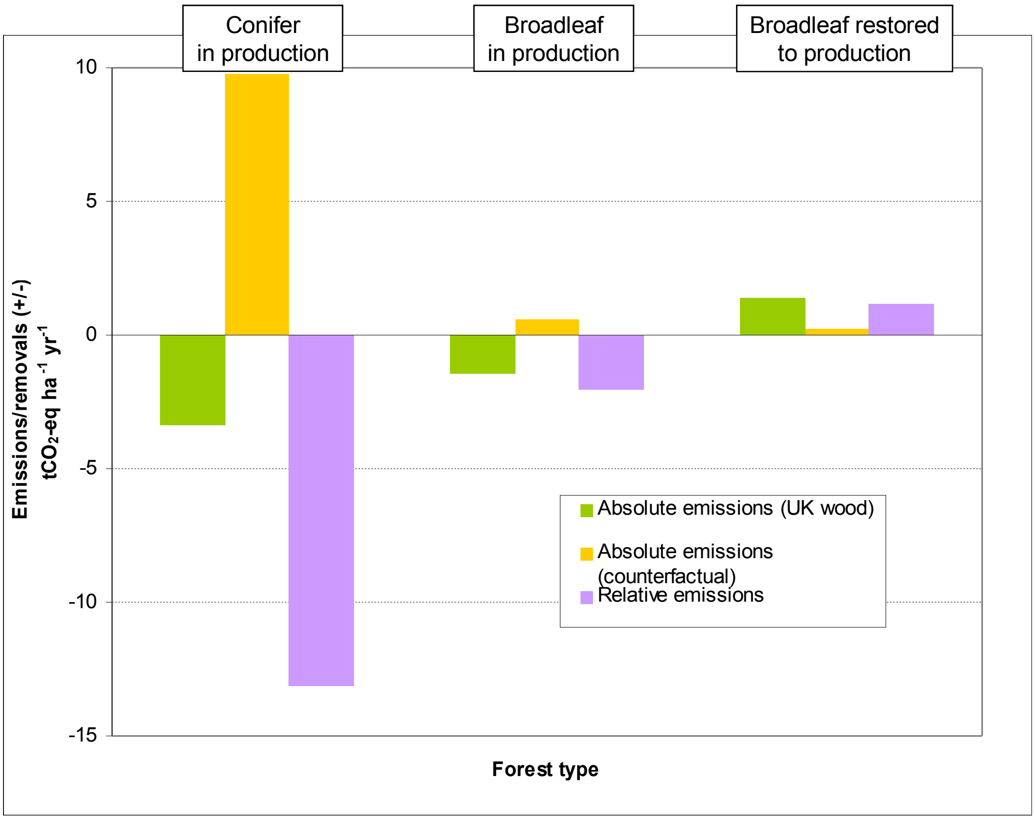


Figure 5.7. Estimation of relative GHG emissions for characteristic UK forest types for example scenarios involving management for production of wood for a range of materials and fuel (Scenario 23.05, for coniferous forest example, Scenario 05.07 for broadleaf forest examples, all without application of CCS). Absolute emissions are shown for production from UK forests, for a counterfactual scenario as well as the resultant relative emissions. Results are shown for 40 year time horizon.

The dark yellow bars in Figure 5.7 show the GHG emissions that would occur if an equivalent amount of materials and energy (to that produced using the raw wood) were to be produced from non-wood sources, or from imported wood in the case of paper and card (see Section 4.2 and in particular Table 4.7). The principles behind the identification of counterfactuals and estimation of associated GHG emissions have already been discussed in Section 4.2 and in the preceding discussion for an 'energy only' scenario. Estimates of relative GHG emissions, as defined in Section 5.1 and illustrated by the violet bars in Figure 5.7, make such a comparison in quantitative form. Thus, taking the example of wood production from coniferous forests already under management as shown in Figure 5.7, relative GHG emissions may be calculated by subtracting the absolute emissions for the counterfactual (dark yellow bar, 9.8 tCO_2-equivalent ha^{-1} yr^{-1}) from the absolute GHG emissions for the scenario based on UK wood production (light green bar, −3.4 tCO_2-equivalent ha^{-1} yr^{-1}), giving the result

Relative GHG emissions = −3.4 − 9.8 = −13.2 tCO_2-equivalent ha^{-1} yr^{-1} (violet bar).

This result implies that producing wood from UK forests and using it to produce the mix of products represented by the scenario would result in a reduction in GHG emissions of 13.2 tCO_2-equivalent ha^{-1} yr^{-1} when compared with (or relative to) the counterfactual of producing the mix of materials and energy from non-wood sources, fossil fuels and imported wood in the case of paper and card.

5.4 Reporting of ranked results

The principal output of this project has consisted of estimates of relative GHG emissions (see Sections 5.1 to 5.3) for the complete set of standard scenarios (as defined in Tables 4.8 to 4.11, Section 4.6). Given the number and diversity of the scenarios considered, a very large number of results can be generated by the LCA workbooks produced as part of this project. In total, there are 282 possible scenarios for managed conifer forests (not including the reference Scenario 00.00) and 215 possible scenarios for broadleaf forest types (not including the reference Scenario 00.00 or 00.01, the latter relevant to the case of restored management in ‘neglected’ broadleaf forests). For each of these scenarios, relative emissions can be calculated with reference to ‘non-wood’ or to ‘(imported) wood’ counterfactuals. For the cases involving non-wood counterfactuals, it is then possible to produce estimates for the seven different options for disposal of wood products at end-of-life (as defined in Section 4.2). In the case of imported wood counterfactuals, it is not necessary to consider impacts of disposal at end-of-life because these are the same for both the UK wood and the imported wood scenario and therefore the ‘cancel out’ when calculating of relative GHG emissions. Finally, results can be calculated for the three selected time horizons of 20, 40 and 100 years.

Rather than attempting to present such a large body of results in substantial tables in this report, complete sets of results have been prepared separately in workbooks. The result for each scenario is given in association with its numerical code (as defined in Tables 4.8 to 4.11, Section 4.6), and a brief description is also given of the specified pattern of wood utilisation. Results for these scenarios are given in terms of annualised relative GHG emissions per unit area of forest, in units of $kgCO_2$–equivalent ha^{-1} yr^{-1}. The results in the workbooks have been ranked in order of increasing relative GHG emissions to assist comparison and subsequent interpretation[11]. In addition to comparison between different scenarios in which products are derived from the forests, as already discussed in Section 5.2, a ‘reference line’ can be specified by Scenario 00.00 which, in the case of currently managed conifer and broadleaf forests, represents the suspension of production, and, in the case of neglected broadleaf forests, involves not restoring management and production. (An alternative reference line can be defined in the case of the latter forest type, an alternative reference line can be defined based on Scenario 00.01, as also discussed in Section 5.2.) It will be appreciated that, in relation to overall GHG emissions, scenarios with relative GHG emissions which are less negative/more

---

[11] Ranked results of the scenarios are also given rank numbers; a lower rank number indicates lower (more negative) relative GHG emissions.

positive than the value of GHG emissions for the reference line offer less benefit compared to simply leaving the forest alone.

Before examining the ranking of results, it is necessary to consider their general features. Depending on the choice of time horizon and end-of-life disposal option for wood products, results can range from comparatively large negative values of relative GHG emissions (of the order of 10^4 kgCO_2–equivalent ha^{-1} yr^{-1}) to sizeable positive values of relative GHG emissions (of the order of 10^4 kgCO_2–equivalent ha^{-1} yr^{-1}). For clarity, it should be noted that negative values indicate that carbon[12] is, in effect, being removed from the atmosphere over the specified time horizon. Conversely, positive values imply that carbon is being released into the atmosphere. In the ranking of results, those with the largest negative values of relative GHG emissions are implicitly 'preferable' to other negative values and all positive values. This assumes that relative GHG emissions are the single most important factor for distinguishing between scenarios.

5.5 Detailed analysis of results

Graphical interpretation of ranked results

The very large number of ranked GHG emissions results resulting from so many different forestry and wood utilisation options presents some obvious challenges in presenting and interpreting results. To permit an overall inspection of the results, graphs may be prepared showing relative GHG emissions for all scenarios plotted against rank number, as illustrated by the example in Figure 5.8. The figure shows relative GHG emissions for all scenarios relevant to:

- UK coniferous forests already under management for production of wood
- Non-wood counterfactuals (as opposed to imported wood)
- All options for disposal of wood at end-of-life
- No application of CCS technologies
- A selected time horizon of 100 years.

Results based on different options for disposal of wood products at end-of-life are plotted as separate, differently coloured lines. Scenarios involving wood utilisation can be compared easily with the 'reference line' of 'leaving wood in the forest', i.e. avoiding harvesting so as to accumulate forest carbon stocks, which is displayed as a horizontal green line in Figure 5.8. Comparison may also be made with the 'zero line' (i.e. the point at which scenarios switch from giving reductions in GHG emissions reductions to giving increases in GHG emissions), which is displayed as a horizontal black line in Figure 5.8.

It is possible to plot graphs such as in Figure 5.8 showing results for combinations for each of the three characteristic UK forest types, either non-wood or imported-wood counterfactuals, the various disposal options (in the case of non-wood counterfactuals), application or otherwise of CCS and each of the three time horizons of 20, 40 or 100

---

[12] Strictly speaking, it is a combination of GHGs (CO_2, CH_4 and N_2O) that is involved rather than "carbon".

years, comprising 36 graphs in all. It is possible to draw a number of insights from consideration of such graphs. However, there are also some difficulties in trying to interpret results presented in this way, for example when trying to distinguish 'better' and 'worse' scenarios for wood utilisation in terms of relative GHG emissions. In particular, the results in Figure 5.8 show that scenarios for wood utilisation, when placed in ranked order, do not form distinctly separate groups, in terms of relative GHG emissions. Rather, successive results for relative GHG emissions, placed in ranked order, form a continuous progression, although sometimes with occasional notable steps in the sequence. Accordingly, further consideration of the complete set of 36 graphs similar to the example in Figure 5.8 is included as a separate discussion in Annex 1 of this report.

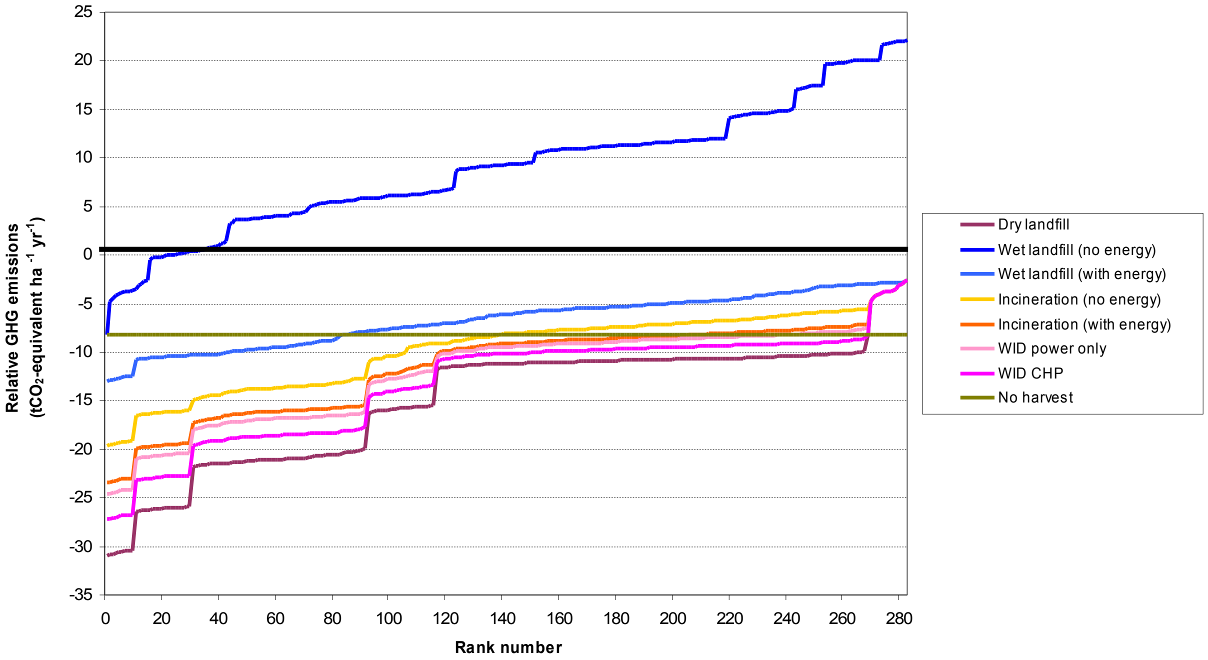


Figure 5.8. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 100 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may occasionally overlap and obscure each other.

Sensitivity to wood disposal at end-of-life

An important insight gained from graphical examination of results such as in Figure 5.8 is that, certainly for a 100 year time horizon, and with non-wood counterfactuals, relative GHG emissions are seen to be strongly dependent on the option for end-of-life disposal. The lowest (most negative) relative GHG emissions are associated with disposal to dry landfill, then incineration with CHP, followed by incineration with power only generation, waste incineration with energy recovery, waste incineration without energy recovery and, finally, disposal to wet landfill with energy recovery followed by disposal to wet landfill without energy recovery. The potentially detrimental impacts on relative GHG emissions associated with disposal to wet landfill without energy recovery are very apparent. These impacts confirm more generally the observations already made for an example scenario as considered in Figure 5.4, Section 5.2.

The dependence of results on end-of-life disposal is particularly strong in the case of non-wood counterfactuals (without or with CCS application) over a 100 year time horizon because all relevant GHG emissions due to disposal come into play by the end of the time horizon. (As already mentioned, strong impacts due to end-of-life disposal do not arise when imported wood counterfactuals are assumed. This is because the GHG emissions due to disposing of UK and imported wood products are the same.)

It is imported to note that assumptions about GHG emissions associated with disposal of wood products to wet landfill were based on emissions factors included in the Environment Agency's BEAT$_2$ software tool. However, impacts of disposal of wood to wet landfill in terms of GHG emissions are uncertain and subject to ongoing debate. Adoption of estimates based on the BEAT$_2$ emissions factors represents a 'precautionary' approach to representing the option of wet landfill within this project.

Utilisation of bark for fuel or mulch

As an alternative to simply plotting graphs of relative GHG emissions for individual scenarios against their rank numbers, another approach to analysis involved pair-wise comparison of results, where this was applicable. For example, it is clear from Tables 4.8 and 4.9 in Section 4.6 that it is possible to identify 'matched pairs' of scenarios in terms of how bark is utilised. For example, in Table 4.8, Main Scenarios 01 and 24 form a pair in that a given Scenario 01.XX involves all stem wood being utilised for fuel, along with bark and harvested branchwood, whilst the equivalent Scenario 24.XX is the same as 01.XX except that bark is utilised for horticultural mulch. Similarly, Main Scenarios 02 and 25 form a pair, and so on.

Figure 5.9 shows the relative GHG emissions estimated for scenarios involving utilisation of bark for horticultural mulch (Scenarios 24.XX to 23.XX) plotted against the relative GHG emissions for the equivalent scenario but with bark utilised for fuel (Scenarios 01.XX to 23.XX). The figure shows results for scenarios based on:

- UK coniferous forests already under management for production of wood
- Non-wood counterfactuals
- A single option for disposal of wood at end-of-life (incineration in a WID-compliant power only plant)
- No application of CCS technologies
- All three time horizons (20, 40 and 100 years).

A single option was selected for end-of-life disposal of wood in order simplify interpretation of the results. The particular disposal option (incineration in a WID-compliant power only plant) was selected on the grounds that it was one of the better options for disposal in terms of GHG impacts (effectively eliminating poorer options as already identified earlier) and at the same time represented a plausible option for disposal of wood in the future (e.g. unlike disposal to dry landfill and involving less technical and logistical constraints than the option of incineration in a WID-compliant CHP plant).

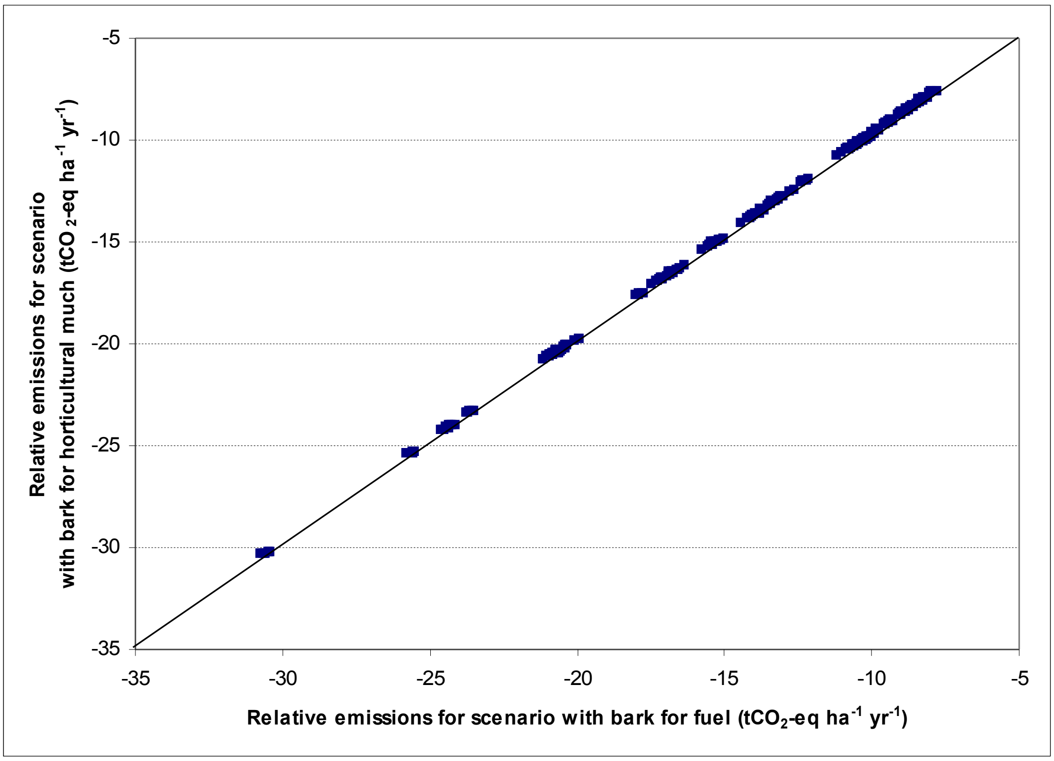


Figure 5.9. Relative greenhouse gas emissions for scenarios involving utilisation of bark for horticultural mulch plotted against relative greenhouse gas emissions for equivalent scenarios in which bark is utilised for fuel: UK conifer forests managed for production, non-wood counterfactuals, CCS not applied, all time horizons.

The results in Figure 5.9 clearly illustrate that, whilst relative GHG emissions for a particular scenario can vary considerably, the impact on relative emissions of using bark for either fuel or horticultural mulch is quite small. Nevertheless comparison of the results with the 1:1 line (also shown in Figure 5.9) reveals that relative GHG emissions for scenarios involving utilisation of bark for horticultural mulch are consistently less negative than for equivalent scenarios in which bark is used for fuel. The difference in relative emissions for paired scenarios is almost constant at about 0.29 tCO_2–equivalent ha^{-1} yr^{-1}. These relatively small impacts of decisions over the utilisation of bark are to some extent (but certainly not entirely) a reflection of the fact that, generally, bark biomass constitutes a small fraction of total harvested biomass. It should also be noted that an estimated difference of this magnitude is likely to be small compared with uncertainties in LCA calculations and variations in relative GHG emissions due to underlying variations in forest types, forestry practices, and wood processing technologies and their local application.

Although the above analysis only considered coniferous forests already under management for production, similar would be expected results (in terms of the relative impacts of decisions over the utilisation of bark)for broadleaf forests managed for production and ‘neglected’ broadleaf forests in which management for production is restored.

Impacts of CCS

Another pair-wise analysis could be carried out by comparing results for scenarios in which CCS technology was assumed to be applied with results for equivalent scenarios in which technology was assumed not to be applied. Figure 5.10 is an example of such an analysis for scenarios based on:

- UK coniferous forests already under management for production of wood
- Non-wood counterfactuals
- A single option for disposal of wood at end-of-life (incineration in a WID-compliant power only plant)
- Bark assumed to be utilised for fuel only
- A single time horizon of 20 years.

As explained in the preceding discussion, a single option was selected for end-of-life disposal of wood in order simplify the interpretation of the results.

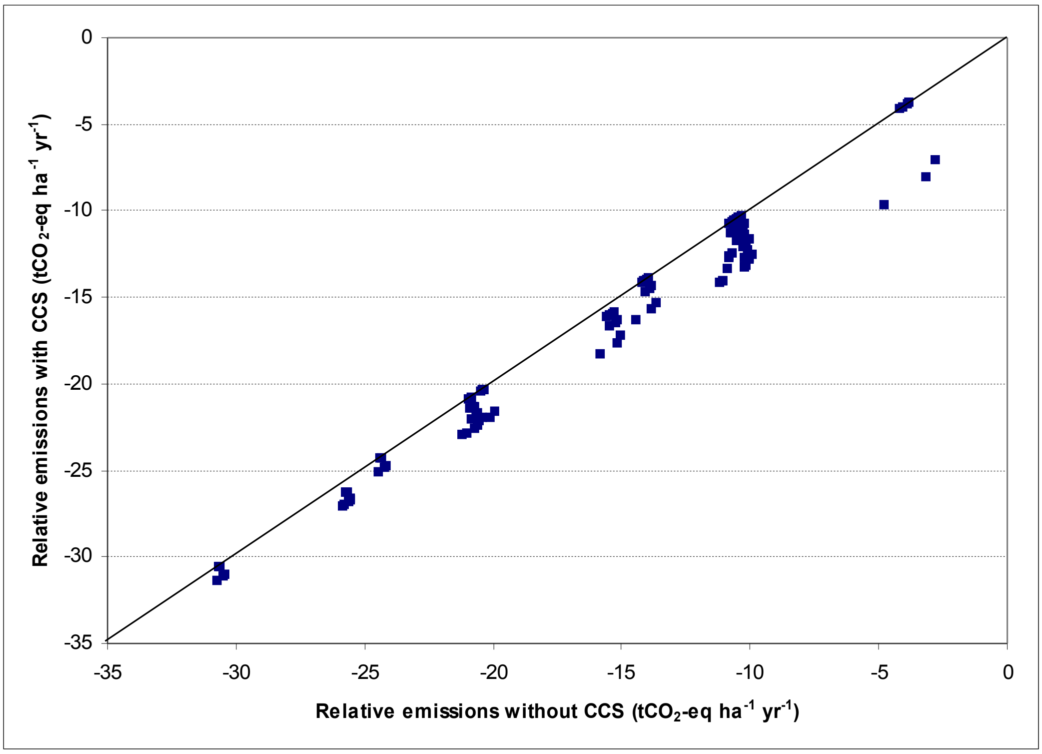


Figure 5.10. Relative greenhouse gas emissions for scenarios involving application of CCS technologies plotted against relative greenhouse gas emissions for equivalent scenarios in which CCS technologies are not applied: UK conifer forests managed for production, non-wood counterfactuals, bark utilised for fuel (not mulch), 20 year time horizon.

Comparison of the results with the 1:1 line (also shown in Figure 5.10) reveals that the application of CCS technologies either has a negligible impact on relative GHG emissions (cases where points coincide with the 1:1 line) or leads to more strongly negative estimates of relative GHG emissions (cases where points fall below the 1:1 line). Non-zero impacts range from about −0.5 tCO_2–equivalent ha^{-1} yr^{-1} to −5 tCO_2–equivalent ha^{-1} yr^{-1}. For a 20 year time horizon, the main factors determining the magnitude of the impact of application of CCS are:

- The extent to which a particular scenario involves the production of woodfuel
- The type of energy conversion system using the woodfuel (i.e. specifically whether energy utilisation is heat generation or power and CHP generation).

It is notable that the biggest impacts due to CCS are observed (top right-hand corner of graph) for scenarios involving woodfuel production only and power only generation (Scenarios 01.06 and 01.07) and commercial and industrial CHP (Scenario 01.05).

It is clear that, over a 20 year time horizon, application of CCS would affect the relative ranking of scenarios, having the greatest beneficial impact on scenarios involving significant utilisation of wood for fuel.

The impacts estimated for CCS on various scenarios change dramatically if the time horizon used for analysis is changed from 20 years to 100 years, as illustrated in Figure 5.11, which shows the same results as Figure 5.10 but for a time horizon of 100 years.

The impacts of the application of CCS technologies over 100 years are estimated to affect many more scenarios and to be much more pronounced than over shorter time horizons (20 or 40 years). In fact, the only scenarios not affected by application of CCS involve all wood being utilised for fuel and used exclusively for heat generation (Scenarios 01.01 to 01.04). Non-zero impacts range from about –2 tCO_2–equivalent ha^{-1} yr^{-1} to –10 tCO_2–equivalent ha^{-1} yr^{-1} (with a percentage change typically around -40%). It is important to appreciate that the main reason for large impacts of CCS over the long time horizon is due to the assumption that CCS would be applied not only to power only and CHP generation when virgin wood is burned but also during power only and CHP generation in a WID-compliant plant when wood disposed of at end-of-life is burned. The results presented in Figures 5.10 and 5.11 are therefore strongly dependent on the selected option for disposal of wood. As noted earlier, this particular disposal option was selected as one of the better and at the same time practical choices for disposal of wood in the future.

As part of the discussion of GHG emissions factors for woodfuel in Section 5.2, it was pointed out that CCS technologies could equally be applied to fossil fuel-based power only and CHP generation and this would be expected to lead to significant reductions in GHG emissions factors for these cases. Nevertheless the results in Figure 5.11 indicate that the application of CCS technologies (where possible) as part of the future disposal of wood products could make an important contribution to carbon impacts in terms of relative emissions.

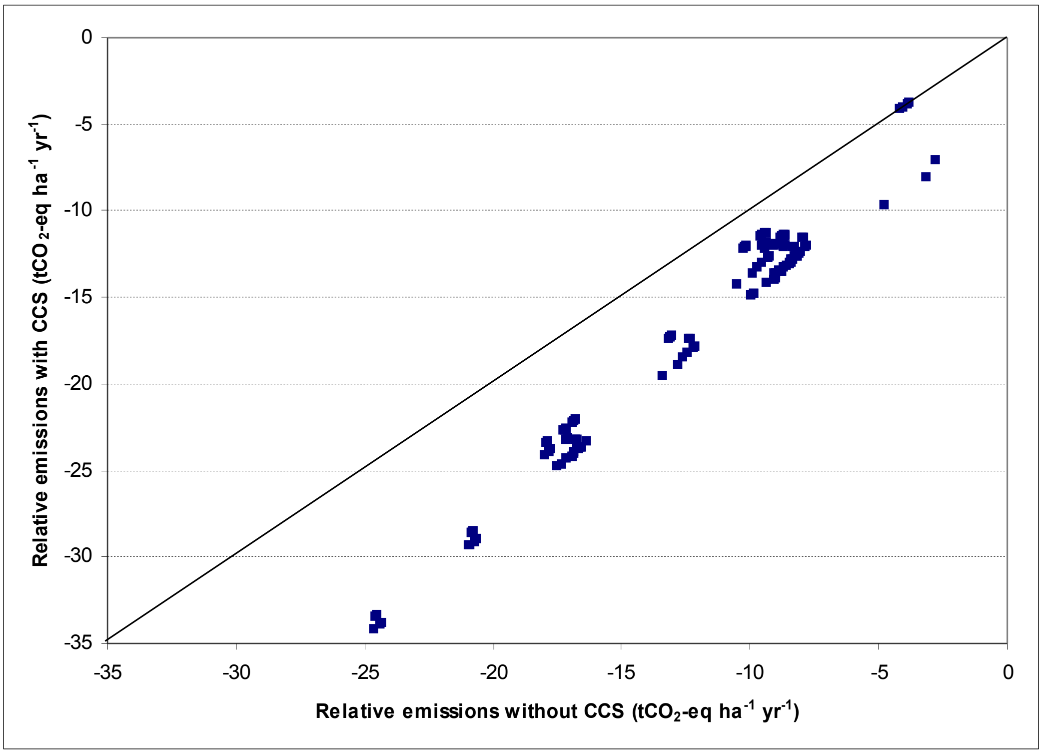


Figure 5.11. Relative greenhouse gas emissions for scenarios involving application of CCS technologies plotted against relative greenhouse gas emissions for equivalent scenarios in which CCS technologies are not applied: UK conifer forests managed for production, non-wood counterfactuals, bark utilised for fuel (not mulch), 100 year time horizon.

Detailed graphical analysis of ranked results

On the basis of the analysis presented earlier in this section, a further detailed graphical analysis of ranked results was carried out based on a specific selection of scenarios:

- Separate analysis of the three characteristic UK forest types
- Non-wood counterfactuals
- A single option for disposal of wood at end-of-life (incineration in a WID-compliant power only plant)
- Bark assumed to be utilised for fuel only
- No application of CCS technologies
- All three time horizons (20, 40 and 100 years).

The analysis involved:

- Grouping scenarios by main scenario number (01.XX, 02.XX and so on)
- Estimating the mean relative GHG emissions for each scenario grouping
- Ranking individual scenarios in terms of mean relative GHG emissions for the main scenario grouping (from largest negative to smallest negative/largest positive)
- Plotting a graph of relative GHG emissions for individual scenarios against the rank for the scenario grouping.

Figure 5.12 shows the results of this analysis for the characteristic forest type of coniferous forests already under management for production. Also shown (as dark olive horizontal lines) are the 'reference lines' for the three time horizons, based on Scenario 00.00, which involves avoiding harvesting so as to accumulate forest carbon stocks.

As a general point, when interpreting the results such as in Figure 5.12 it should be noted that sensitivity analysis of parameters and estimates used in LCA calculations suggests that results for relative GHG emissions falling with 10% of each other are probably indistinguishable.

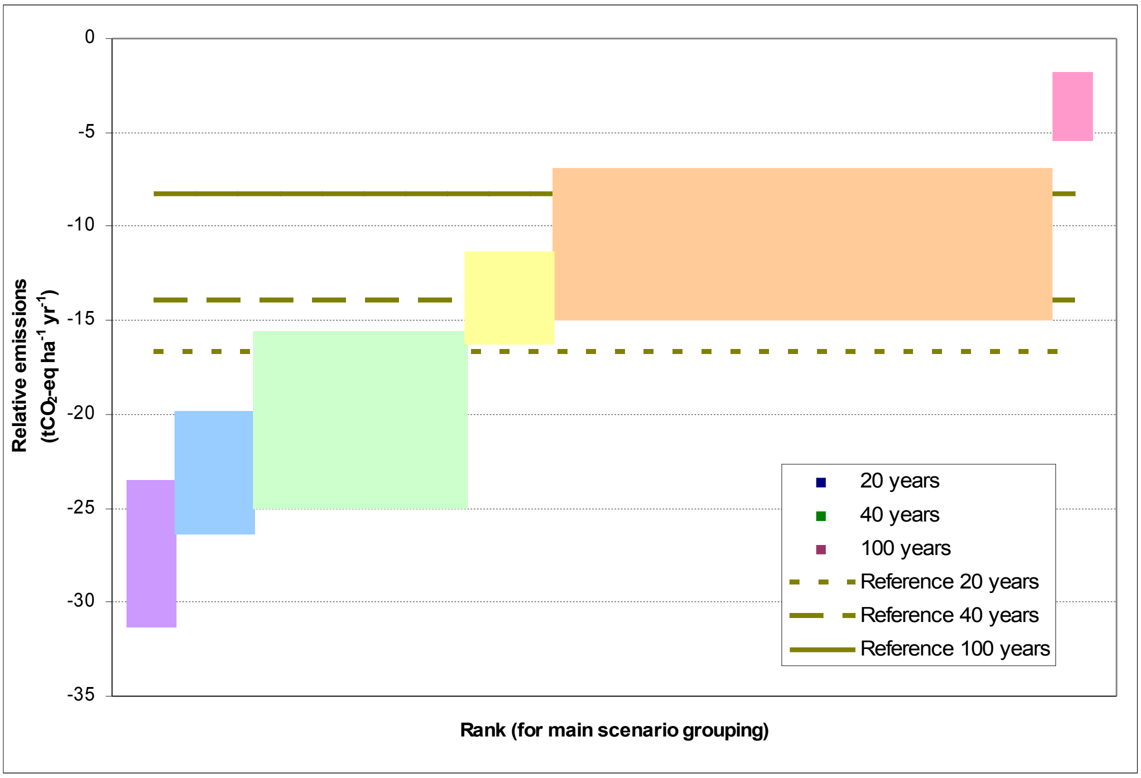


Figure 5.12. Relative greenhouse gas emissions for individual scenarios plotted against rank number for scenario grouping: UK conifer forests managed for production, non-wood counterfactuals, bark utilised for fuel (not mulch), CCS not applied, 20, 40 and 100 year time horizons. Note that results for a 20 year time horizon are almost coincident with those for a 40 year time horizon and are obscured. The coloured bands indicate groups of results in terms of similar levels of relative GHG emissions.

The number of results is now sufficiently reduced, and the method of preparation refined enough for distinct 'groups' of results to be discerned (in terms of similar levels of relative GHG emissions), as indicated by the coloured bands in Figure 5.12. The scenarios represented by the points falling in each coloured band are described in Table 5.2.

Table 5.2 Key to main scenarios falling in coloured bands (representing groupings on the basis of mean relative GHG emissions) as depicted in Figure 5.12

Group number	Mean relative emissions (tCO_2-eq ha^{-1} yr^{-1})		Scenarios forming group*
	20/40 year time horizon	100 year time horizon	
1	-31	-24	**04**: Sawn timber, particleboard, fuel
2	-26	-21	**10**: Sawn timber, particleboard, pallets, fuel **16**: Sawn timber, particleboard, fencing, fuel
3	-21	-17	**03, 05**: Sawn timber, fuel, particleboard **15, 17**: Sawn timber, particleboard, fencing, MDF, fuel **22**: Sawn timber, particleboard, paper and card, fuel
4	-15	-13	**13**: Sawn timber, fuel, fencing, particleboard **19**: Sawn timber, fuel, pallets
5	-11	-9	**02**: Sawn timber, fuel **06, 07, 08**: Sawn timber, MDF, fuel **09**: Sawn timber, fuel, pallets **11**: Sawn timber, MDF, pallets, fuel **12**: Sawn timber, fuel, fencing **14**: Sawn timber, fuel, fencing, MDF **18**: Sawn timber, fuel, MDF, fencing **20**: Sawn timber, MDF, fuel, fencing **21**: Sawn timber, fuel, paper and card **23**: Sawn timber, MDF, paper and card, fuel
6	-4	-4	**01**: Fuel only

*Note: wood product types are listed broadly in order of their importance as a component in each scenario.

Broadly, a hierarchy in terms of relative GHG emissions (from most negative to least negative) can be discerned in the groupings suggested in Figure 5.12 and Table 5.2:

7. Sawn timber, particleboard and fuel
8. Sawn timber, particleboard, fencing and pallets, fuel
9. Sawn timber, particleboard and fuel, fencing, MDF and paper and card
10. Sawn timber, fuel, fencing and pallets
11. Sawn timber and a mix of products other than particleboard
12. Fuel only.

The highest ranking scenarios (Groups 1 to 3 in Table 5.2) actually represent what might be described as the 'conventional mix' for the use of harvested wood in the UK (see Section 2.4). Whilst describing such scenarios as a 'conventional mix', it should be clarified that the extent of production of woodfuel from branchwood (and indeed the reporting of production from branchwood) is uncertain. It is likely that currently little is produced from branchwood from coniferous forests whilst production from the branchwood of broadleaf forests could be significant.

It is noteworthy that the majority of scenarios in Figure 5.12 involve large negative relative GHG emissions, with nearly all results falling below the 'reference line' result representing the scenario of 'leaving carbon in the forest' (no harvesting, see Sections 2.6 and 5.1). In the majority of cases (the exception being Main Scenario 01), the magnitudes of the estimates of relative GHG emissions drop when longer time horizons are considered (i.e. 100 years). However, the magnitude of the reference line also drops at longer time horizons. Over time horizons even longer than 100 years, the reference line would be expected to drop to zero (see Section 3).

Results shown in Figure 5.12 and Table 5.2 involving significant negative relative GHG emissions frequently involve production of particleboard. As already discussed in Section 4.2, assumptions about inputs of recycled wood into the manufacture of board products have a significant influence on estimated GHG emissions. The percentage of recycled wood assumed as input to particleboard production was taken as 70% but can be varied in the LCA workbook calculations. The alternative of setting this percentage to zero was found to result in larger estimates of relative GHG emissions for (UK) particleboard. For example, Scenario 04.03 is the highest ranked scenario, having relative GHG emissions for a time horizon of 40 years of −31 tCO_2–equivalent ha^{-1} yr^{-1} and involving:

- Production of sawn timber from sawlogs
- Production of particleboard from sawlog offcuts and 100% of roundwood
- Production of woodfuel from bark and (50% of) branchwood.

However, if the LCA calculations are varied simply by changing the percentage of recycled wood as input to particleboard production to zero, then the estimated relative GHG emissions are only about −16 tCO_2–equivalent ha^{-1} yr^{-1}, a result which would place the scenario in 'Group 4' rather than 'Group 1' as identified in Figure 5.12 and Table 5.2. This emphasises the importance of utilising recycled wood in this sector in terms of overall GHG emissions.

The only set of scenarios lying significantly above the reference lines for all time horizons in Figure 5.12 involves production of woodfuel only from all harvested wood (Main Scenario 01). There is some sensitivity in this result to certain assumptions, for example, the potential for application of CCS technologies when using woodfuel (or indeed disposed wood at end-of-life) for power only and CHP generation (see earlier discussion of results for CCS in this section), and also assumptions about counterfactuals. For example, Scenario 01.03 involves production of woodfuel only from all harvested wood and utilisation as wood pellets for domestic heating. The estimated relative GHG emissions for this scenario (based on a counterfactual of natural gas-fired domestic heating) are about −4 tCO_2–equivalent ha^{-1} yr^{-1}, but this estimate changes to about −5 tCO_2–equivalent ha^{-1} yr^{-1} if a counterfactual of oil-fired domestic heating is assumed, and would become even more negative for counterfactuals involving coal and electricity (the latter being a realistic case for many domestic dwellings and commercial properties in rural areas). Such observations apply more generally to any scenario in which woodfuel forms a component of production.

Figure 5.13 shows the results of the detailed graphical analysis for the characteristic forest type of broadleaf forests already under management for production. Also shown (as dark olive horizontal lines) are the 'reference levels' for the three time horizons, based on Scenario 00.00, which involves avoiding harvesting so as to accumulate forest carbon stocks.

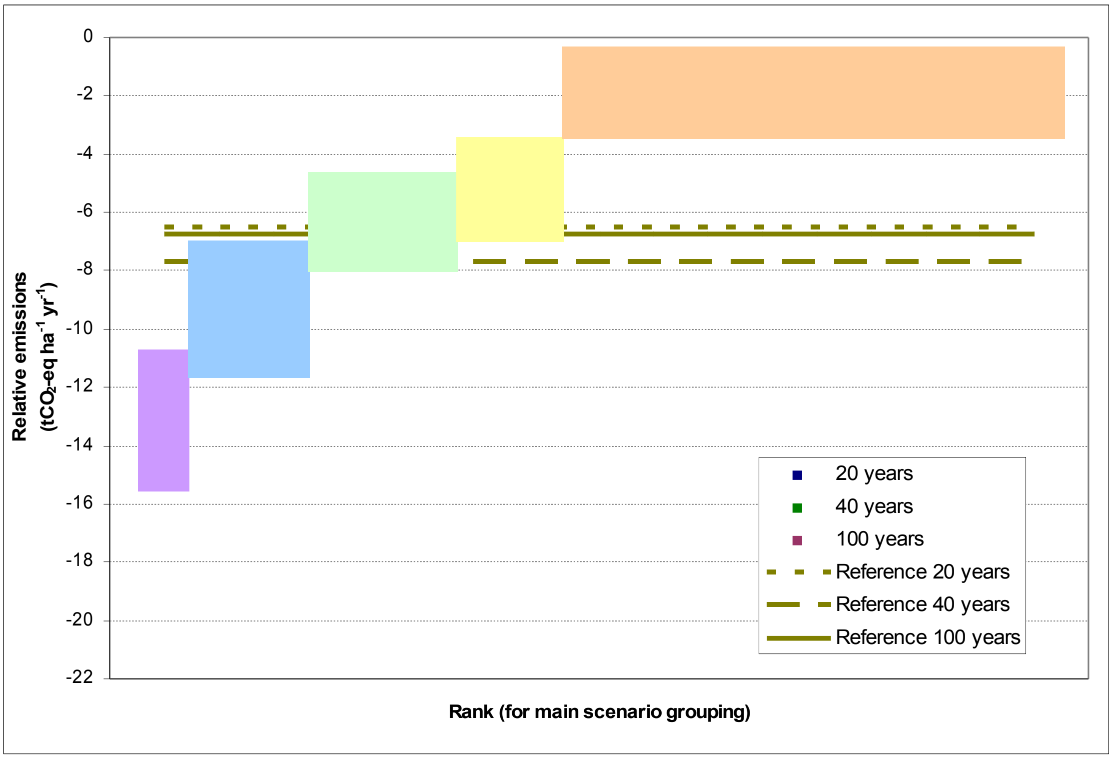


Figure 5.13. Relative greenhouse gas emissions for individual scenarios plotted against rank number for scenario grouping: UK broadleaf forests managed for production, non-wood counterfactuals, bark utilised for fuel (not mulch), CCS not applied, 20, 40 and 100 year time horizons. Note that results for a 20 year time horizon are almost coincident with those for a 40 year time horizon and are obscured. The coloured bands indicate groups of results in terms of similar levels of relative GHG emissions.

As was the case for managed conifer forests, distinct 'groups' of results may be discerned (in terms of similar levels of relative GHG emissions), as indicated by the coloured bands in Figure 5.13. The scenarios represented by the points falling in each coloured band are described in Table 5.3.

As for managed coniferous forests (Figure 5.12, Table 5.2), the results for managed broadleaf forests in Figure 5.13 and Table 5.3 suggest, in broad terms, a hierarchy in terms of relative GHG emissions (from most negative to least negative). The highest ranking scenarios (Groups 1 and 2 in Table 5.3) have estimated relative emissions that are more negative than the reference lines shown in Figure 5.13 for the three time horizons, based on Scenario 00.00, which involves avoiding harvesting so as to accumulate forest carbon stocks. However, the patterns of wood production represented by scenarios in Groups 1 and 2 cannot be described as the 'conventional mix' in the case of broadleaf forests (see Section 2.4). Almost no wood produced from broadleaf forests is utilised for particleboard or panel products, rather it is estimated that the bulk of broadleaf (i.e. hardwood) production is utilised for sawn timber, fuel and (round) fencing (see Section 2.4). Scenarios relevant to such a pattern of wood utilisation are associated most closely with Group 5 in Figure 5.13 and Table 5.3. In general, estimates of relative emissions for this group are significantly less negative than the 'reference lines' shown in Figure 5.13. Estimates of relative GHG emissions for other sets of 'less conventional' scenarios for hardwood utilisation (Groups 3 and 4), involving a proportion of particleboard production, are either comparable with or somewhat less negative than the reference lines. It should be noted that, over time horizons even longer than 100 years, the reference line would be expected to drop to zero (see Section 3).

Reference should be made to comments made in the preceding discussion of results for managed coniferous forests, concerning the significance of recycled wood as input to production of particleboard, application of CCS technologies in scenarios involving power only and CHP generation from woodfuel (or wood disposed of at end-of-life) and sensitivity to selected counterfactual in the case of domestic heat from woodfuel.

Table 5.3 Key to main scenarios falling in coloured bands (representing groupings on the basis of mean relative GHG emissions) as depicted in Figure 5.13

Group number	Mean relative emissions (tCO_2-eq ha^{-1} yr^{-1})		Scenarios forming group*
	20/40 year time horizon	100 year time horizon	
1	-15	-11	**04**: Sawn timber, particleboard, fuel
2	-11	-8	**03**: Sawn timber, particleboard, fuel **13**: Sawn timber, particleboard, fencing, fuel
3	-7	-6	**05**: Sawn timber, fuel, particleboard **12:** Sawn timber, particleboard, fuel, fencing **14**: Sawn timber, particleboard, fencing, MDF, fuel
4	-6	-5	**10**: Sawn timber, fuel, fencing, particleboard **16**: Sawn timber, MDF, fencing, particleboard, fuel
5	-2	-1	**01:** Fuel only **02**: Sawn timber, fuel **06, 07, 08**: Sawn timber, MDF, fuel **09**: Sawn timber, fuel, fencing **11**: Sawn timber, fuel, fencing, MDF **15, 17**: Sawn timber, MDF, fencing, fuel

*Note: wood product types are listed broadly in order of their importance as a component in each scenario.

Figure 5.14 shows the results of the detailed graphical analysis for the characteristic forest type of 'neglected' broadleaf forests in which management for wood production is restored. Also shown (as dark olive horizontal lines) are the 'reference lines' for the three time horizons, based on Scenario 00.00, which involves avoiding harvesting so as to accumulate forest carbon stocks. In addition, a set of alternative reference levels (dark yellow lines) are shown based on Scenario 00.01, which involves the restoration of management in 'neglected' broadleaf forests to meet environmental and amenity objectives but without the harvesting of wood for use as products and fuel.

As was the case for managed conifer forests and managed broadleaf forests, distinct 'groups' of results may be discerned (in terms of similar levels of relative GHG emissions), as indicated by the coloured bands in Figure 5.14. The scenarios represented by the points falling in each coloured band are described in Table 5.4.

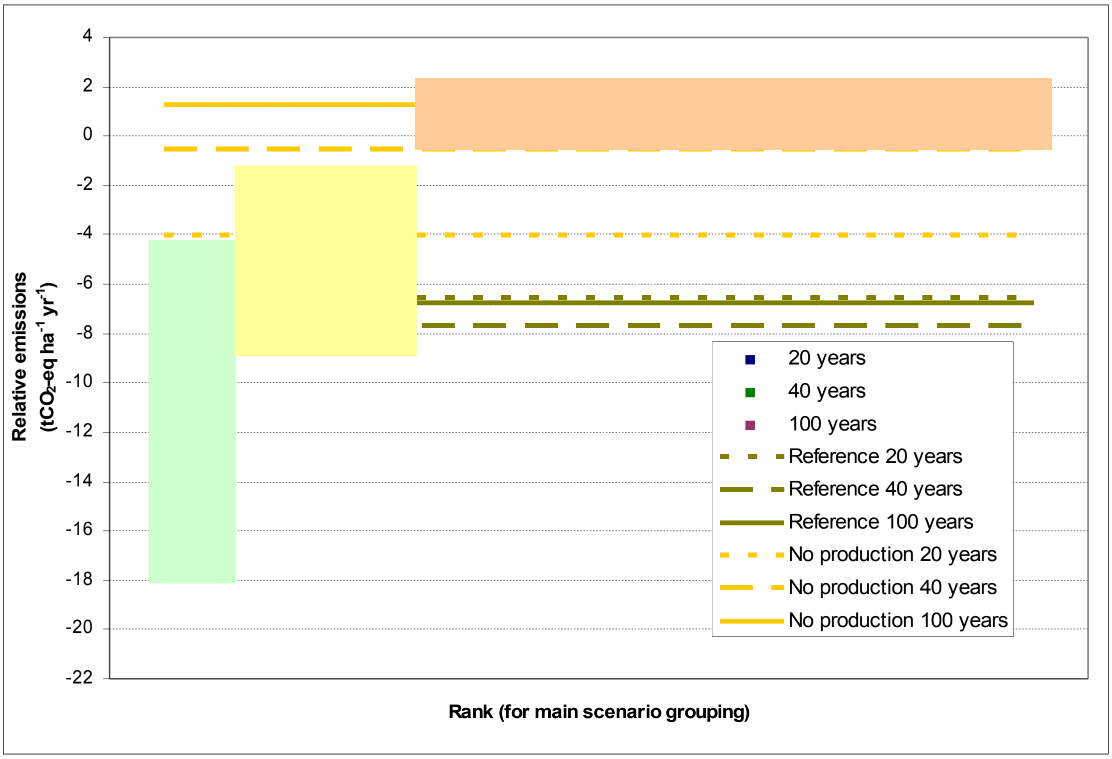


Figure 5.14. Relative greenhouse gas emissions for individual scenarios plotted against rank number for scenario grouping: UK 'neglected' broadleaf forests in which management for production is restored, non-wood counterfactuals, bark utilised for fuel (not mulch), CCS not applied, 20, 40 and 100 year time horizons. The coloured bands indicate groups of results in terms of similar levels of relative GHG emissions.

The discussion of results for managed broadleaf forests with regard to 'conventional' or 'less conventional' groups of scenarios in terms of the mix of products also applies in the case of 'neglected' broadleaf forests in which management is restored. In addition:

- Results for most scenarios fall into the lowest ranking group in terms of relative GHG emissions (Group 3 in Table 5.4), with estimates taking relatively small positive values (implying increased emissions in these cases).
- Only a relatively small set of highest ranking scenarios (Group 1 in Table 5.4) have estimated relative GHG emissions significantly more negative than the 'reference lines', based on Scenario 00.00, which represents avoiding harvesting so as to conserve and accumulate forest carbon stocks, and then only for time horizons of 20 and 40 years (for 100 years relative emissions are slightly less negative).
- If the 'alternative reference lines' based on Scenario 00.01 are referred to, results for the two highest ranking scenarios (Groups 1 and 2 in Table 5.4) have relative emissions that are more negative than these reference lines. Relative emissions for results in Group 3 are less negative than these reference lines for time horizons of 20 and 40 years and comparable with the reference line for a time horizon of 100 years.

It should be noted that, over time horizons even longer than 100 years, the ‘reference line’ (based on either Scenario 00.00 or Scenario 00.01) would be expected to tend to zero (see Section 3).

Table 5.4 Key to main scenarios falling in coloured bands (representing groupings on the basis of mean relative GHG emissions) as depicted in Figure 5.14

Group number	Mean relative emissions (tCO_2-eq ha^{-1} yr^{-1})		Scenarios forming group**
	20 year time horizon*	100 year time horizon	
1	-17	-5	**03, 04**: Sawn timber, particleboard, fuel
2	-8	-2	**10**: Sawn timber, fuel, fencing, particleboard **13**: Sawn timber, particleboard, fencing, fuel **16**: Sawn timber, MDF, fencing, particleboard, fuel
3	+1	+1	**01:** Fuel only **02**: Sawn timber, fuel **05**: Sawn timber, fuel, particleboard **06, 07, 08**: Sawn timber, MDF, fuel **09**: Sawn timber, fuel, fencing **11**: Sawn timber, fuel, fencing, MDF **12:** Sawn timber, particleboard, fuel, fencing **14**: Sawn timber, particleboard, fencing, MDF, fuel **15, 17**: Sawn timber, MDF, fencing, fuel

Note:

* Results for a 40 year time horizon are different to those for a 20 year time horizon in the case of this forest type and are not shown in the table.

** Wood product types are listed broadly in order of their importance as a component in each scenario.

Impacts of imported wood

The detailed graphical analysis discussed immediately above has only considered results for relative GHG emissions based on non-wood counterfactuals. Some consideration of results based on imported-wood counterfactuals is appropriate. As an example, Figure 5.15 shows the results of a detailed graphical analysis for the characteristic forest type of coniferous forests already under management for production, based on imported-wood counterfactuals. Also shown (as dark olive horizontal lines) are the ‘reference lines’ for the three time horizons, based on Scenario 00.00, which involves avoiding harvesting so as to accumulate forest carbon stocks.

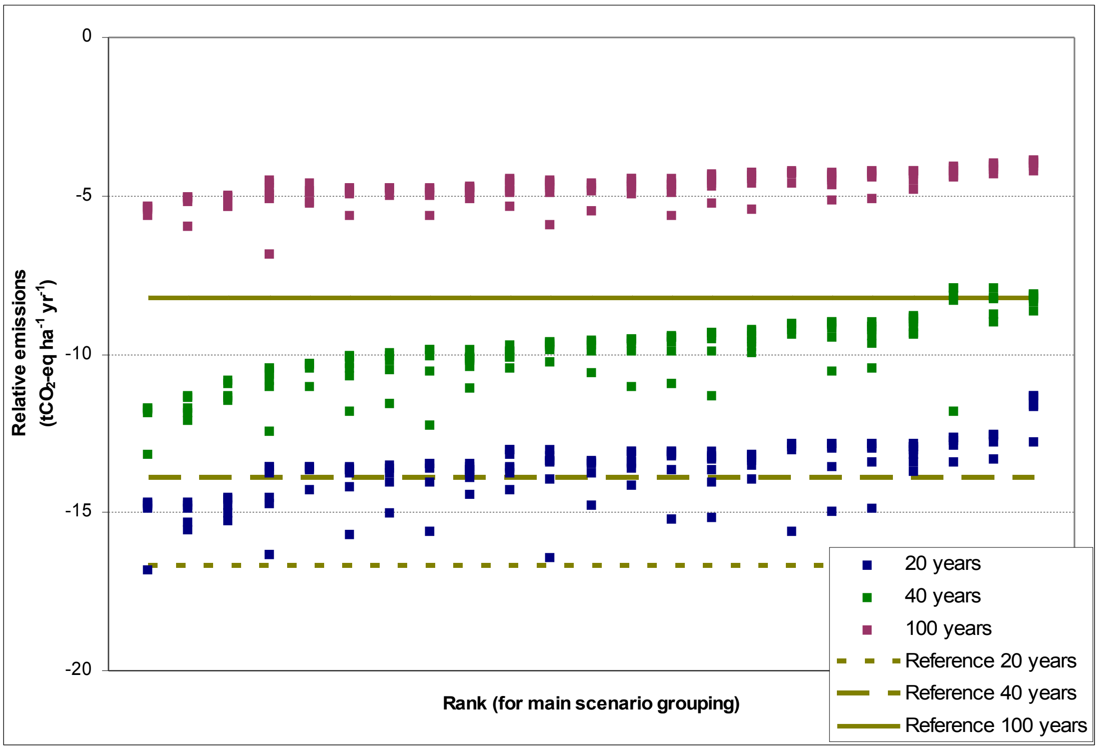


Figure 5.15. Relative greenhouse gas emissions for individual scenarios plotted against rank number for scenario grouping: UK conifer forests managed for production, imported-wood counterfactuals, bark utilised for fuel (not mulch), CCS not applied, 20, 40 and 100 year time horizons. The coloured bands indicate groups of results in terms of similar levels of relative GHG emissions.

The results in Figure 5.15 make a striking contrast to the equivalent results based on non-wood counterfactuals as already presented in Figure 5.12. It is apparent that, when imported-wood counterfactuals are referred to instead of non-wood counterfactuals:

- The differences in results for different scenarios (in terms of relative GHG emission) are much less pronounced (in fact, it is difficult to distinguish between results for different scenarios in terms of 'rank').
- The magnitudes of the (negative) values for relative GHG emissions are generally smaller.
- Estimated relative GHG emissions are generally less negative than (or sometimes close to) the 'reference lines', which represent avoiding harvesting so as to conserve and accumulate forest carbon stocks.

Such results require careful interpretation. The relatively small differences between results for different scenarios (as shown in Figure 5.15), and the relatively small magnitudes of negative relative GHG emissions should be understandable, since the counterfactual is imported wood, which in general will have similar characteristics to UK wood. Therefore, differences in relative emissions will be due to relatively small variations in LCA parameters such as transport distance, the relative productive potentials of UK and non-UK forest types, and the carbon stock changes associated with management of forests in the UK and in importing countries. Whilst these variations are important, it is to be expected that relative GHG emissions will be very much larger when a non-wood counterfactual is referred to, generally involving fossil fuels or a completely different material with very different physical properties and a completely different associated production process.

One very important question arises from comparison of the results in Figures 5.12 and 5.15. Specifically, how can the relative GHG emissions estimated based on non-wood counterfactuals be large and negative and frequently well below the 'reference lines', whereas the magnitudes of relative GHG emissions estimated based on imported-wood counterfactuals are much smaller and generally similar to or actually above the reference lines? Part of this question has already been answered in the previous paragraph. However, the fact that estimates of relative GHG emissions based on imported-wood counterfactuals fall above or close to the 'reference lines' requires further consideration. The combined implications of the results in Figures 5.12 and 5.15 are that:

- Generally speaking, harvesting and production of wood products and woodfuel from managed coniferous forests in the UK can result in large negative relative GHG emissions (i.e. large 'GHG emissions savings') when compared with the alternative of consuming fossil fuels or non-wood materials.
- The above statement is also true when considering imported wood products and woodfuel. The 'GHG emissions savings' (relative to fossil fuels and non-wood materials) associated with imported wood are generally larger than or similar to those associated with UK wood and sometimes larger (e.g. due to differences in the productive potential of UK and non-UK forests).
- Consequently, wood produced from forests both in the UK and abroad can contribute to achieving significant 'GHG emissions savings'.
- Strictly in terms of relative GHG emissions, there is not much to distinguish between producing wood in the UK or importing wood; in some cases the impacts cannot be distinguished however there are also many cases where use of imported wood may actually involve slightly larger 'GHG emissions savings'. When comparing the options of producing wood from UK forests or importing wood, any 'additional' emissions savings attributable to using UK wood (as opposed to using imported wood, if any) are indistinguishable from the option of leaving carbon in UK forests.

This result and its interpretation must be treated with great caution, as estimates of relative GHG emissions are extremely sensitive to assumptions about the relative productive potentials of UK and non-UK forests and also to assumptions about carbon stock changes that may be associated with management for wood production. It is also possible that the scope of the LCA methodology adopted in this study may not capture the full impacts of using imported wood, for example it may be necessary to consider the impacts of the 'counterfactual case' for non-UK economies when diverting wood from other uses in order to supply UK requirements.

6. Inferring carbon impacts

In Section 1 of this report, the aims and objectives of this study were stated as:

- An assessment of the potential carbon (GHG) impacts of using different types of bioenergy feedstocks (in the form of suitable woodfuels) to displace carbon (GHG) emissions from fossil fuels, against the role played by forests stocks as carbon storage facilities (including diverting wood from landfill/forest floor to bioenergy).
- An assessment of the impact on carbon (GHG) emissions of diverting these woody biomass feedstocks from a range of other uses (such as construction) and from landfill at the end of the product life to bioenergy. This should include an assessment of the potential carbon (GHG) impacts of changes in the patterns of use of biomass products in other sectors (e.g. carbon impacts of moving from the use of domestic biomass to imported biomass).

The discussion presented in this report is reaching its conclusion but it is noteworthy that, so far, the concept of carbon impacts and/or GHG impacts has not been the subject of explicit discussion. Currently, there is intense debate about the GHG emissions and GHG impacts attributable to the use of harvested wood, in general, and bioenergy, in particular. In some instances, these subjects have been presented as being uncertain. This interpretation would appear to be due, at least in part, to differences in understanding (and misunderstanding) of how GHG emissions and GHG impacts should be calculated and also due to the lack of a commonly accepted terminology for key relevant phenomena and results, e.g. ‘carbon debt’. The discussion in this section therefore, attempts to clarify understanding of the essential aspects of calculations for GHG emissions and GHG impacts.

6.1 Definition of carbon and GHG impacts

An essential first step is to define what is meant by the terms ‘carbon impacts’ and ‘GHG impacts’ in the context of this study. (It should be noted that these terms have not been commonly used by LCA researchers until quite recently and no standard or generally accepted definition exists.)

First of all, for the purposes of this study, ‘carbon impacts’ and ‘GHG impacts’ are taken to be synonymous (i.e. the term carbon impacts is taken to imply some sort of assessment of impacts covering all relevant GHGs, such as methane and nitrous oxide, not just carbon as carbon dioxide or sequestered in biomass). The term ‘carbon impacts’ is used consistently in the ensuing discussion on this basis.

The specific definition for carbon impacts adopted in this study follows from an understanding of the stated aims and objectives. These strongly indicate that the purpose of the assessment is to address and answer a particular set of research questions of the form:

What would be the consequence, in terms of changes in GHG emissions, of a policy that caused 'X' to occur?

Relevant examples of 'X' include:

- **The suspension of management involving harvesting of wood in forests currently managed for production of a specific mix of materials and/or bioenergy.**
- **The introduction of management involving harvesting and production of a specified mix of materials and/or bioenergy in forests currently not under management and with associated high carbon stocks.**
- **The continued management of forests involving harvesting but in which the mix of materials and/or bioenergy being produced shifts from one combination to another.**

It follows that the definition used for carbon impacts in this study should be:

The change (or changes) in GHG emissions due to a policy that would cause 'X' to occur (where examples of 'X' are given above).

To calculate carbon impacts as defined above it is necessary to:

- Specify what has been and will continue happening if 'X' does not occur (i.e. specify a 'baseline' or 'business as usual' scenario)
- Specify what 'X' involves (i.e. specify a scenario for the policy of interest in terms of changes compared with 'business as usual')
- Calculate GHG emissions for the 'business as usual' scenario and for the 'policy' scenario, for a specified time horizon (e.g. over the 20 year interval from the point when 'X' occurs)
- Calculate the carbon impacts as the difference between the GHG emissions for the 'policy' scenario and the GHG emissions for the 'business as usual' scenario. (If the GHG emissions for the 'business as usual' scenario are subtracted from the GHG emissions for the 'policy' scenario, the resultant carbon impacts will be negative if the 'policy' scenario leads to a reduction in GHG emissions compared with the 'business as usual' scenario, whereas carbon impacts will be positive if the 'policy' scenario leads to an increase in GHG emissions compared with the 'business as usual' scenario. Carbon impacts will be zero if there is no change in GHG emissions.)

The definition of carbon impacts and the approach to their calculation as specified above should be generally understood and agreed by LCA researchers, and, therefore, should not be contentious or controversial. However, confusion and controversy can arise if the aims and objectives of this study, the consequent research questions and specific meaning of carbon impacts in this context are misunderstood or misapplied. For example, results for carbon impacts as defined above would frequently, if not always, be unsuitable for answering the question:

What credit, in terms of reduced GHG emissions, should a power generating installation report and/or claim as a result of using a certain quantity of bioenergy to generate some or all of its delivered energy over a particular period?

This is certainly the case if the consumption of bioenergy by the power generating installation is related to a policy that has been implemented (with the effect that the policy and any response to it have become part of 'business as usual').

6.2 Calculating carbon impacts

As already explained in the preceding discussion, carbon impacts should be calculated as the difference between the GHG emissions for a specified 'policy' scenario and the GHG emissions for a specified 'business as usual' scenario. Accordingly, when calculating carbon impacts, it is important for there to be clarity and common understanding of what constitutes the 'business as usual' scenario and what constitutes the 'policy' scenario. There also needs to be clarity and common understanding of how 'GHG emissions' need to be calculated for these two scenarios, so that carbon impacts can be derived from these results. In practice, it is easy for misunderstandings to arise concerning these points; moreover, different researchers may use different approaches to carrying out and presenting calculations. It is, therefore, very important for there to be clarity over the approaches adopted in this study to:

- Selecting 'business as usual' and 'policy' scenarios
- Calculating and presenting results for GHG emissions for scenarios
- Deriving carbon impacts by comparing GHG emissions for scenarios.

These approaches are best illustrated using examples for specific research questions.

Example 1

What would be the carbon impacts over 20 years of a policy that caused the suspension of management involving harvesting of wood in UK conifer forests currently managed for production of a mix of materials and/or bioenergy?

Identification of 'business as usual' scenario

The first step in calculating the carbon impacts is to identify a scenario that represents 'business as usual'. For the question posed, 'business as usual' clearly involves a scenario in which UK conifer forests are already being managed for production of materials and/or bioenergy. It is also necessary for the selected scenario to be representative of the mix of wood materials and bioenergy typically produced from such forests as part of current practice. Although a great many scenarios for wood utilisation have been modelled in this study, they are intentionally theoretical, allowing research questions involving specified changes in the way wood might be used for different combinations of products to be investigated. Of the scenarios modelled for UK conifer forests already under management for production (see Table 4.8, Section 4.6), Scenario 17.04 can be viewed as the closest representation of the mix of wood products for 'business as usual' in a generic sense. Scenario 17.04 represents:

- 60% of sawlog material used for sawn timber
- 40% of sawlog material used for particleboard
- 50% of small roundwood used for fencing
- 50% of small roundwood used for MDF
- 100% of bark used as bioenergy for power only generation
- 50% of branchwood used as bioenergy for power only generation.

Counterfactuals of non-wood materials and UK grid-average electricity were assumed (see Table 4.4, Section 4.2).

Identification of 'policy' scenario

The next step in calculating carbon impacts is to identify a scenario that represents the intended outcome of the policy. For the question posed, the most relevant scenario modelled as part of this study is clearly Scenario 00.00, which explicitly represents the suspension of harvesting in forests that have previously been under management involving harvesting.

Calculation of GHG emissions and carbon impacts

For this first example, the calculation of GHG emissions and carbon impacts is explored in detail. In particular, three different systematic and explicit approaches reflecting calculation of GHG emissions and carbon impacts are described and discussed as the organisation of these calculations and their perceived interpretation constitutes one of the most significant sources of misunderstanding, misapplication, confusion and debate. A time horizon of 20 years has been used in this example, in accord with the research question specified.

Approach 1

This is the approach adopted in this study. It is based on calculating relative GHG emissions, as defined in Sections 5.1 and 5.3, for the 'business as usual' and 'policy' scenarios, which are then compared to derive the carbon impacts. The numbers quoted for the 'business as usual' and 'policy' scenarios (Scenarios 17.04 and 00.00) are taken directly from the detailed GHG emission calculations in the MS Excel workbooks produced as part of this study (Section 4.4).

Under the 'business as usual' scenario (Scenario 17.04):

- *There is* ongoing carbon sequestration in forests amounting to -1.0 tCO_2 ha^{-1} yr^{-1}
- *There are* emissions due to processing and utilisation of harvested wood of -6.2 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood in particleboard production)
- Counterfactual emissions of 13.4 tCO_2 ha^{-1} yr^{-1} *are avoided.*

Consequently, the relative GHG emissions for the 'business as usual' scenario are calculated as (see Sections 5.1 and 5.3):

$$= -1.0 + (-6.2) - 13.4 = \underline{\mathbf{-20.6\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

If the policy was to cause a shift from business as usual to the 'policy' scenario (Scenario 00.00), then:

- The relative GHG emissions due to business as usual management *would not* occur
- There *would be* carbon sequestration in forests amounting to $\underline{\mathbf{-16.7\ tCO_2\ ha^{-1}\ yr^{-1}}}$. (This result effectively represents the relative GHG emissions for Scenario 00.00.)

The carbon impacts of the policy are calculated as the relative GHG emissions for the 'policy' scenario minus the relative GHG emissions for the 'business as usual' scenario:

$$= -16.7 - (-20.6) = \underline{\mathbf{+3.9\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

It can be concluded that a policy aimed at suspending all management and harvesting of wood in managed conifer forests in the UK would lead to an increase in GHG emissions of 3.9 tCO_2 ha^{-1} yr^{-1} *over 20 years.*

Approach 2

This approach is based on calculating absolute GHG emissions, as defined in Sections 5.1 and 5.2, for the 'business as usual' scenario and calculating the GHG emissions that would occur for the 'policy' scenario; these two quantities are then compared to derive the carbon impacts. The numbers quoted for the 'business as usual' and 'policy' scenarios (Scenarios 17.04 and 00.00) are taken directly from the detailed GHG emission calculations in the MS Excel workbooks produced as part of this study (Section 4.4).

Under the 'business as usual' scenario (Scenario 17.04):

- *There is* ongoing carbon sequestration in forests amounting to -1.0 tCO_2 ha^{-1} yr^{-1}
- *There are* emissions due to processing and utilisation of harvested wood of -6.2 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood in particleboard production).

Consequently, the absolute GHG emissions for the 'business as usual' scenario are calculated as (see Sections 5.1 and 5.2):

$$= -1.0 + (-6.2) = \underline{\mathbf{-7.2\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

If the policy was to cause a shift from business as usual to the 'policy' scenario (Scenario 00.00), then:

- The absolute emissions due to business as usual management *would not* occur
- There *would be* carbon sequestration in forests amounting to -16.7 tCO_2 ha^{-1} yr^{-1}
- There *would be* counterfactual emissions of 13.4 tCO_2 ha^{-1} yr^{-1}

The carbon impacts of the policy are calculated as the GHG emissions for the 'policy' scenario minus the absolute GHG emissions for the 'business as usual' scenario:

$$= -16.7 +13.4 - (-7.2) = \underline{\mathbf{+3.9\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

It can be concluded that a policy aimed at suspending all management and harvesting of wood in managed conifer forests in the UK would lead to an increase in GHG emissions of 3.9 tCO_2 ha^{-1} yr^{-1} *over 20 years.*

Approach 3

This approach takes a holistic view by calculating carbon impacts in a single step based on an intrinsic comparison of continuing with 'business as usual' compared with the 'policy' scenario, rather than involving the calculation of intermediate quantities (such as absolute or relative GHG emissions) for the two scenarios which are subsequently compared, as is the case for Approaches 1 and 2. The numbers quoted in the calculation are taken directly from the detailed GHG emission calculations for Scenarios 17.04 and 00.00 in the MS Excel workbooks produced as part of this study (see Section 4.4).

Under the 'business as usual' scenario (Scenario 17.04):

- *There is* ongoing carbon sequestration in forests amounting to -1.0 tCO_2 ha^{-1} yr^{-1}
- *There are* emissions due to processing and utilisation of harvested wood of -6.2 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood in particleboard production).
- Counterfactual emissions of 13.4 tCO_2 ha^{-1} yr^{-1} *are avoided.*
- Carbon sequestration in forests amounting to -16.7 tCO_2 ha^{-1} yr^{-1} *is 'foregone'* (based on comparison with Scenario 00.00).

The carbon impacts of the policy are calculated directly from the above quantities as:

$$= -1.0 + (-6.2) -13.4 - (-16.7) = \underline{\mathbf{-3.9\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

It can be concluded that, over a 20 year time horizon, continuing with 'business as usual' management and harvesting of wood in UK conifer forests involves GHG emissions that are 3.9 tCO_2 ha^{-1} yr^{-1} *less than would be the case if a policy aimed at suspending all management and harvesting of wood were to be introduced.*

Strengths and weaknesses of calculation approaches

It could be argued quite reasonably that all the calculation approaches illustrated as part of Example 1 above are equally very strong, in that all three give the same answer for carbon impacts and the conclusion is also the same (although in the case of Approach 3, the result is expressed with opposite sign and the conclusion is expressed by considering the 'business as usual' scenario in relation to the 'policy' scenario rather than the other way round). Certainly, the agreement demonstrated by the example calculations and conclusions is very gratifying. However, the strengths and weaknesses of the three approaches lie in the details of how calculations are made and presented and final results may be interpreted (and potentially misinterpreted).

Approach 1 could be viewed as having the strength that the separate calculations and results for the 'business as usual' and 'policy' scenarios express transparently and unambiguously 'what is happening now' under the 'business as usual' scenario and 'what would happen' under the 'policy' scenario in terms of contributions to GHG emissions balances, i.e. in this example:

- Under the 'business as usual' scenario, net carbon sequestration *actually takes place* in the forest-wood products system under consideration and GHG emissions *are actually avoided* because an alternative requirement for non-wood products and fossil fuels *is obviated*.
- Under the 'policy' scenario, larger net carbon sequestration *would take place* due to increases in forest carbon stocks after the suspension of harvesting but *there*

would not be any GHG emissions avoided due to the use of harvested wood in place of non-wood products and fossil fuels.

If this interpretation is accepted, then the approach to calculation of carbon impacts involving these intermediate results is clearly on the basis of the difference between 'what would happen' and 'what is happening now'. However, it can be strongly argued that the results for the 'business as usual' scenario do not necessarily (and certainly do not always) represent 'what is happening now'. Specifically, it is not necessarily obvious that GHG emissions "are actually avoided because an alternative requirement for non-wood products and fossil fuels is obviated" (see earlier). Such a statement can be viewed as implying some sort of counterfactual scenario to business as usual, i.e. comparison of 'business as usual' with an alternative course of action. Whether or not the pursuit of 'business as usual' actually avoids this alternative course of action is subjective and debatable, and arguably the inclusion of a term representing such avoided GHG emissions to the result for 'business as usual' is inappropriate. This sensitivity in the definition of GHG emissions illustrates the potential for subtleties that can arise in the calculation, presentation and interpretation of results for GHG emissions, and the potential risks of misunderstanding and misapplication of such results.

The major strength of Approach 1 arises from the use of consistently defined and calculated results for relative GHG emissions for each distinct scenario of interest. This means it is possible to compile tables or charts of standard values for relative GHG emissions for a set of scenarios (such as illustrated in Figures 5.12 to 5.14, Section 5.5). It is then a relatively simple matter to assess the carbon impacts of a policy option by identifying the two values in the table or chart representing the 'business as usual' scenario and the 'policy' scenario and calculating the difference between them. This approach significantly reduces the total number of results that would need to be tabulated or plotted under other approaches and provides considerable flexibility for application of results to address emerging research questions about policy options such as illustrated in this section. The lack of such economy and flexibility constitutes weaknesses in Approaches 2 and 3.

Approach 1 has the weakness that the calculations and results for the 'business as usual' scenario do not represent the absolute GHG emissions directly due to the activities taking place in the forest-wood products system under consideration (see Sections 5.1 and 5.2), in that the contribution due to avoided counterfactual GHG emissions is included. As such, the GHG emissions calculated for the 'business as usual' scenario do not represent GHG emissions occurring as an explicit and direct outcome of 'business as usual' management of the forests and the 'business as usual' processing and utilisation of harvested wood. This means, for example, that the result for the 'business as usual' scenario should not be used in the calculation of GHG emissions factors for the ongoing management of forests and utilisation of harvested wood – to do so would be to misunderstand what a result for relative GHG emissions means and would lead to a misapprehension of the GHG emissions that arise from ongoing forest management (i.e. in UK conifer forests), harvesting and wood utilisation. Additionally, the calculation and results are also contingent on a specific set of assumptions about counterfactuals that apply under the 'business as usual' scenario (i.e. different types of non-wood materials, fossil fuels and imported wood).

Approach 2 has the strengths that the calculations and results for the 'business as usual' scenario correctly represent the absolute GHG emissions directly due to the activities taking place in the forest-wood products system under consideration, and there is no ambiguity caused by including any contributions due to avoided counterfactual GHG emissions. This means that the results for the 'business as usual' scenario can be legitimately quoted as the 'GHG emissions' arising from ongoing forest management in the UK including harvesting and wood utilisation. Equally, GHG emissions (and/or sequestration) associated with counterfactuals are all included unambiguously in the calculations and results for the 'policy' scenario, whilst the calculations and results for the 'business as usual' scenario are not contingent on any assumptions about counterfactuals.

The weakness of Approach 2 lies in the calculation and presentation of results for the 'policy' scenario. These could be viewed as comprising a mixture of 'what is happening now' as part of the 'business as usual' scenario (which would stop happening if the 'policy' scenario was adopted) and 'what would happen' under the 'policy' scenario. Certainly the results for the 'policy' scenario are unsuitable for quoting as the GHG emissions as a direct result of the activities assumed to take place as part of the 'policy' scenario since they do not represent the absolute GHG emissions for the 'policy' scenario. It is not even particularly clear what the result for the 'policy' scenario actually means or represents, leading to risks that the calculations and results may be misunderstood (or not understood at all) and may be misapplied. Careful consideration of the results for the 'policy' scenario reveals that it may be viewed as representing the absolute GHG emissions (or sequestration) that occur directly in forests and also in other sectors as a result of the adoption of the 'policy' scenario over the 'business as usual' scenario. However, it can be strongly argued that such an interpretation is only true when considering the implementation of the 'policy' scenario as a replacement for the 'business as usual' scenario, and does not apply in a general sense. The argument presented here is complementary to the earlier discussion of GHG emissions as calculated for the 'business as usual' scenario under Approach 1 and, as previously, serves to illustrate the potential for subtleties that can arise in the calculation, presentation and interpretation of results for GHG emissions, and the potential risks of misunderstanding and misapplication of such results.

Approach 3 has the strengths that carbon impacts are calculated explicitly in relation to the policy question being asked, with all the relevant terms included in a single equation or calculation step. In this respect, the approach could be viewed as aiding transparency by clearly including all the contributions that need to be taken into account when assessing research questions about policy options. In principle, this should also make clear what a result for carbon impacts actually represents and how it should be interpreted and used.

Unfortunately, in practice, there are significant weaknesses in Approach 3 including with regard to transparency and interpretation. Rather than aiding transparency and understanding, the reliance on a single calculation step as illustrated in Example 1, effectively making an assessment of 'business as usual' in relation to a policy option, means that the GHG emissions due to the 'business as usual' scenario ('what is happening now') and the 'policy' scenario ('what would happen') are mixed together and this may, in fact, cause significant confusion over what the result actually represents. In particular, a mistaken impression may be given that the calculation and result represent in some sense the 'true' GHG emissions due to the 'business as usual' scenario, rather than the carbon impacts due to a shift from 'business as usual' to the activities that would take place under the 'policy' scenario.

It must be stated unequivocally that results for carbon impacts, as illustrated by the examples in this section, should not be confused with results for absolute or relative GHG emissions (see Sections 5.1 to 5.3). It should be evident that the calculations, as presented for Approach 3 in Example 1, do not represent the GHG emissions due to 'business as usual' (i.e. the absolute or, in some contexts, relative GHG emissions) since the calculations for Approach 3 include a term for carbon sequestration that is 'foregone' by not opting to pursue Scenario 00.00 (suspending management involving harvesting in forests). The inclusion of this term in the calculation of GHG emissions ostensibly for 'business as usual' is a major potential source of misunderstanding and misapprehension.

An assessment of GHG emissions actually occurring as a result of 'business as usual' activities should not be confused with an assessment seeking to compare 'business as usual' with an alternative course of action. Furthermore, there is nothing unique or particularly special about Scenario 00.00 in relation to the many other possible scenarios that may be compared with 'business as usual'. To suggest the 'foregone carbon sequestration' implied by Scenario 00.00 must be included when calculating absolute or relative GHG emissions for the 'business as usual' scenario (or to go as far as to suggest that non-inclusion would be to make an 'accounting error', see Section 3.6) would be to attribute undue importance to Scenario 00.00. This would effectively distort calculations of GHG emissions by treating Scenario 00.00 as a reference against which all other scenarios must be compared. This has the effect of elevating the status of Scenario

00.00 to that of ‘business as usual’, which clearly does not apply in the context of Example 1, and which can lead to significant misunderstanding and misapplication of results and misapprehension of conclusions about ‘business as usual’ forestry activities and impacts of policies aimed at supporting certain forestry activities or certain patterns for the use of harvested wood.

As a further point of clarification in the context of this report, the inclusion of ‘reference lines’ based on Scenario 00.00 in Figures 5.12 to 5.14 in Section 5.5 should not necessarily be interpreted as a threshold for distinguishing other scenarios in terms of whether they are beneficial or detrimental in terms of carbon impacts. The ‘reference lines’ have been included in the figures to enable an assessment to be made of the potential carbon (GHG) impacts of using different types of bioenergy (and wood products in general) to displace carbon (GHG) emissions from fossil fuels (and non-wood products), *against the role played by forests stocks as carbon storage facilities*, as required by the objectives of this study. As such, these ‘reference lines’ serve as a helpful benchmark for the relative GHG emissions of various scenarios, but no more than this. However, in the case of neglected broadleaf woodlands in which management is restored, for most meaningful purposes Scenario 00.00 will represent the ‘business as usual’ scenario, hence in this case the ‘reference lines’ are of greater relevance for comparison with other scenarios.

Example 2

What would be the carbon impacts over 20 years of a policy that diverted wood harvested from managed UK conifer forests from the manufacture of a ‘conventional mix’ of wood products, including fencing and MDF, to a mix including pallets and increased particleboard production?

Identification of ‘business as usual’ scenario

The scenario selected is the same as that in Example 1, i.e. of the scenarios modelled for UK conifer forests already under management for production (see Table 4.8, Section 4.6), Scenario 17.04 can be viewed as the closest representation of the mix of wood products for ‘business as usual’ in a generic sense. Scenario 17.04 represents:

- 60% of sawlog material used for sawn timber
- 40% of sawlog material used for particleboard
- 50% of small roundwood used for fencing
- 50% of small roundwood used for MDF
- 100% of bark used as bioenergy for power only generation
- 50% of branchwood used as bioenergy for power only generation.

Counterfactuals of non-wood materials and UK grid-average electricity were assumed (see Table 4.4, Section 4.2).

Identification of 'policy' scenario

The next step in calculating carbon impacts is to identify a scenario that represents the intended outcome of the policy. For the question posed, of the scenarios modelled as part of this study, Scenario 10.04 is selected as most representative of the new mix of wood products. This scenario is similar to Scenario 17.04 but differs specifically in the following ways:

- 50% of small roundwood used for pallets instead of fencing
- 50% of small roundwood used for particleboard instead of MDF.

Counterfactuals of non-wood materials and UK grid-average electricity were assumed (see Table 4.4, Section 4.2).

Calculation of GHG emissions and carbon impacts

For this and subsequent examples, Approach 1 is used to calculate the GHG emissions and carbon impacts. A time horizon of 20 years has been used in this example, in accord with the research question specified.

The numbers quoted for the 'business as usual' and 'policy' scenarios (Scenarios 17.04 and 10.04) are taken directly from the detailed GHG emission calculations in the MS Excel workbooks produced as part of this study (Section 4.4).

Under the 'business as usual' scenario (Scenario 17.04):

- *There is* ongoing carbon sequestration in forests amounting to -1.0 tCO_2 ha^{-1} yr^{-1}
- *There are* emissions due to processing and utilisation of harvested wood of -6.2 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood in particleboard production)
- Counterfactual emissions of 13.4 tCO_2 ha^{-1} yr^{-1} *are avoided.*

Consequently, the relative GHG emissions for the 'business as usual' scenario are calculated as (see Sections 5.1 and 5.3):

$$= -1.0 + (-6.2) - 13.4 = \underline{\mathbf{-20.6\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

If the policy was to cause a shift from business as usual to the 'policy' scenario (Scenario 10.04), then:

- The relative emissions due to business as usual management *would not* occur
- *There would still be* ongoing carbon sequestration in forests amounting to -1.0 tCO_2 ha^{-1} yr^{-1}

- *There would be* emissions due to processing and utilisation of harvested wood of $-7.6\ tCO_2\ ha^{-1}\ yr^{-1}$ (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood)
- *There would be* avoided counterfactual emissions of $17.0\ tCO_2\ ha^{-1}\ yr^{-1}$

Consequently, the relative GHG emissions for the 'policy' scenario are calculated as (see Sections 5.1 and 5.3):

$$= -1.0 + (-7.6) - 17.0 = \underline{\mathbf{-25.6\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

The carbon impacts of the policy are calculated as the relative GHG emissions for the 'policy' scenario minus the relative GHG emissions for the 'business as usual' scenario:

$$= -25.6 - (-20.6) = \underline{\mathbf{-5.0\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

It can be concluded that policies aimed at shifting the utilisation of wood harvested in managed conifer forests in the UK from the pattern described in Scenario 17.04 consistent with a 'conventional mix' (representing 'business as usual') to the pattern described in Scenario 10.04 implying increased utilisation of wood for particleboard and pallets would reduce GHG emissions by 5.0 $tCO_2\ ha^{-1}\ yr^{-1}$ *over 20 years.*

Example 3

What would be the carbon impacts over 20 years of a policy that diverted wood harvested from managed UK conifer forests from the manufacture of a 'conventional mix' of wood products including fencing and MDF to the supply of bioenergy in the form of wood pellets to provide domestic heating specifically in place of coal?

Identification of 'business as usual' scenario

The scenario selected is the same as that in Example 1, i.e. of the scenarios modelled for UK conifer forests already under management for production (see Table 4.8, Section 4.6), Scenario 17.04 can be viewed as the closest representation of the mix of wood products for 'business as usual' in a generic sense. Scenario 17.04 represents:

- 60% of sawlog material used for sawn timber
- 40% of sawlog material used for particleboard
- 50% of small roundwood used for fencing
- 50% of small roundwood used for MDF
- 100% of bark used as bioenergy for power only generation
- 50% of branchwood used as bioenergy for power only generation.

Counterfactuals of non-wood materials and UK grid-average electricity were assumed (see Table 4.4, Section 4.2).

Identification of ‘policy’ scenario

The next step in calculating carbon impacts is to identify a scenario that represents the intended outcome of the policy. For the question posed, of the scenarios modelled as part of this study, Scenario 05.03 is selected as most representative of the new mix of wood products. This scenario is similar to Scenario 17.04 but differs specifically in the following way:

- 100% of small roundwood used for fuel instead of 50% used for fencing and 50% used for MDF.

Counterfactuals of non-wood materials and UK grid-average electricity were assumed (see Table 4.4, Section 4.2).

Calculation of GHG emissions and carbon impacts

Approach 1 is used to calculate the GHG emissions and carbon impacts. A time horizon of 20 years has been used in this example, in accord with the research question specified.

The numbers quoted for the ‘business as usual’ and ‘policy’ scenarios (Scenarios 17.04 and 05.03) are taken directly from the detailed GHG emission calculations in the MS Excel workbooks produced as part of this study (Section 4.4).

Under the ‘business as usual’ scenario (Scenario 17.04):

- *There is* ongoing carbon sequestration in forests amounting to -1.0 tCO_2 ha^{-1} yr^{-1}
- *There are* emissions due to processing and utilisation of harvested wood of -6.2 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood in particleboard production)
- Counterfactual emissions of 13.4 tCO_2 ha^{-1} yr^{-1} *are avoided.*

Consequently, the relative GHG emissions for the ‘business as usual’ scenario are calculated as (see Sections 5.1 and 5.3):

$$= -1.0 + (-6.2) - 13.4 = \underline{\mathbf{-20.6\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

If the policy was to cause a shift from business as usual to the ‘policy’ scenario (Scenario 05.03), then:

- *There would still be* ongoing carbon sequestration in forests amounting to -1.0 tCO_2 ha^{-1} yr^{-1}
- *There would be* emissions due to processing and utilisation of harvested wood of -5.4 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood)
- *There would be* avoided counterfactual emissions of 16.0 tCO_2 ha^{-1} yr^{-1}

Consequently, the relative GHG emissions for the 'policy' scenario are calculated as (see Sections 5.1 and 5.3):

$$= -1.0 + (-5.4) - 16.0 = \underline{\mathbf{-22.4\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

The carbon impacts of the policy are calculated as the relative GHG emissions for the 'policy' scenario minus the relative GHG emissions for the 'business as usual' scenario:

$$= -22.4 - (-20.6) = \underline{\mathbf{-1.8\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

It can be concluded that a policy aimed at shifting the utilisation of wood harvested in managed conifer forests in the UK from the pattern described in Scenario 17.04, consistent with a 'conventional mix' (representing 'business as usual') to the pattern described in Scenario 05.03 (specifically with bioenergy replacing coal) would reduce GHG emissions by -1.8 $tCO_2\ ha^{-1}\ yr^{-1}$ over 20 years.

It should be noted that this example presents an interesting case in which an assessment is made of carbon impacts due to diverting wood used make material products to bioenergy (as sought by the project objectives), in this case leading to a reduction in GHG emissions.

Example 4

What would be the carbon impacts over 20 years of a policy that caused the suspension of management involving harvesting of wood in UK broadleaf forests currently managed for production of a mix of materials and/or bioenergy?

Identification of 'business as usual' scenario

The first step in calculating the carbon impacts is to identify a scenario that represents 'business as usual'. For the question posed, 'business as usual' clearly involves a scenario in which UK broadleaf forests are already being managed for production of materials and/or bioenergy. It is also necessary for the selected scenario to be representative of the mix of wood materials and bioenergy typically produced from such forests as part of current practice. Although a great many scenarios for wood utilisation have been modelled in this study, they are intentionally theoretical, allowing research questions involving specified changes in the way wood might be used for different combinations of products to be investigated. Of the scenarios modelled for UK broadleaf forests already under management for production (see Table 4.9, Section 4.6), Scenario 09.01 can be viewed as the closest representation of the mix of wood products for 'business as usual' in a generic sense. Scenario 09.01 represents:

- 50% of sawlog material used for sawn timber
- 50% of sawlog material used as bioenergy for domestic heat
- 50% of small roundwood used for fencing
- 50% of small roundwood used as bioenergy for domestic heat
- 100% of bark used as bioenergy for domestic heat
- 50% of branchwood used as bioenergy for domestic heat.

Counterfactuals of non-wood materials and oil-fired domestic heating are assumed (see Table 4.4, Section 4.2).

Identification of 'policy' scenario

The next step in calculating carbon impacts is to identify a scenario that represents the intended outcome of the policy. For the question posed, the most relevant scenario modelled as part of this study is clearly Scenario 00.00, which explicitly represents the suspension of harvesting in forests that have previously been under management involving harvesting.

Calculation of GHG emissions and carbon impacts

Approach 1 is used to calculate the GHG emissions and carbon impacts. A time horizon of 20 years has been used in this example, in accord with the research question specified.

The numbers quoted for the 'business as usual' and 'policy' scenarios (Scenarios 09.01 and 00.00) are taken directly from the detailed GHG emission calculations in the MS Excel workbooks produced as part of this study (Section 4.4).

Under the 'business as usual' scenario (Scenario 09.01):

- *There is* ongoing carbon sequestration in forests amounting to -0.1 $tCO_2\ ha^{-1}\ yr^{-1}$
- *There are* emissions due to processing and utilisation of harvested wood of -0.9 $tCO_2\ ha^{-1}\ yr^{-1}$ (overall, emissions are negative due to carbon sequestration in wood products)
- Counterfactual emissions of 1.9 $tCO_2\ ha^{-1}\ yr^{-1}$ *are avoided.*

Consequently, the relative GHG emissions for the 'business as usual' scenario are calculated as (see Sections 5.1 and 5.3):

$$= -0.1 + (-0.9) - 1.9 = \underline{\mathbf{-2.9\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

If the policy was to cause a shift from business as usual to the 'policy' scenario (Scenario 00.00), then:

- The relative GHG emissions due to business as usual management *would not* occur

- There *would be* carbon sequestration in forests amounting to **-6.5 tCO$_2$ ha^{-1} yr^{-1}**. (This result effectively represents the relative GHG emissions for Scenario 00.00.)

The carbon impacts of the policy are calculated as the relative GHG emissions for the 'policy' scenario minus the relative GHG emissions for the 'business as usual' scenario:

$$= -6.5 - (-2.9) = \mathbf{-3.6\ tCO_2\ ha^{-1}\ yr^{-1}}$$

It can be concluded that a policy aimed at suspending all management and harvesting of wood in managed broadleaf forests in the UK would lead to a decrease in GHG emissions relative to 'business as usual' of 3.6 tCO$_2$ ha^{-1} yr^{-1} over 20 years.

Example 5

What would be the carbon impacts over 20 years of a policy that diverted wood harvested from managed UK broadleaf forests from the manufacture of a 'conventional mix' of wood products consisting of sawn timber, fencing and fuel to a mix consisting of sawn timber, particleboard and less fuel, with the fuel prioritised for power only generation?

Identification of 'business as usual' scenario

The scenario selected (Scenario 09.01) is the same as that in Example 4, i.e. of the scenarios modelled for UK broadleaf forests already under management for production (see Table 4.9, Section 4.6). Scenario 09.01 can be viewed as the closest representation of the mix of wood products for 'business as usual' in a generic sense. Scenario 09.01 represents:

- 50% of sawlog material used for sawn timber
- 50% of sawlog material used as bioenergy for domestic heat
- 50% of small roundwood used for fencing
- 50% of small roundwood used as bioenergy for domestic heat
- 100% of bark used as bioenergy for domestic heat
- 50% of branchwood used as bioenergy for domestic heat.

Counterfactuals of non-wood materials and oil-fired domestic heating are assumed (see Table 4.4, Section 4.2).

Identification of 'policy' scenario

The next step in calculating carbon impacts is to identify a scenario that represents the intended outcome of the policy. For the question posed, of the scenarios modelled as part of this study, Scenario 03.06 is selected as most representative of the new mix of wood products. This scenario is similar to Scenario 09.01 but differs specifically in the following ways:

- 50% of sawlogs used for particleboard instead of fuel
- 100% of small roundwood used for particleboard instead of fencing and fuel.

Counterfactuals of non-wood materials and UK grid-average electricity were assumed (see Table 4.4, Section 4.2).

Calculation of GHG emissions and carbon impacts

For this and subsequent examples, Approach 1 is used to calculate the GHG emissions and carbon impacts. A time horizon of 20 years has been used in this example, in accord with the research question specified.

The numbers quoted for the ‘business as usual’ and ‘policy’ scenarios (Scenarios 09.01 and 03.06) are taken directly from the detailed GHG emission calculations in the MS Excel workbooks produced as part of this study (Section 4.4).

Under the ‘business as usual’ scenario (Scenario 09.01):

- *There is* ongoing carbon sequestration in forests amounting to -0.1 tCO_2 ha^{-1} yr^{-1}
- *There are* emissions due to processing and utilisation of harvested wood of -0.9 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products)
- Counterfactual emissions of 1.9 tCO_2 ha^{-1} yr^{-1} *are avoided.*

Consequently, the relative GHG emissions for the ‘business as usual’ scenario are calculated as (see Sections 5.1 and 5.3):

$$= -0.1 + (-0.9) - 1.9 = \underline{\mathbf{-2.9\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

If the policy was to cause a shift from business as usual to the ‘policy’ scenario (Scenario 03.06), then:

- The relative emissions due to business as usual management *would not* occur
- *There would still be* ongoing carbon sequestration in forests amounting to -0.1 tCO_2 ha^{-1} yr^{-1}
- *There would be* emissions due to processing and utilisation of harvested wood of -3.3 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood)
- *There would be* avoided counterfactual emissions of 6.6 tCO_2 ha^{-1} yr^{-1}

Consequently, the relative GHG emissions for the ‘policy’ scenario are calculated as (see Sections 5.1 and 5.3):

$$= -0.1 + (-3.3) - 6.6 = \underline{\mathbf{-10.0\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

The carbon impacts of the policy are calculated as the relative GHG emissions for the 'policy' scenario minus the relative GHG emissions for the 'business as usual' scenario:

$$= -10.0 - (-2.9) = \underline{\mathbf{-7.1\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

It can be concluded that policies aimed at shifting the utilisation of wood harvested in managed broadleaf forests in the UK from the pattern described in Scenario 09.01 consistent with a 'conventional mix' (representing 'business as usual', also involving oil-fired domestic heating as the bioenergy counterfactual) to the pattern described in Scenario 03.06 (with UK grid-average electricity as the bioenergy counterfactual) would reduce GHG emissions by 7.1 $tCO_2\ ha^{-1}\ yr^{-1}$ *over 20 years.*

Example 6

What would be the carbon impacts over 20 years of a policy that caused neglected broadleaf woodlands in the UK to be brought into management involving harvesting of wood with the aim of producing a mix of sawn timber, fencing, particleboard and fuel, with the fuel used as bioenergy for power only generation?

Identification of 'business as usual' scenario

The first step in calculating the carbon impacts is to identify a scenario that represents 'business as usual'. For the question posed, the most relevant scenario modelled as part of this study is clearly Scenario 00.00, which explicitly represents the continued suspension of harvesting in broadleaf forests that are neglected.

Identification of 'policy' scenario

The next step in calculating the carbon impacts is to identify a scenario that represents the intended outcome of the policy. For the question posed, of the scenarios modelled as part of this study, Scenario 10.06 is selected as most representative of the new mix of wood products. Scenario 10.06 represents:

- 50% of sawlogs used for sawn timber
- 50% of sawlogs used for fuel
- 50% of small roundwood used for fencing
- 50% of small roundwood used for particleboard
- 100% of bark used for fuel
- 50% of branchwood used for fuel.

Counterfactuals of non-wood materials and UK grid-average electricity were assumed (see Table 4.4, Section 4.2).

Calculation of GHG emissions and carbon impacts

Approach 1 is used to calculate the GHG emissions and carbon impacts. A time horizon of 20 years has been used in this example, in accord with the research question specified.

The numbers quoted for the 'business as usual' and 'policy' scenarios (Scenarios 00.00 and 10.06) are taken directly from the detailed GHG emission calculations in the MS Excel workbooks produced as part of this study (Section 4.4).

Under the 'business as usual' scenario (Scenario 00.00):

- *There is* ongoing carbon sequestration in forests amounting to **-6.5 tCO_2 ha^{-1} yr^{-1}**. (This result effectively represents the relative GHG emissions for Scenario 00.00.)

If the policy was to cause a shift from business as usual to the 'policy' scenario (Scenario 10.06), then:

- *There would be* forest carbon stock changes (emissions) amounting to 2.3 tCO_2 ha^{-1} yr^{-1}
- *There would be* emissions due to processing and utilisation of harvested wood of -3.5 tCO_2 ha^{-1} yr^{-1} (overall, emissions are negative due to carbon sequestration in wood products, including a contribution due to recycled wood)
- Counterfactual emissions of 6.9 tCO_2 ha^{-1} yr^{-1} *would be avoided.*

Consequently, the relative GHG emissions for the 'policy' scenario are calculated as (see Sections 5.1 and 5.3):

$$= 2.3 + (-3.5) - 6.9 = \underline{\mathbf{-8.1\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

The carbon impacts of the policy are calculated as the relative GHG emissions for the 'policy' scenario minus the relative GHG emissions for the 'business as usual' scenario:

$$= -8.1 - (-6.5) = \underline{\mathbf{-1.6\ tCO_2\ ha^{-1}\ yr^{-1}}}$$

It can be concluded that a policy aimed at introducing management and harvesting of wood in broadleaf forests that were previously neglected in the UK, with the aim of producing a mix of sawn timber, fencing, particleboard and fuel (with the fuel used as bioenergy for power only generation) would lead to a decrease in GHG emissions relative to 'business as usual' of 1.6 tCO_2 ha^{-1} yr^{-1} *over 20 years.*

7. Conclusions and key messages

Reference should be made to conclusions already drawn in Sections 2.5 and 3.7 concerning the status of UK forests and forest industries and the fundamentals of forest GHG dynamics and to the worked examples and discussion in Section 6 concerning the calculation of GHG emissions, carbon impacts and drawing inferences from the results of this study.

The main results of this study have been reported in a set of workbooks, as annualised relative GHG emissions (see Section 5.1) expressed in units of $kgCO_2$ –equivalent ha^{-1} yr^{-1}, taking into account full life cycle emissions and also taking account of forest carbon stock changes and temporary sequestration in wood products using consequential LCA, for specified scenarios for the management of conifer (282 production scenarios), the management of broadleaf forests (215 production scenarios) and the restoration of neglected broadleaf forests (between 69 and 215 production scenarios) in the UK over time horizons of 20, 40 and 100 years.

A considerable number of general and specific observations can be made about these results, as discussed in Annex 2 of this report.

7.1 Main conclusions

The large body of results, conclusions and key messages discussed above can be summarised as a set of 'headlines' in terms of implications for forest management and wood utilisation. This interpretation is based on the results presented in Section 5 of this report, notably Section 5.5 and more specifically on:

- Taking a long-term perspective (i.e. 100-year time horizon),
- avoiding/ignoring 'worst case' and unfeasible disposal options for wood products (i.e. wet landfill without energy recovery/dry landfill)

and considering GHG emissions as the *sole* criterion for decision-making.

The conclusions below involve consideration of results with particular regard to a scenario option of *not harvesting* wood with the aim of sequestering carbon in forests. Such an approach has been important for this project and us derived directly from the project objectives (see Section 1.2). However, as discussed in Section 6.2 of this report as part of the description of an example calculation of carbon impacts (Example 1 in Section 6.2), the use of a 'no harvest' scenario as a 'reference case' can serve as a helpful benchmark for the relative GHG emissions of various scenarios, but should not necessarily be interpreted as a threshold for distinguishing scenarios in terms of whether they are beneficial or detrimental with respect to carbon impacts.

Wood versus non-wood: existing conifer and broadleaf production

- It is *generally* better to *maintain production* from *conifer forests* in the UK than to leave wood in the forest and meet needs for materials and bioenergy from *non-wood sources*.
- It is *often* better to *maintain production* from *broadleaf forests* in the UK than to leave wood in the forest and meet needs for materials and bioenergy from *non-wood sources*.
- Some scenarios are better than others.
- The 'best' scenarios generally involve using small roundwood and sawlogs as a source for materials and some sawlog and roundwood co-products, bark and branchwood as a source for bioenergy (i.e. a *'conventional product mix'* for UK conifer forests, but an 'unconventional mix' for broadleaf forests, see Section 2.4).
- Scenarios involving use of small roundwood and sawlogs as well as bark and branchwood *solely for as a source for bioenergy* are less effective.

Wood versus non-wood: 'neglected' broadleaf forests

- It *can be* better to *restore production* in *'neglected' broadleaf forests* in the UK than to leave wood in the forest and meet needs for materials and bioenergy from *non-wood sources*, provided that suitable mixes of wood products and bioenergy are prioritised.
- Some scenarios are better than others.
- The 'best' scenarios generally involve using small roundwood and sawlogs as a source for materials and some sawlog and roundwood co-products, bark and branchwood as a source for bioenergy.
- *This conclusion is highly sensitive to assumptions about how management is restored in 'neglected' broadleaf forests* and this subject requires more research*.*

UK wood versus imported wood

- Both UK wood and imported wood can result in lower GHG emissions compared to using non-wood sources for materials and bioenergy.
- It is equally effective and *often* better to meet needs for materials and bioenergy from *imported-wood sources* than through harvesting and production from UK forests. *This conclusion is highly sensitive to assumptions about how the management of both UK and non-UK forests would be changed to meet increased requirements for wood in the UK and also to details of LCA methodology.*
- Differences between scenarios are less pronounced when comparing UK wood with imported wood. However, the 'best' scenarios generally involve using small roundwood and sawlogs as a source for materials and some sawlog and roundwood co-products, bark and branchwood as a source for bioenergy (i.e. a *'conventional product mix'* for UK conifer forests, see Section 2.4).

‘Neglected’ broadleaf forests: wider implications of results

- Restoration of management in *‘neglected’ broadleaf forests* needs to be carried out with care, this subject requires further research.
- Appropriate silvicultural systems and guidance need to be developed
- An approach based on ‘forestry packages’ may be appropriate (e.g. a combination of forestry measures involving both restoration of management in existing neglected forests and sequestration through new creation of new forests).

Recycling and disposal of wood products

- It is *generally* better to recycle wood products at end-of-life and then finally dispose of wood (after recycling) through use as bioenergy, than to dispose of wood through use as bioenergy after initial use as a material.
- Disposal to wet landfill without energy recovery looks like a poor option but impacts of disposal of wood to wet landfill are uncertain and subject to ongoing debate.
- Prioritising use of wood as a material *now* implicitly requires the adoption of effective recycling and disposal strategies in the future.

7.2 Key messages

The conclusions of this project and the wider discussion in this report may be summarised as a set of key messages relevant to policy on UK forests, wood production and, in particular, the utilisation of wood for fuel:

- Management of UK forests for wood production can contribute to UK carbon objectives e.g. to 2050. However, there are some wide variations in carbon emissions and removals, depending on the specific circumstances.
- Using wood as a construction material or in a product maintains a carbon stock and delays emissions of carbon to the atmosphere. Using wood for bioenergy can also reduce carbon emissions, compared to burning fossil fuels for energy.
- These results suggest that policy should support managing UK forests to produce wood for a mix of products and bioenergy.
- GHG emissions are influenced by the end-of-life destination of wood products. Policies should address the long term fate of wood products to ensure maximum GHG emissions benefits.
- Currently, only about 20% of the wood consumed for materials and bioenergy in the UK is produced from UK forests. This contribution is forecast to increase over the next 20 years but imports will remain the largest source of wood consumed in the UK.
- Using imported wood for materials or bioenergy can result in low relative GHG emissions, but can also lead to large GHG emissions (see for example Figure 5.6, Section 5.3). Benefits in terms of GHG emissions will only be achieved if the harvesting of wood does not involve the permanent and long-term depletion of

carbon stocks in forests, or if reductions in carbon stocks are managed carefully over time.

- If areas of ‘neglected’ forest in the UK are restored to management, this could lead to reductions of carbon stocks in some forest areas.
- Globally, an increased requirement for wood could lead to the intensification of harvesting in forests with potential adverse impacts on forest carbon stocks. Standards for forest management (such as the UK Forest Standard) and more general biomass sustainability standards can help ensure that supplies of harvested wood achieve GHG emissions savings.

Acknowledgements

The authors wish to express their gratitude for the comments and suggestions made on a draft of this report by Dr. Astley Hastings, School of Biological Sciences, University of Aberdeen, who acted as an external reviewer.

The authors wish to express their appreciation for the guidance offered by the commissioning team at DECC, notably Ben Davison and Stella Matakidou.

Special thanks are due to Anna Stephenson of DECC for her detailed review of the MS Excel Workbooks produced as part of this project and subsequent discussions about details of LCA methodology and reporting of results.

Many useful points, comments and questions were raised in discussions with representatives of DECC, Defra and the Forestry Commission during the development of the report. The authors particularly wish to thank Mark Broadmeadow, James Davey, Ben Davison, Alison Griffin, Ewa Kmeitowicz, Davinder Lail, Stella Matakidou, Cameron Maxwell, Martin Meadows, Sekai Ngarize, Caroline Season, Janos Suto, Jonathan Michael Taylor and Ian Tubby.

The authors are especially grateful to Dr Sampo Soimakallio (VTT Technical Research Centre of Finland) for review and comments on Section 6 of this report.

References

Bates, J., Matthews, R., Mortimer, N. (2011) *Including UK and international forestry in Biomass Environmental Assessment Tool (BEAT2)*. Environment Agency Report SC090022/R1, Environment Agency, Bristol.

Bertrand, J.-L., and Simon, P. (2007) *Quantification of Net $CO_{2,eq}$ Emissions Reductions for the Manufacturing of Pallets Made from 100% Recycled Plastic by Solplast Inc (2002-2006).* Solplast Inc., Montreal, Canada, 17 August 2007.

Birdlife International (2010) *Bioenergy: a carbon accounting time bomb.* Report of Birdlife International, European Environmental Bureau and Transport & Environment. Birdlife International.

Croezen, H., Bergsma, G., Otten, M. and van Valkengoed, M. (2010) *Biofuels: indirect land use change and climate impact*. CE Delft: Delft.

DEFRA (2007) *Biomass Environmental Assessment Tool Version 2: User Manual* by AEA Energy and Environment and North Energy Associates Ltd., ED05300, for Department for Environment, Food and Rural Affairs, London, United Kingdom, 17 October 2007.

DEFRA (2008) *Biomass Environmental Assessment Tool, Version 2.0* prepared by AEA Group plc and North Energy Associates Ltd for Department for Environment, Food and Rural Affairs and the Environment Agency, London, United Kingdom, www.biomassenergycentre.org, November 2008.

ECCM (2006) *The Carbon Benefits of Timber in Construction* by Edinburgh Centre for Carbon Management, Report 196 for Forestry Commission Scotland, Appendix II, Edinburgh, United Kingdom.

Edwards, P.N. and Christie, J.M. (1981) *Yield models for forest management*. Forestry Commission Booklet 48. Forestry Commission: Edinburgh.

Forestry Commission (2011a) *Forestry Statistics 2011*, at http://www.forestry.gov.uk/website/forstats2011.nsf/LUContentsTop?openview&RestrictToCategory=1

Forestry Commission (2011b) *The UK Forestry Standard*, at www.forestry.gov.uk/theukforestrystandard.

Haberl. H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O., Johnson, R.K., Kastrup, U., Laconte, P., Lange, E., Novak, P., Paavola, J., Reenburg, A., van den Hove, S., Vermeire, T., Wadhams, P. and Searchinger, T. (2012) Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy*, **45**, 18-23.

IPCC (2007) "Climate Change 2007: Synthesis Report: Fourth Assessment Report" Inter-governmental Panel on Climate Change, www.ipcc.ch/pdf/assessment-report/ar4/ar-syn.pdf

Lesschen, J.P., Matthews, R., Oenema, O., Mackie, E., Kuikman, P., Watterson, J., Schelhaas, M., Webb, J., Ward, J., Mould, R. and Eycott, A. (2012) *What policy instruments could incentivise further mitigation efforts in the LULUCF sector?* Policy options for including LULUCF in the EU reduction commitment and policy instruments for increasing GHG mitigation efforts in the LULUCF and agriculture sectors: Background Report 3. European Commission DG CLIMA.

Lippke, B. and Oneil, E., Harrison, R., Skog, K., Gustavsson, L. and Sathre, R. (2011) Life cycle impacts of forest management and wood utilization on carbon mitugation: knowns and unknowns. *Carbon Management*, **2**, 303-333.

Maclaren, J.P. (1996) Plantation forestry – its role as a carbon sink: conclusions from calculations based on New Zealand's planted forest estate.. In Apps, M.J. and Price, D.T. (eds.) *Forest ecosystems, forest management and the global carbon cycle*. NATO ASI Series **I 40**. Springer-Verlag: Berlin, Germany, 257-270.

Maclaren, J.P. (2000) *Trees in the greenhouse - the role of forestry in mitigating the enhanced greenhouse effect*. Forest research bulletin number 219, New Zealand Forest research Institute Ltd.: Rotorua.

Matthews, R.W. (1994) Towards a methodology for the evaluation of the carbon budget of forests. In Kanninen, M. (ed.) *Carbon balance of the world's forested ecosystems: towards a global assessment.* Proceedings of a workshop held by the Intergovernmental Panel on Climate Change AFOS, Joensuu, Finland, 11-15 May 1992, 105-114. Painatuskeskus: Helsinki.

Matthews, R.W. (1996) The influence of carbon budget methodology on assessments of the impacts of forest management on the carbon balance. In Apps, M.J. and Price, D.T. (eds.) *Forest ecosystems, forest management and the global carbon cycle*. NATO ASI Series **I 40**. Springer-Verlag: Berlin, 233-243.

Matthews, R.W. and Robertson, K.A. (eds.) (2006) *Answers to ten frequently asked questions about bioenergy, carbon sinks and global climate change*. Information leaflet prepared by IEA Bioenergy Task 38, Greenhouse Gas Balances of Biomass and Bioenergy Systems. Second edition. IEA Bioenergy Task 38: Graz.

Matthews, R.W. and Broadmeadow, M.S.J. (2009) The potential of UK forestry to contribute to Government's emissions reduction commitments. In: Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds.) *Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change*. The Stationery Office: Edinburgh, 139-161.

Matthews, R.W., Craig, I.R., Mackie, E.D. and Randle, T.J. (2011) *Estimating the woodfuel potential of Woolhope Dome: Final Report revised May 2011*. Report to Herefordshire Wildlife Trust, Natural England and Forestry Commission England by Forest Research. Forest Research: Alice Holt.

Matthews, R., Lesschen, J.P., Mackie, E., Kuikman, P., Watterson, J., Oenema, O., Schelhaas, M.J., Webb, J., Ward, J., Mould, R., Eycott, A. and Miller, G. (2012) *What is LULUCF and what is the potential magnitude of its contribution to the EU's GHG reduction effort?* Policy options for including LULUCF in the EU reduction commitment and policy instruments for increasing GHG mitigation efforts in the LULUCF and agriculture sectors: Background Report 1. European Commission DG CLIMA.

McKechnie, J., Colombo, S., Chen, J., Mabee, W. and MacLean, H.L. (2011) Forest bioenergy that or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology*, **45**, 789-795.

Moffat, A.J., Jones, B.M. and Mason, B. (2006) Managing brash on conifer clearfell sites. Forestry Commission Pratice Note 13. Forestry Commission: Edinburgh.

Morison, J.I.L., Matthews, R., Miller, G., Perks, M., Randle, T., Vanguelova, E., White, M. and Yamulki, S. (2012) *Understanding the carbon and greenhouse gas balance of UK forests*. Forestry Commission Research Report, in press. Forestry Commission: Edinburgh.

Oneil, E. and Lippke, B. (2010) Integrating Products, Emission Offsets and Wildfire into Carbon Assessments of Inland Northwest Forests. *Wood and Fiber Science*, **42** (CORRIM Special Issue), 144-164.

NNFCC (2009) *Primary Energy and Greenhouse Gas Multipliers for Fuels and Electricity, United Kingdom, 2004*. Workbook NF0614Energy0402.xls, North Energy Associates Ltd., for the National Non-Food Crop Centre, York, United Kingdom, 2009, www.nnfcc.co.uk.

NNFCC (2010) *Analysis of the Greenhouse Gas Emissions for Thermochemical BioSNG Production and Use in the United Kingdom* by Mortimer, N. D., Evans, A. K. F., Mwabonje, O., Whittaker, C. L., and Hunter, A. J., North Energy Associates Ltd., Project Code NNFCC 10-009 for the National Non-Food Crops Centre, York, United Kingdom, June 2010.

NATURALHY (2010) Preparing for the Hydrogen Economy by Using the Existing Natural Gas System as a Catalyst, at www.naturalhy.net.

Read, D.J., Freer-Smith, P.H., Morison, J.L., Hanley, N., West, C.C. and Snowdon, P. (eds.) (2009) *Combating climate change – a role for UK forests: An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change.* The Stationery Office: Edinburgh

SDC (2005) *Fuel for Warmth: A Report on the Issues Surrounding the Use of Woodfuel for Heat in Scotland, for the Sustainable Development Commission* by Brady, K., Brindley, J., Gulliver-Goodall, G., Hale, S., Hall, A., Hunter, J., Macdonald, E., Mackie, E., Matthews, R., Mortimer, N., Smith, N., and Tubby, I, Forest Research and North Energy Associates Ltd., for Sustainable Development Commission (Scotland), Edinburgh, United Kingdom.

Sedjo, R. A. (2011) *Carbon Neutrality and Bioenergy: A Zero-Sum Game?* Resources for the Future Discussion Paper No. 11-15. Available at SSRN: http://ssrn.com/abstract=1808080.

Thompson, D.A. and Matthews, R.W. (1989) *The storage of carbon in trees and timber*. Research Information Note 160. Forestry Commission: Edinburgh.

Viebahn, P., Nitsch, J., Fischedick, M., Esken, A., Schüwer, D., Supersberger, N., Zuberbühler, U., and Edenhofer, O. (2007) Comparison of Carbon Capture and Storage with Renewable Energy Technologies. *International Journal of Greenhouse Gas Control*, **Issue 23**, 121-133, January 2007.

West, V. (2011) Soil carbon and the Woodland Carbon Code, at http://www.forestry.gov.uk/forestry/infd-8jue9t#soil.

Whittaker, C.L., Mortimer, N.D. and Matthews, R.W. (2010) *Understanding the Carbon Footprint of Timber Transport in the United Kingdom*. Report produced by North Energy Associates and Forest Research for the Confederation of Forest Industries (UK) Ltd on behalf of the Timber Transport Forum, April 2010. North Energy Associates: Sheffield.

Wilson, J. B. (2009a) *Life-Cycle Inventory of Particleboard in Terms of Resources, Emissions, Energy and Carbon*. Department of Wood Science and Engineering, Oregon State University, Corvallis, United States of America, April 2009

Wilson, J. B. (2009b) *Life-Cycle Inventory of Medium Density Fibreboard in Terms of Resources, Emissions, Energy and Carbon*. Department of Wood Science and Engineering, Oregon State University, Corvallis, United States of America, April 2009

Zanchi, G., Pena, N. and Bird, N. (2010) *The upfront carbon debt of bioenergy*. Report prepared for Birdlife International. Joanneum Research: Graz, Austria.

Glossary

Biomass
The mass of material comprising one or more living organisms, usually expressed as a dry weight. In this report biomass usually refers to plants and trees growing on an area of land.

Clearfell, clearfelling
The felling of all the trees forming an area of forest, usually as part of wood harvesting. In a UK context, clearfelling of entire forests does not normally occur; generally clearfelling is constrained to stands within forests.

Forest
In general terms a forest is a substantial area of land consisting of a number of component stands. (See Stand.)

Growing stock
In general the terms growing stock refers to the standing, living trees forming a stand or forest, expressed as (for example) number of stems, total tree biomass, or more commonly as standing volume. Measures of growing stock are sometimes used as indicators of sustainability of forest management (e.g. through the achievement of target levels).

kgCO_2
1 kgCO_2 = 1 kilogram (1000 grams) carbon dioxide or carbon dioxide equivalent (see Section 1.5 of this report).

kgCO_2-equivalent
Specifically, a unit of kilograms carbon dioxide equivalent. 1 kgCO_2-equivalent = 1 kilogram (1000 grams) carbon dioxide equivalent (see Section 1.5 of this report).

Overstocked
A subjective term used to describe a stand composed of:

> *Either* trees whose continued growth is constrained by extensive competition between their crowns.
> *Or* Trees whose stocking density is greater than a specified target level, for example as obtained from a standard yield table.
> *Or* both of the above.

Sequestration
The process of increasing the carbon content of a carbon reservoir other than the atmosphere. Biological sequestration includes direct removal of CO_2 from the

atmosphere through land-use change, afforestation, reforestation, carbon storage in landfills and practices that enhance soil carbon in agriculture.

Sink
Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere.

Source
Source mostly refers to any process, activity or mechanism that releases a greenhouse gas, an aerosol, or a precursor of a greenhouse gas or aerosol into the atmosphere. Source can also refer to e.g. an energy source.

Stand, forest
A group of trees of similar properties which may include those of species (or species mix), tree age (or age distribution), numbers of tree stems per unit area and management history. A stand is a sub-set of a forest.

Stocking/stocking density
Usually the number of trees in a given area. usually expressed on a per hectare basis.

tC, tCO$_2$
1 tC = 1 metric tonne (10^6 grams) carbon or carbon equivalent (see Section 1.5 of this report).
1 tCO$_2$ = 1 metric tonne (10^6 grams) carbon dioxide or carbon dioxide equivalent (see Section 1.5 of this report).

Thinning
The periodic harvesting of trees in a forest stand, involving the removal of some trees for commercial utilisation and the retention of others for future production or long-term retention.

Tonne, green
A measure of the weight of wood including moisture content, usually at time of harvest.

Yield class
Forest productivity in the UK is measured using yield class (Edwards and Christie, 1981). Yield class indicates the potential cumulative production over a typical rotation for a given tree species, expressed in cubic metres of stem volume over bark per hectare per year (m^3 ha^{-1} yr^{-1}). For more discussion see Matthews *et al*. (2011).

Annex 1 General analysis of results

A1.1 General considerations

The ranking of results under circumstances with different time horizons, counterfactuals, end-of-life disposal options and application of CCS are presented in detail in workbooks rather than in any other format simply because of the sheer number of results available. Examination of these results indicates that, in many instances, there are only small differences between neighbouring values. For example, results for relatively large groupings of scenarios (up to 30 scenarios) can cover comparatively small differences in values (such as 5%). This is significant because small differences in results can be generated by possible variations in key parameters in each relevant biomass chain. Operating in default mode, the calculation workbooks adopt values for parameters such as transport round trip distances, wood losses and, for bioenergy options, ash content of woodfuel, and the net output rating, thermal efficiency and load factor of energy generating plants. These default values reflect average or typical values obtained, principally, from the original studies and sources of data incorporated into the calculation workbooks.

In order to interpret the ranked results, it is necessary to take into account a number of considerations. First, there is the matter of the time horizons that can be adopted in national policy analysis. These can be divided into the short-term, which is taken to be equivalent to 20 years in this study, the medium-term, which is set at 40 years, and the long-term, which is assumed to be 100 years. These time horizons affect, primarily, the magnitude of forest carbon stock changes. However, they also interact with the assumed lifetimes of wood products derived from the forest and how these products are disposed at the end of their useful lives. Many different combinations of these considerations are possible and interactions between them result in very specific outcomes for the relative GHG emissions and the relative ranking of the scenarios. This is because the lifetimes of specific wood products determines how long their carbon remains sequestered and, hence, removed from the atmosphere.

Each wood product has a certain assumed lifetime which can range from a few years in the case of pallets, paper, card and horticultural mulch, a few decades in the case of fencing, and up to a century in the case of sawn timber, particleboard and MDF. When the chosen time horizon exceeds the assumed lifetime of a given wood product, the sequestered carbon can be released into the atmosphere depending on the chosen end-of-life disposal option. With disposal to dry landfill, it is assumed that no significant degradation takes place and so the carbon is effective “locked away” from the atmosphere. If the discarded wood product is burnt, then its carbon is released as CO_2 during combustion, possibly with small amounts of CH_4 and N_2O. Whilst this would be the case for disposal by waste incineration without energy recovery, other options which involve energy recovery, including WID-compliant power only and CHP generation, may more than offset these emissions by displacing fossil fuel energy generation, the magnitude of which will depend on the chosen energy counterfactual.

The worst end-of-life cases for wood products concern disposal to wet landfill because a part of the carbon in the product will be converted to CH_4. If there is energy recovery, some of this CH_4 will be captured and burnt to generate energy (usually electricity) which may more than offset the GHG emissions of combustion depending of the energy counterfactual that has been displaced. However, some CH_4 will escape into the atmosphere from the landfill site, as will any CO_2 produced by the degradation of wood in the site. The most extreme worst case is disposal to wet landfill without energy recovery since all the CO_2 and CH_4 produced by degradation of the wood will eventually escape into the atmosphere.

From this, it will be appreciated that the actual results, in the form of relative GHG emissions, and their relative ranking depend on the complex interplay of assumptions about the use of forest products, as represented by the given scenarios, the chosen counterfactuals, the chosen time horizon as it affects the forest carbon stock and its relativity to the assumed lifetime of wood products, the chosen end-of-life disposal option, and the potential application of CCS to certain means of energy production from woodfuels. Furthermore, fundamental to all these interactions is the type of forest under consideration as each type has different carbon stock dynamics and profiles of forest products in terms of the relative amounts of sawlogs, roundwood, bark and branchwood, in odt ha^{-1} yr^{-1}, at any given point in time. For all these reasons, there are distinct differences in the absolute values of relative GHG emissions for given scenarios under different circumstances and, in some instances, important alterations to their relative rankings. This is particularly relevant for the ranking of results for wood product production scenarios relative to the reference line of scenario 00.00 which involves suspending production in managed conifer and broadleaf forests and not restoring production in neglected broadleaf forests.

The ranking of results that have lower relative GHG emissions (larger negative relative GHG emissions) than the reference line is clearly relevant to the project objectives, although it is important not to attach too great importance to such a comparison as explained in Section 6, and specifically Section 6.2, of this report. Such results indicate that the production of forest products in such scenarios achieves better GHG emission outcomes than the alternative of not producing products from the forest. By examining the ranked results, it is possible to identify scenarios that are more preferable than others although relatively small differences between relative GHG emissions should be discounted due to practical variability or likely variations in biomass chain parameters. Within the limits of such variability, which may be around 5% to 10%, any of the scenarios might be regarded as providing a description of the “best use of forest products”. By examining the rankings, it will be seen that there are some scenarios which have relative GHG emissions that are consistently higher than the reference line. These are mainly scenarios in which all the forest products, in the form of sawlogs, roundwood, bark and branchwood, are used exclusively for bioenergy generation. This is clearly the outcome when using natural gas as the counterfactual for wood-fired heating and UK grid electricity in 2004 as the counterfactual for wood-fired electricity generation. Such relative ranking is also affected by the potential application of CCS.

The challenge of selecting meaningful counterfactuals to refer to in LCA calculations for material wood products has already been discussed in Section 4.2. A comprehensive analysis of the sensitivity of results (i.e. estimates of relative GHG emissions for specific wood products) to selection of counterfactuals could not be carried out within the scope of this project. However, as part of progress on the project, various calculations were made for certain wood products (notably sawn timber and particleboard) involving different counterfactuals to the ones finally selected. Generally, these counterfactuals involved greater GHG emissions than the cases ultimately referred to in this project, for example sawn timber roof trusses could have been compared to the alternative of steel trusses, whilst particleboard flooring could have been compared to the alternative of concrete screed flooring. The basis for decisions about selection of counterfactuals has been discussed in some detail in Section 4.2. It is asserted that the counterfactuals actually used in this project are reasonable and representative for specific examples of wood product types, but it should be noted that examples can be found where utilisation of wood substitutes for counterfactuals with even greater relative GHG emissions than those considered.

A1.2 Graphical analysis of ranked results

To permit a general inspection of the results, Figures A1.1 to A1.36 display the relative GHG emissions for all scenarios, plotted against their rank number. Figures A1.1 to A1.12 cover cases involving UK conifer forests managed for production, Figures A1.13 to A1.24 cover cases involving UK broadleaf forests managed for production and Figures A1.25 to A1.36 cover cases involving restoration of management in ‘neglected’ UK broadleaf forests. In each of these cases, there are four series of graphs illustrating ranked results for scenarios reflecting the effects of adopting non-wood counterfactuals without and with the application of CCS, and imported wood counterfactuals without and with the application of CCS. There are three graphs for each series which present ranked results for 20 year, 40 year and 100 year time horizons. In each graph, results based on different options for disposal of wood products at end-of-life are plotted as separate, differently coloured lines. Scenarios involving wood utilisation can be compared easily with the ‘reference case’ (or ‘reference level’) of ‘leaving wood in the forest’, i.e. avoiding harvesting so as to accumulate forest carbon stocks, which is displayed as a horizontal green line in each of Figures A1.1 to A1.36[13]. Comparison may also be made with the 'zero line' (i.e. the point at which scenarios switch from giving relative GHG emissions reductions to giving relative GHG emissions increases), which is displayed as a horizontal black line in each graph.

Conifer forests managed for production

With a 20 year time horizon and assuming non-wood counterfactuals, there are very many scenarios for managed UK forests that result in lower relative GHG emissions than those of the reference case of leaving wood in the forest (Figure A1.1). This outcome is unaffected by the application of CCS in relevant circumstances to bioenergy production (Figure A1.2). However, when imported wood counterfactuals are assumed for a 20 year time horizon, there are few scenarios (2 from 282) for managed UK forests with lower relative GHG emissions than those of the reference case although the difference is marginal (Figure A1.3). This outcome is slightly improved by the application of CCS (4 from 282) in relevant circumstances (Figure A1.4). It will be noted in all cases with a 20 year time horizon for managed UK conifer forests, ranked results for different end-of-life disposal options are fairly indistinguishable (Figures A1.1 to A1.4). This is because many important harvested wood products (specifically sawn timber, particleboard, MDF and fencing) are still in use over this short period and, hence, there are no impacts from their end-of-life disposal.

Similar but more emphatic outcomes occur with a 40 year time horizon, although the impact of end-of-life disposal for certain wood products (specifically fencing) means that there is slightly more variation in scenarios for different end-of-life disposal options. This is apparent from the distinctions that start to emerge between end-of-life disposal options for non-wood counterfactuals without and with application of CCS (Figures A1.5 and A1.6). Moving to a 40 year time horizon also reduces to zero (Figure A1.7) the number of scenarios with relative GHG emissions lower than those of the reference line assuming imported wood counterfactuals. With the relevant application of CCS, there are also no scenarios with relative GHG emissions lower than those of the reference line assuming imported wood as the counterfactuals (Figure A1.8).

---

[13] It should be noted that, in some instances, lines for different end-of-life disposal options can overlap so that some become obscured, graphically by others. Additionally, there are instances in which there is no distinction between the effects of end-of-life disposal options so that ranked results are represented, graphically, by just one line.

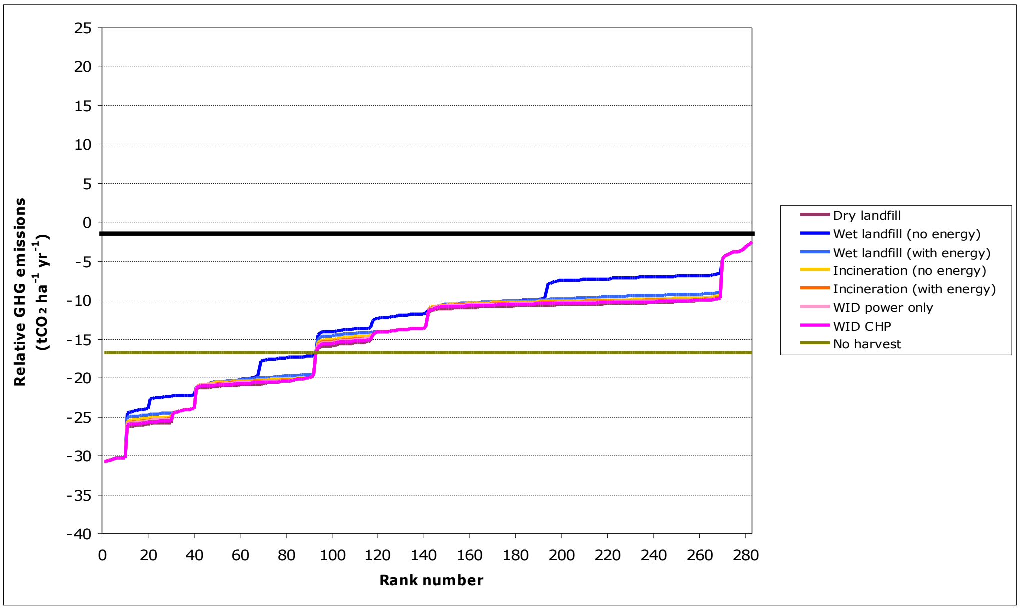


Figure A1.1. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 20 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

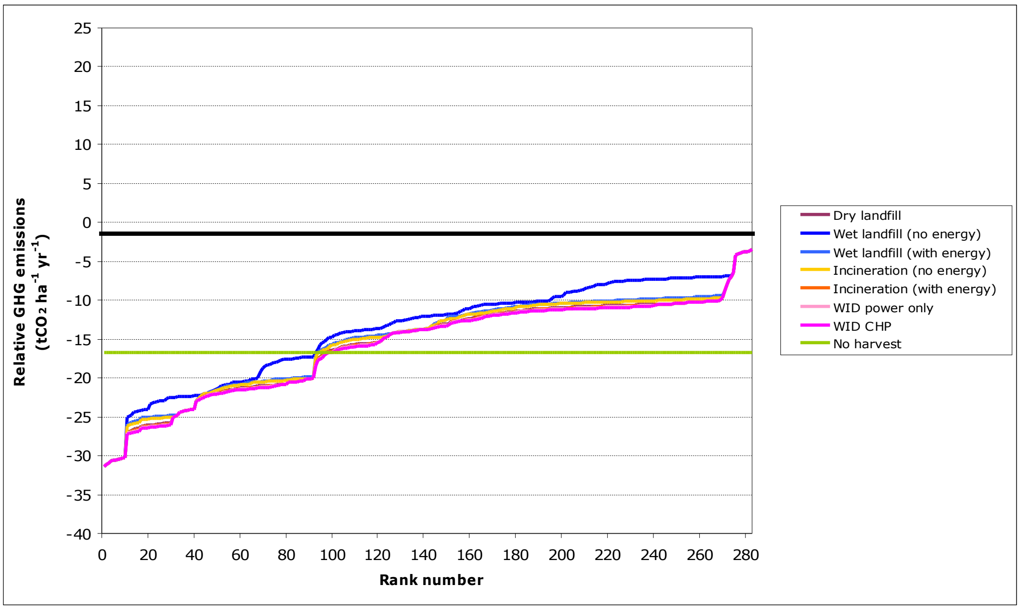


Figure A1.2. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 20 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

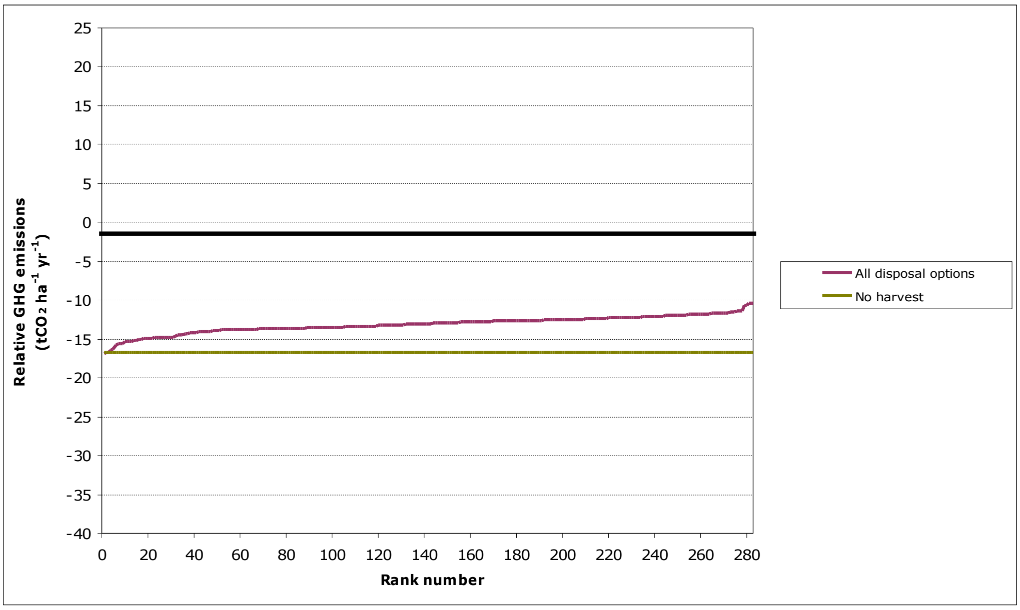


Figure A1.3. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 20 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

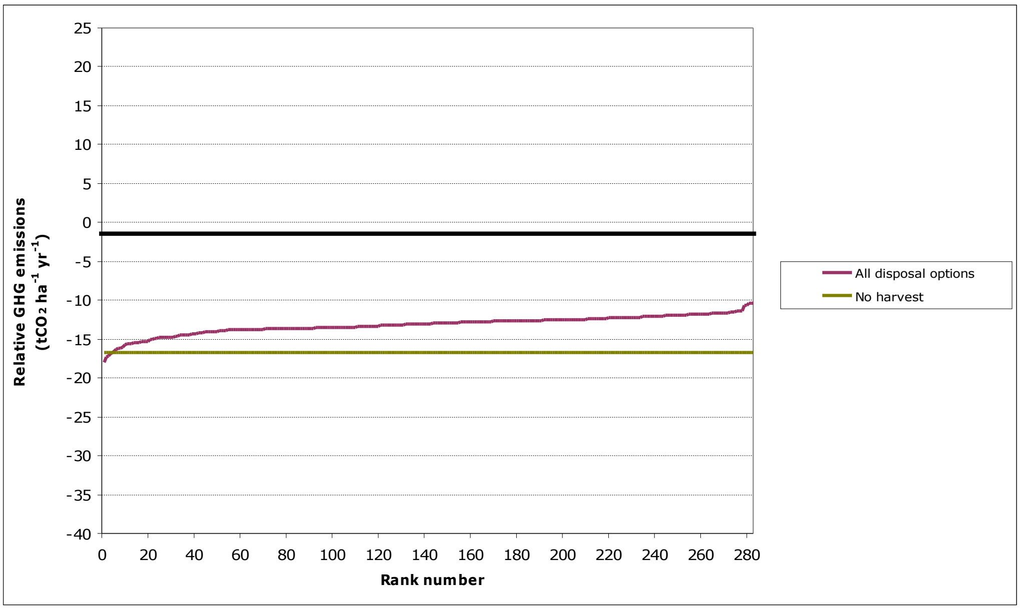


Figure A1.4. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 20 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

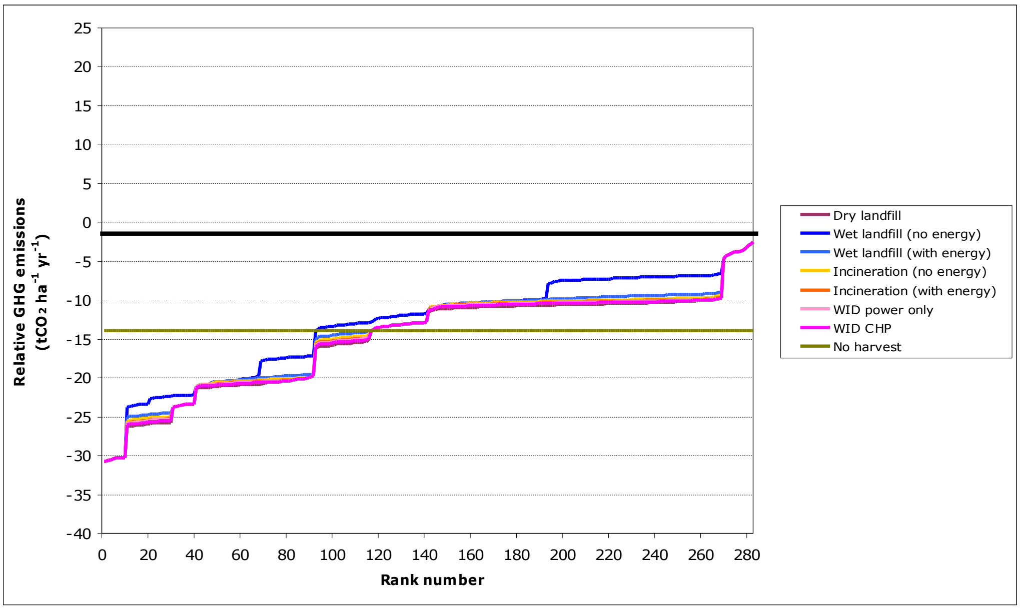


Figure A1.5. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 40 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

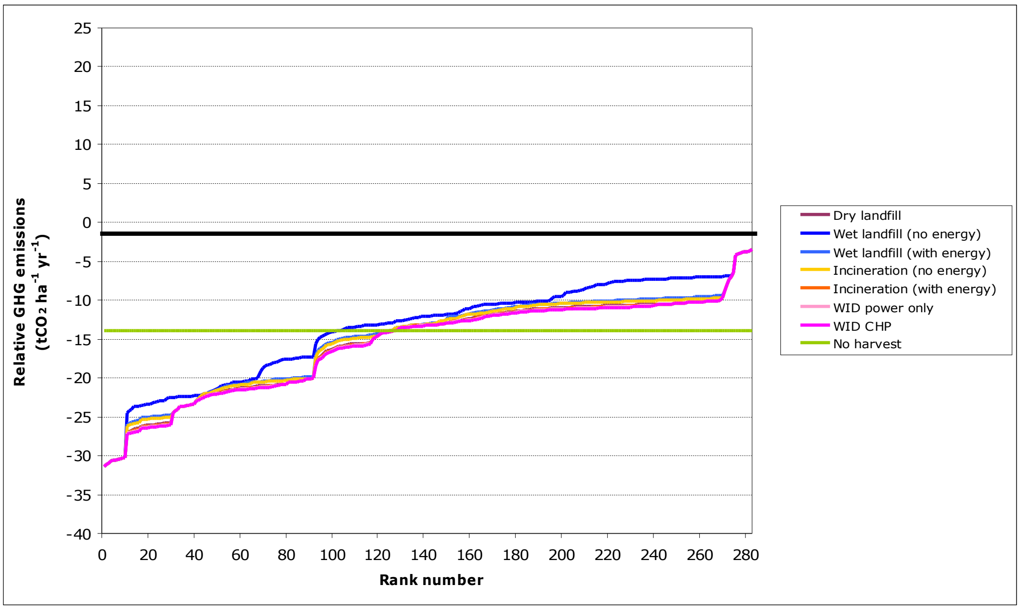


Figure A1.6. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 40 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

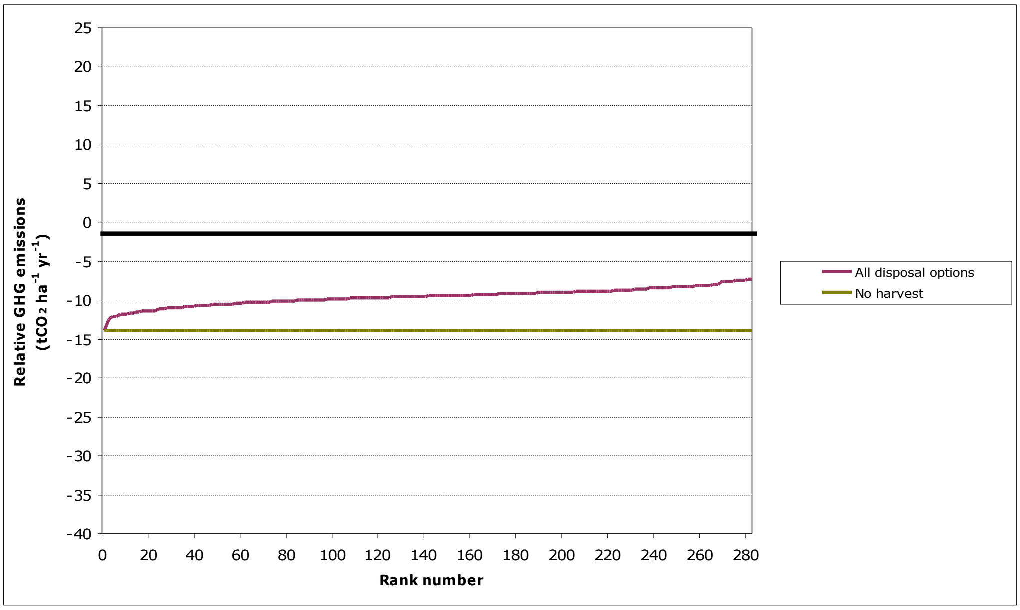


Figure A1.7. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 40 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

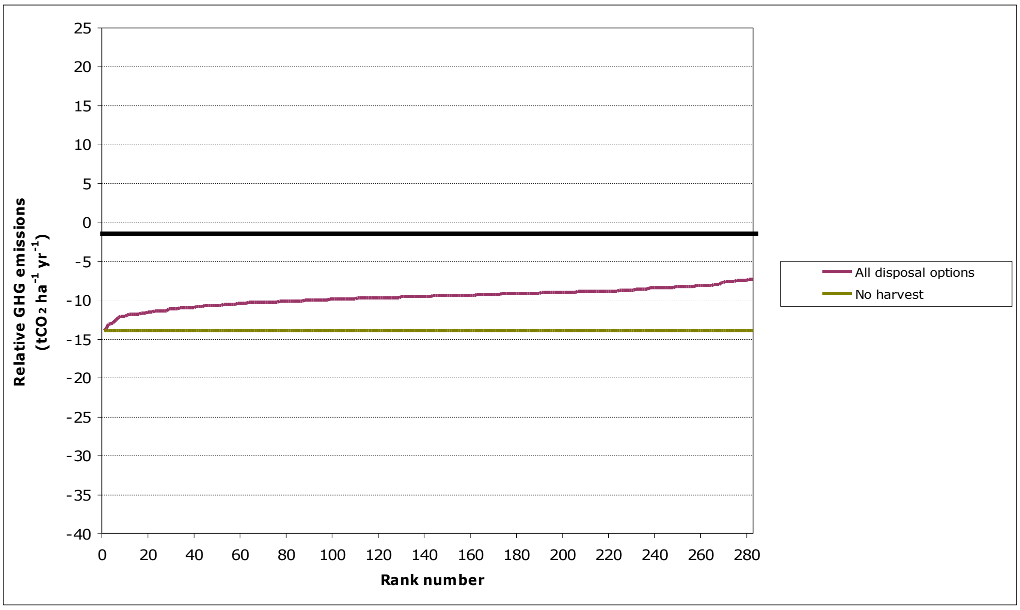


Figure A1.8. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 40 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

For a 100 year time horizon and with non-wood counterfactuals, relative GHG emissions are seen to be strongly dependent on the option for end-of-life disposal (Figures A1.9 and A1.10). In these cases, the lowest relative GHG emissions are associated with disposal to dry landfill, then incineration with CHP, followed by incineration with power only generation, waste incineration with energy recovery, waste incineration without energy recovery and, finally, disposal to wet landfill with energy recovery followed by disposal to wet landfill without energy recovery. The detrimental impacts on relative GHG emissions associated with disposal to wet landfill without energy recovery are very apparent.

The reason why dependence of results on end-of-life disposal is so strong in the case of non-wood counterfactuals (without or with CCS application) is that all relative GHG emissions impacts of disposal come into play with a 100 year time horizon. However, these relative impacts also reflect GHG emissions differences between the disposal wood products and their counterfactuals. However, these differences do not arise when imported wood counterfactuals are assumed. This is because the relative GHG emissions from disposing of UK and imported wood products effectively cancel each other out. This means that other considerations become relatively more apparent such as the effect of time horizons on the carbon stock changes for UK and overseas conifer forests.

The outcome of this is that, with a 100 year time horizon and imported wood as counterfactuals, there are no scenarios with lower relative GHG emissions than those of the reference line either with or without CCS application (Figures A1.11 and A1.12).

All these results (Figures A1.1 to A1.12) also show that scenarios for wood utilisation, when placed in ranked order, do not form distinctly separate groups, in terms of relative GHG emissions. Rather, successive results for relative GHG emissions, placed in ranked order, form a continuous progression, although sometimes with occasional notable steps in the sequence.

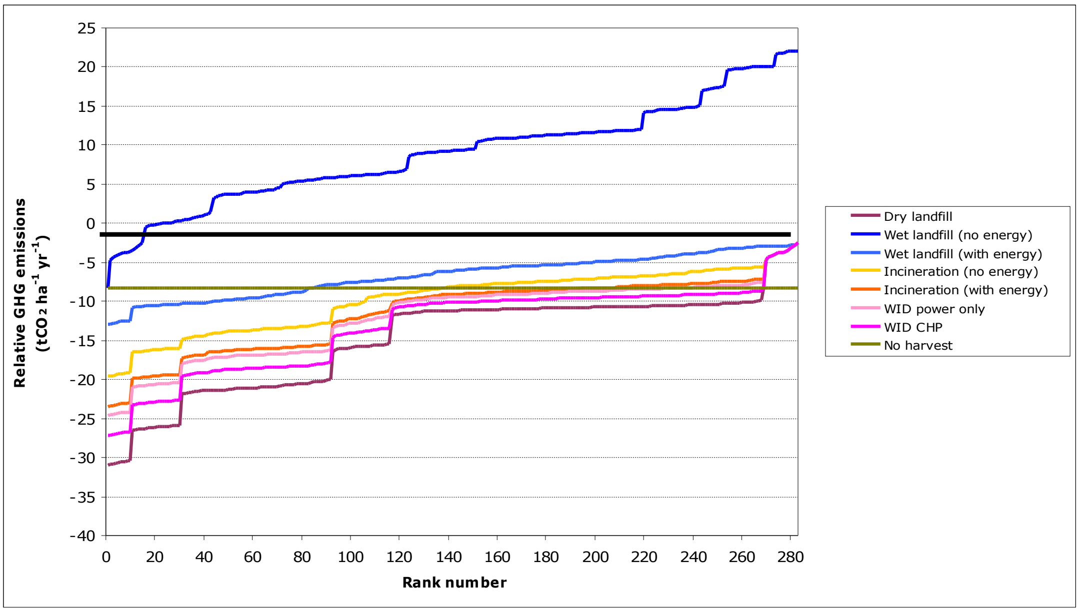


Figure A1.9. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 100 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

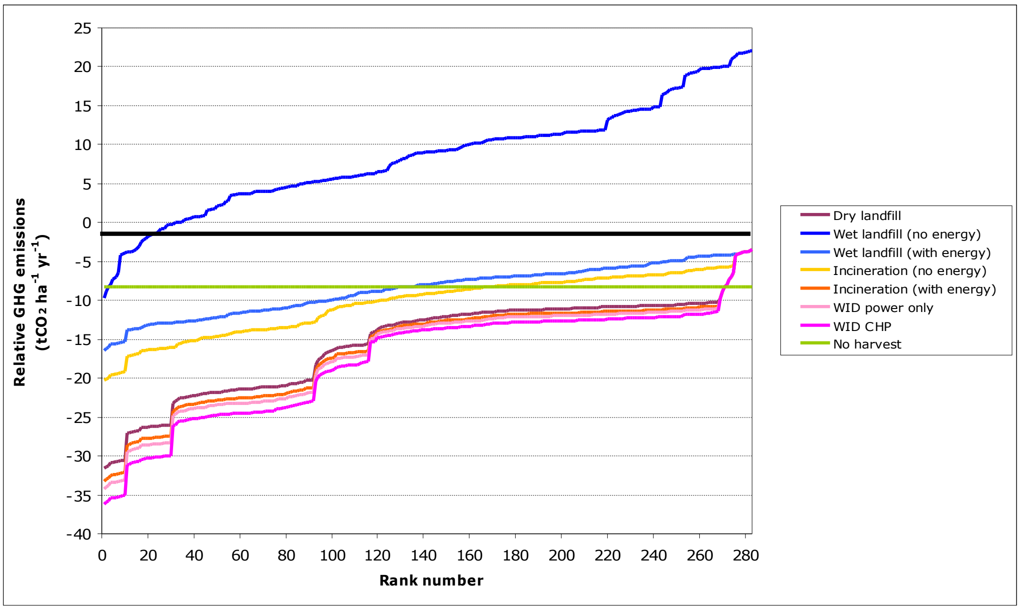


Figure A1.10. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 100 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

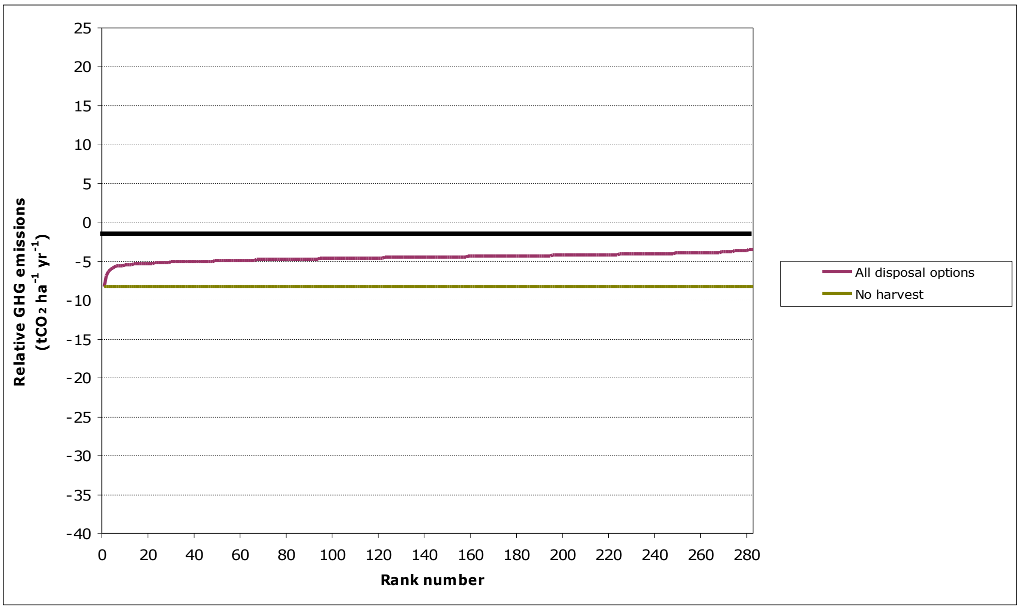


Figure A1.11. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 100 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

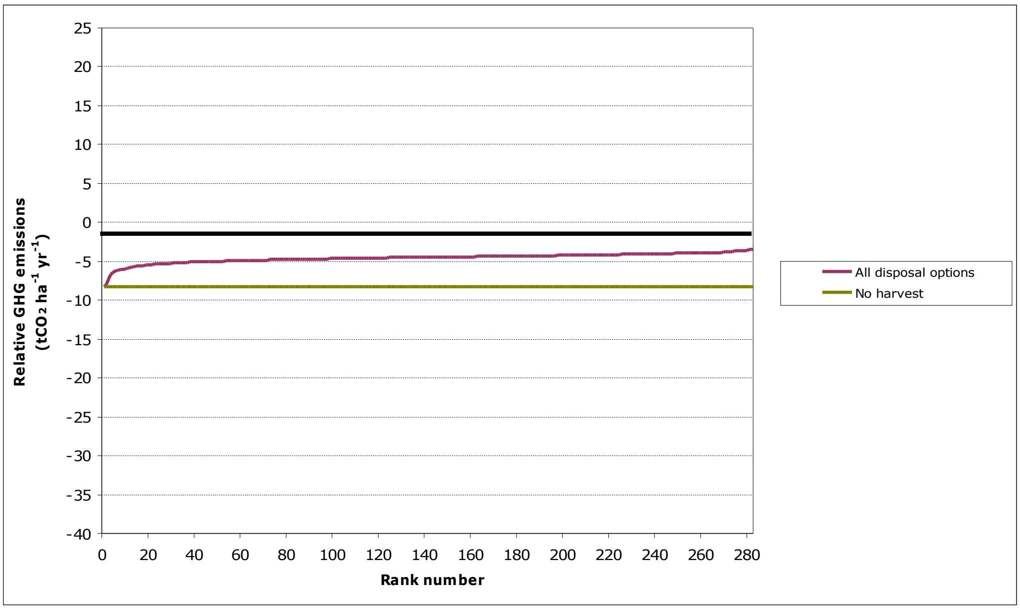


Figure A1.12. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK conifer forests managed for production: 100 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

Broadleaf forests managed for production

There are some clear differences between the ranked results for managed UK broadleaf forests and those for managed UK conifer forests. The first difference can be seen from the results over a 20 year time horizon (Figures A1.13 to A1.16). In particular, only small distinctions are apparent between disposal options in any of these cases. The reasons for this are that chosen profiles of products from UK broadleaf forests are not as extensive as for UK conifer forests[14]. Specifically, pallets, and paper and card are not included in the production profile for broadleaf forests. Hence, these products with relatively short lives (less than 20 years) are not incorporated in the calculations and the GHG emissions impacts of their disposal do not materialise. As will be seen later, this situation changes as time horizons are extended and other wood products become liable for disposal.

With a 20 year time horizon and assuming non-wood counterfactuals without application of CCS where relevant, there are many scenarios (typically about 70 from 215) which have lower relative GHG emissions than those for the reference line that represents suspending production in managed UK broadleaf forests (Figure A1.13). There are also many scenarios (typically 80 from 215) when CCS is incorporated into the evaluation of managed UK broadleaf forest with a 20 year time horizon and non-wood counterfactuals (Figure A1.14). There are several scenarios (16 from 215) with lower relative GHG emissions than those of the reference line when imported wood counterfactuals are adopted, without the relevant application of CCS, and with a 20 year time horizon (Figure A1.15). A similar number of scenarios (19 from 215) are observed when CCS is applied in relevant circumstances over a 20 year time horizon and assuming imported wood counterfactuals (Figure A1.16). It should be noted, however, that, with either of these cases assuming imported wood counterfactuals, relative GHG emissions are only marginally lower than those of suspending production (Figures A1.15 and A1.16). One new consideration which comes into play specifically for broadleaf forests in this regard is that many of the imported wood counterfactuals are being derived from overseas conifer rather than broadleaf forests[15].

---

[14] It should be noted because of changes in the production profile, the number of scenarios reduces from 282 in the case of conifer forests to 215 for broadleaf forests.

[15] It should be noted that it has been assumed that the counterfactuals for wood fuel imported from Canadian conifer forests, particleboard and MDF from Irish conifer forests, fencing from Baltic States conifer forests, and only sawn timber for hardwood window frames from US broadleaf forests.

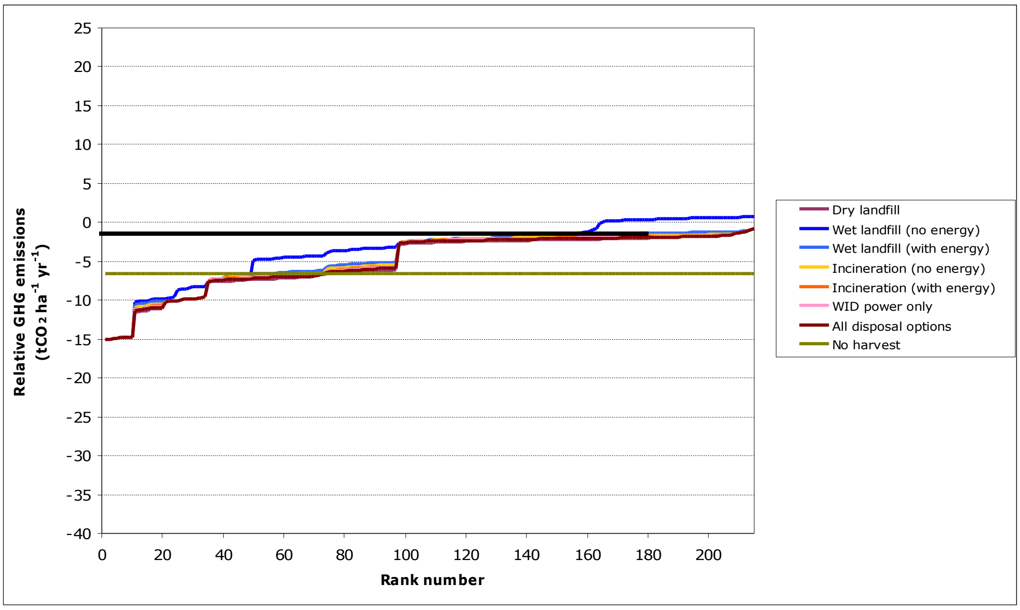


Figure A1.13. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 20 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

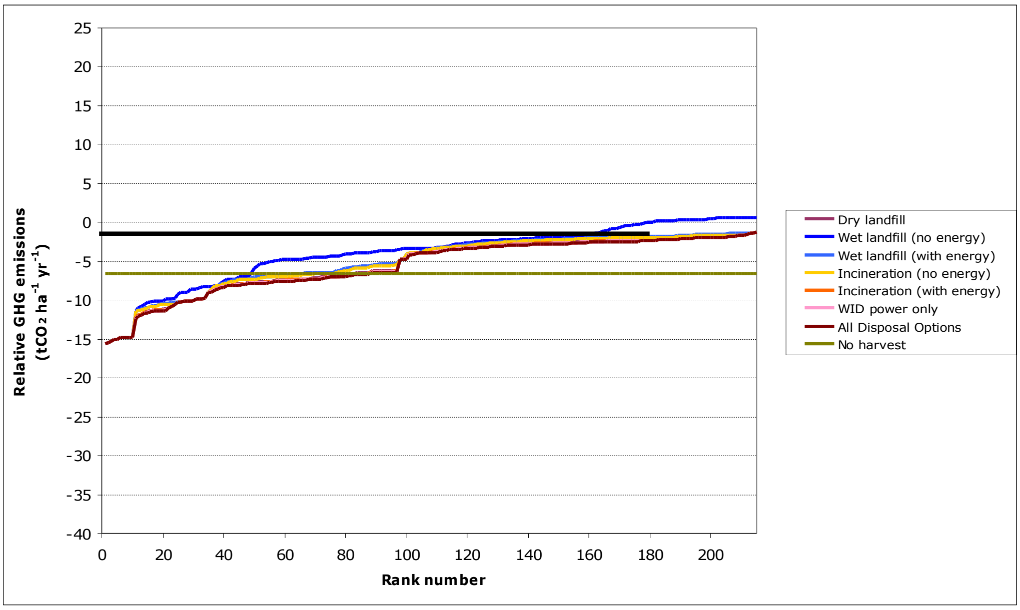


Figure A1.14. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 20 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

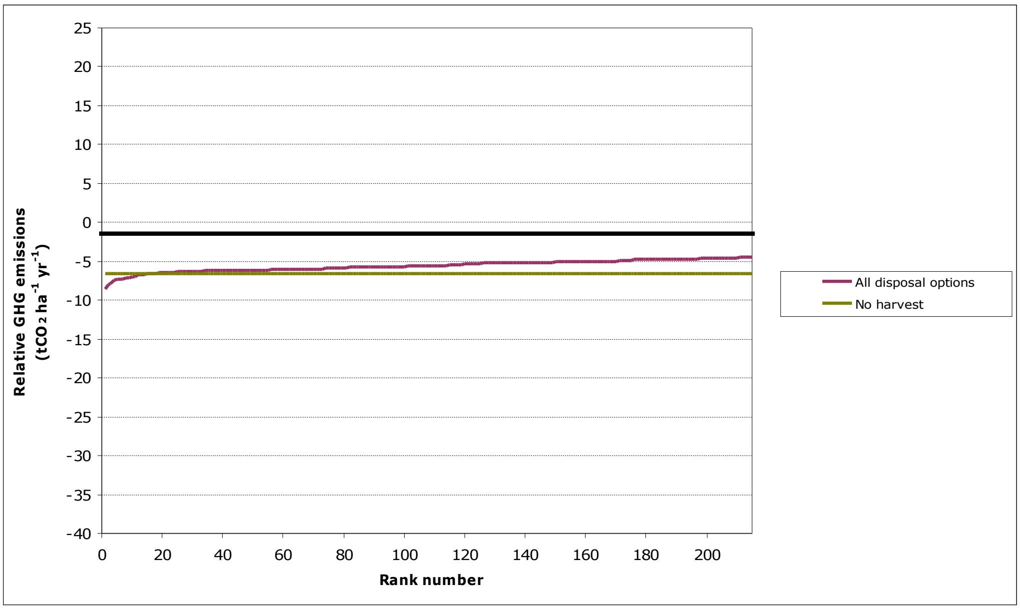


Figure A1.15. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 20 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

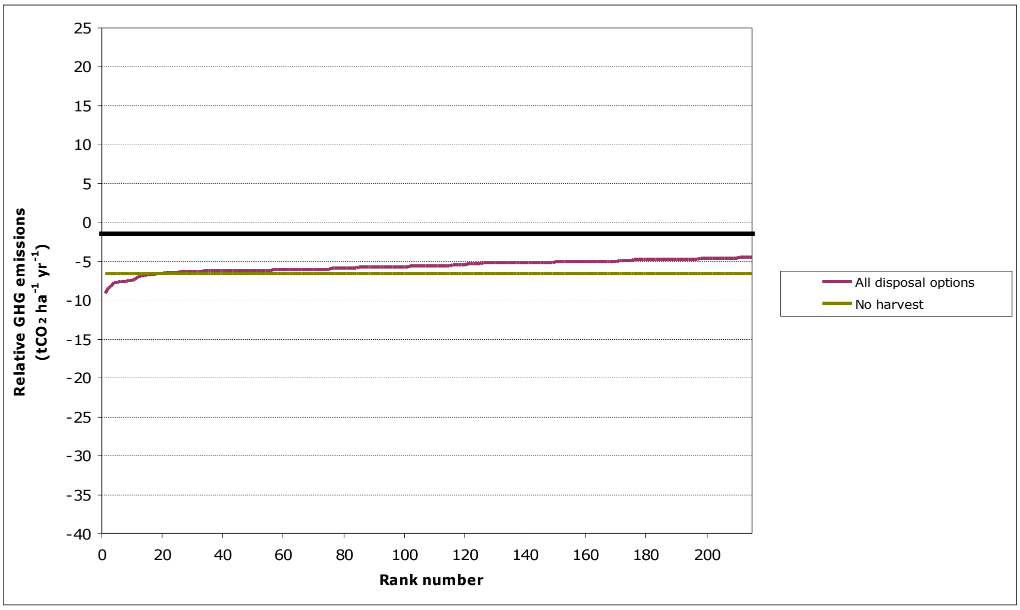


Figure A1.16. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 20 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

As mentioned previously, distinctions between disposal options become more enhanced when the time horizon is extended from 20 years to 40 years for production in managed UK broadleaf forests (Figures A1.17 to A1.20). This is because certain wood products (specifically fencing) are now ready for disposal within this longer time period. However, in the case of a 40 year time horizon with non-wood counterfactuals and no CCS applications, there are still many scenarios which have lower relative GHG emissions than those of the reference line for suspended production (Figure A1.17). The same is also true when relevant CCS application is taken into account over a 40 year time horizon for non-wood counterfactuals (Figure A1.18). However, there is a significant change when imported wood counterfactuals are taken into account for managed UK broadleaf forest over a 40 year time horizon. Regardless of whether CCS is applied in relevant circumstances, over a 40 year time horizon for managed UK broadleaf forests compared with imported wood counterfactuals, there are no production scenarios which have lower relative GHG emissions than those of the reference line of suspended production (Figures A1.19 and A1.20). In some cases, the differences in relative GHG emissions between the production scenarios and those of suspended production are relatively marginal. Despite this, the apparent GHG emissions benefits of importing wood products and woodfuels instead of production from managed UK broadleaf forests is partly a consequence of displacing hardwood by softwood, as reflected in the carbon stock dynamics of UK broadleaf forests relative to those of selected overseas conifer forests over a 40 year time horizon.

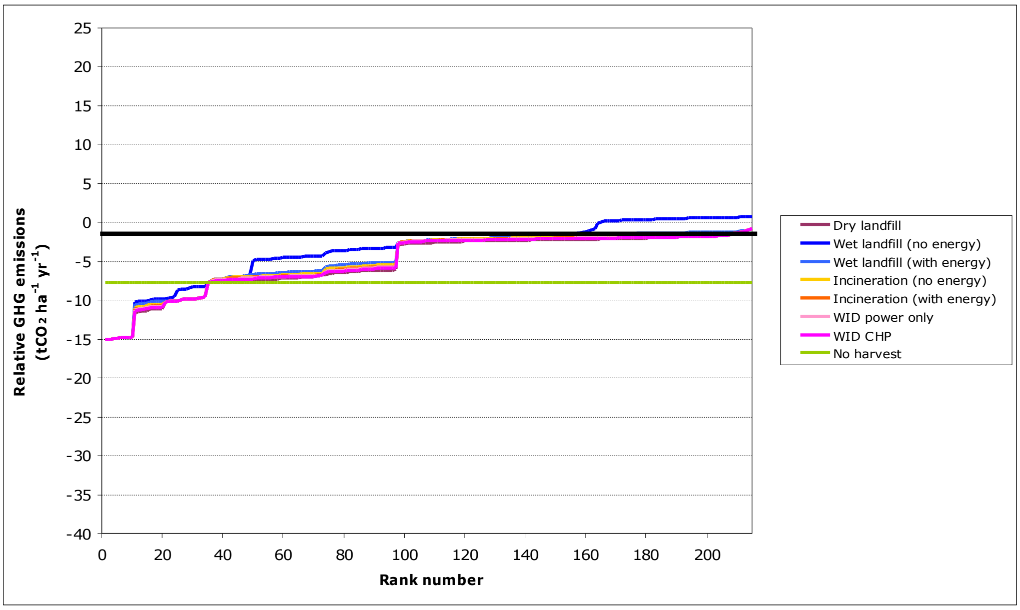


Figure A1.17. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 40 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

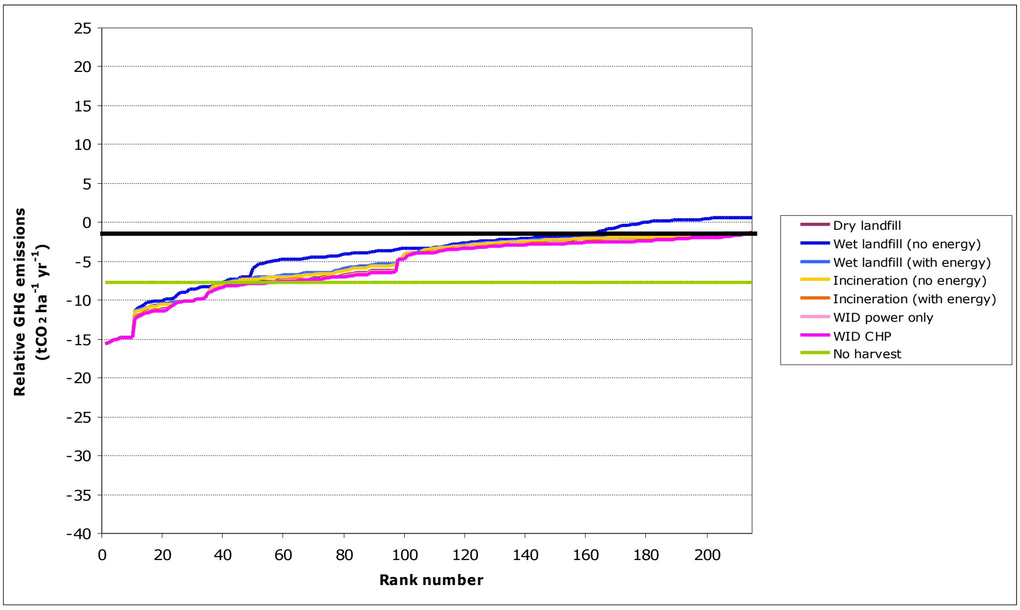


Figure A1.18. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 40 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

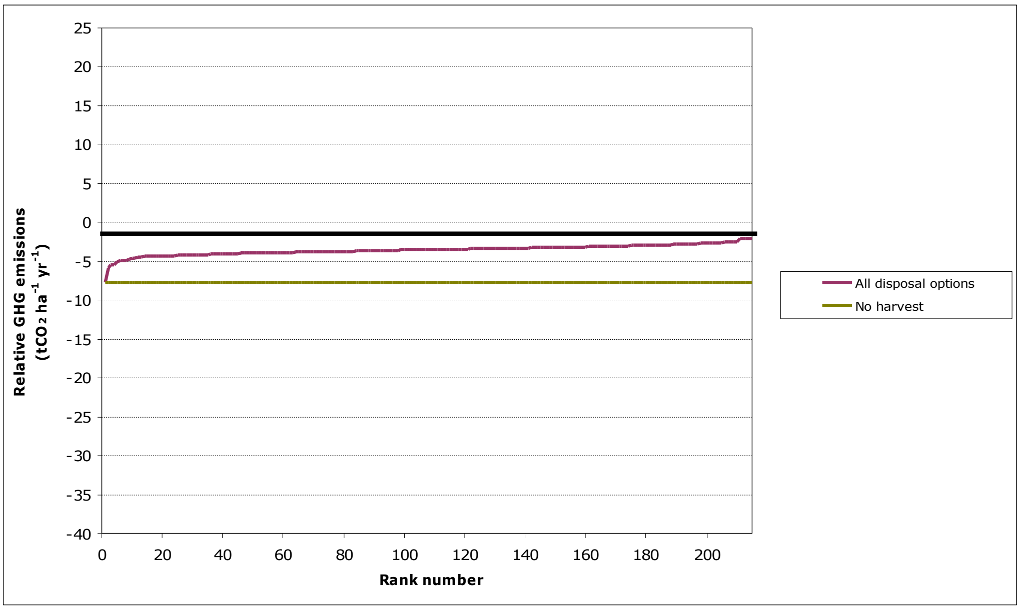


Figure A1.19. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 40 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

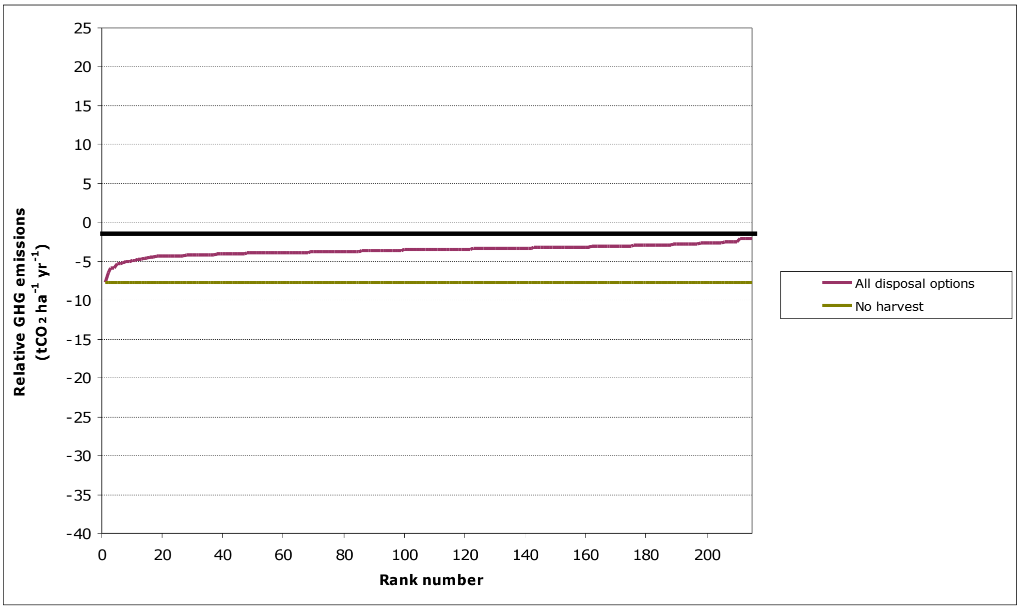


Figure A1.20. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 40 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

Ranked results over a 100 year time horizon for managed UK broadleaf forests tend to reinforce outcomes for shorter time horizons (Figures A1.21 to A1.24). There are still many scenarios over this time horizon which have lower relative GHG emissions than those of the reference line when non-wood counterfactuals are chosen either without relevant application of CCS (Figure A1.21) or with CCS application (Figure A1.22). However, in both these cases, the importance of avoiding wood product disposal to wet landfill without energy recovery is apparent. These GHG emissions effects of disposal options become more prominent because all wood products are assumed to have reached the end of their lives within this time horizon. The GHG emissions hierarchy of disposal options is the same as that for managed UK conifer forests. Again, there are no scenarios when imported wood counterfactuals are adopted with managed UK broadleaf forests over a 100 year time horizon either without CCS application (Figure A1.23) or with CCS application (Figure A1.24). However, as before, differences with the reference line are marginal.

As with results for managed UK conifer forests in production, all these ranked results for scenarios (Figures A1.13 to A1.24) for utilising wood from managed UK broadleaf forests, when placed in ranked order, do not form distinctly separate groups in terms of relative GHG emissions. Instead, successive results for relative GHG emissions, placed in ranked order, form a continuous progression, although sometimes with occasional notable steps in the sequence.

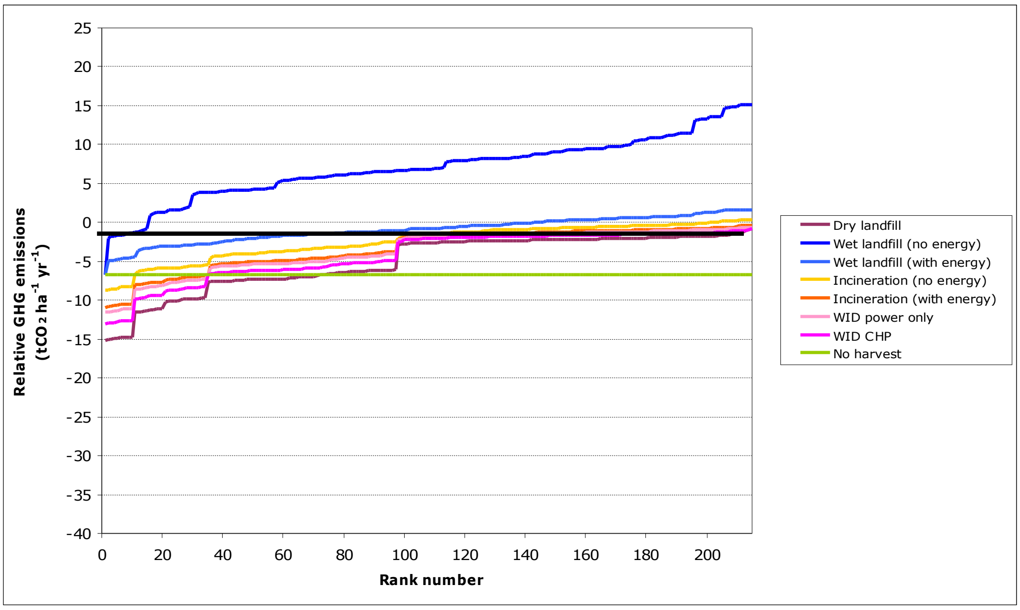


Figure A1.21. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 100 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

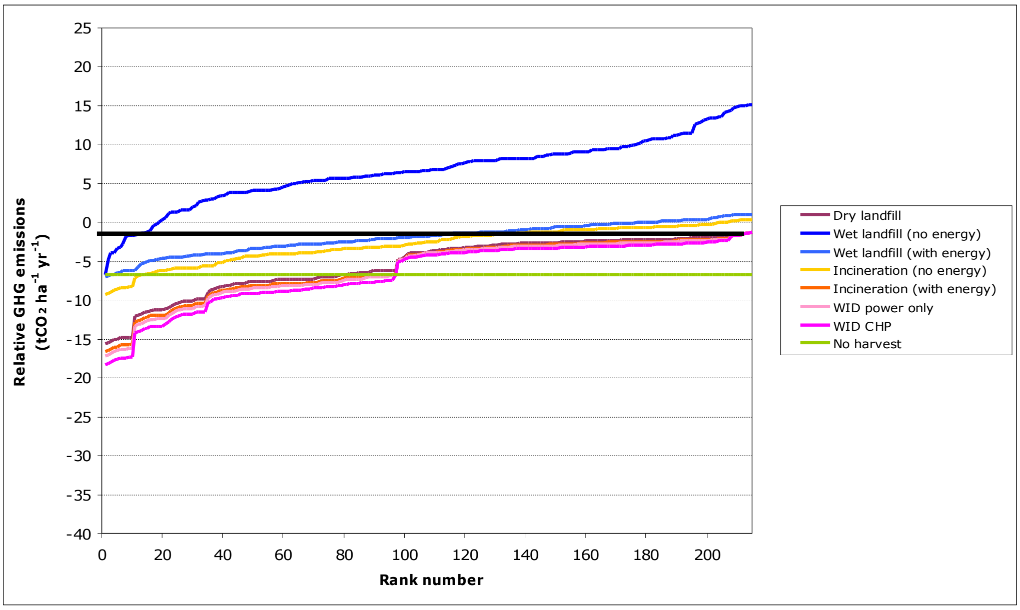


Figure A1.22. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 100 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

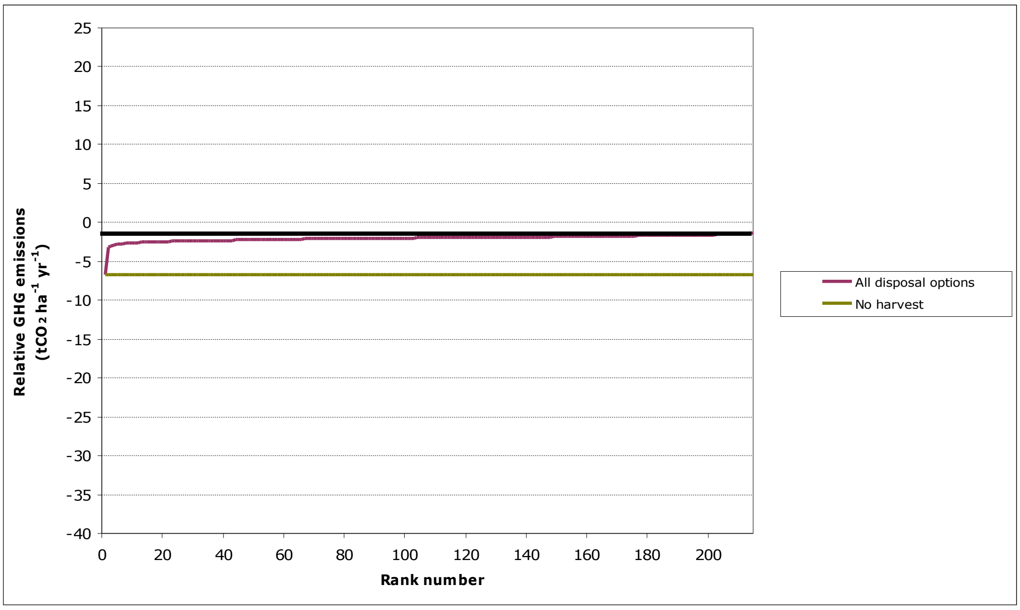


Figure A1.23. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 100 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

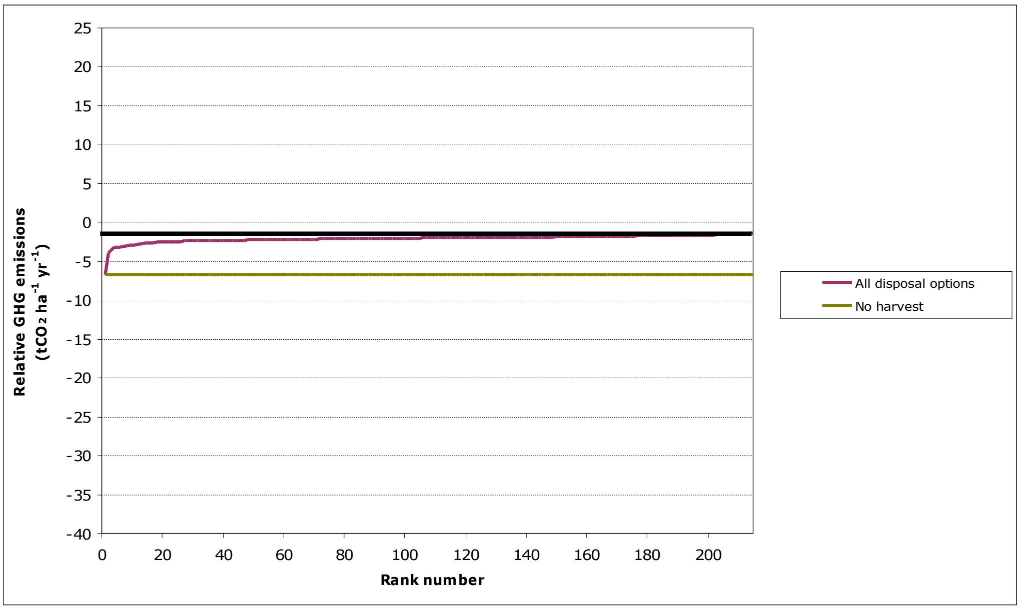


Figure A1.24. Relative greenhouse gas emissions plotted against rank number for scenarios involving UK broadleaf forests managed for production: 100 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

Restoration of management in ‘neglected’ broadleaf forests

For the same reasons as those with managed UK broadleaf forests, the ranked results for restoring production in neglected UK broadleaf forests over a 20 year time period show only small distinctions with respect to the chosen end-of-life disposal option (Figures A1.25 to A1.28). The additional factor over this time period of 20 years which has to be taken into account is that there are no sawlogs available for producing sawn timber. Hence, there are even fewer production scenarios for restored broadleaf forest production (reduced significantly from 215 to 69). However, the GHG emissions outcomes when non-wood counterfactuals are assumed bear resemblance to those for managed UK broadleaf forests.

With a 20 year time horizon and non-wood counterfactuals without CCS application, there are many scenarios (typically 20 from 69) which have lower relative GHG emissions than those of the reference line that represents not restoring production in neglected UK broadleaf forests (Figure A1.25). The application of CCS has almost no effect on this outcome (Figure A1.26). As with managed UK broadleaf forests over a 20 year time horizon, the switch to imported wood counterfactual without CCS application means that there are only two scenarios which have lower relative GHG emissions than the reference line (Figure A1.27). In addition, some of the production scenarios are only marginally higher than those when production is not restored. Similar results are obtained when relevant CCS application is incorporated with restored UK broadleaf forest production over a 20 year time horizon with imported wood counterfactuals (Figure A1.28).

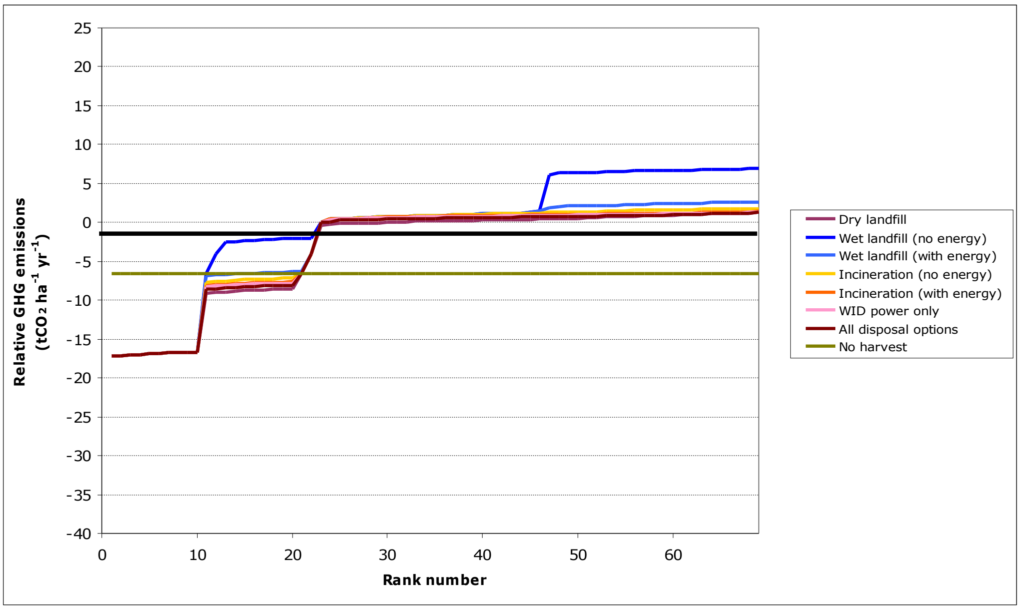


Figure A1.25. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 20 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

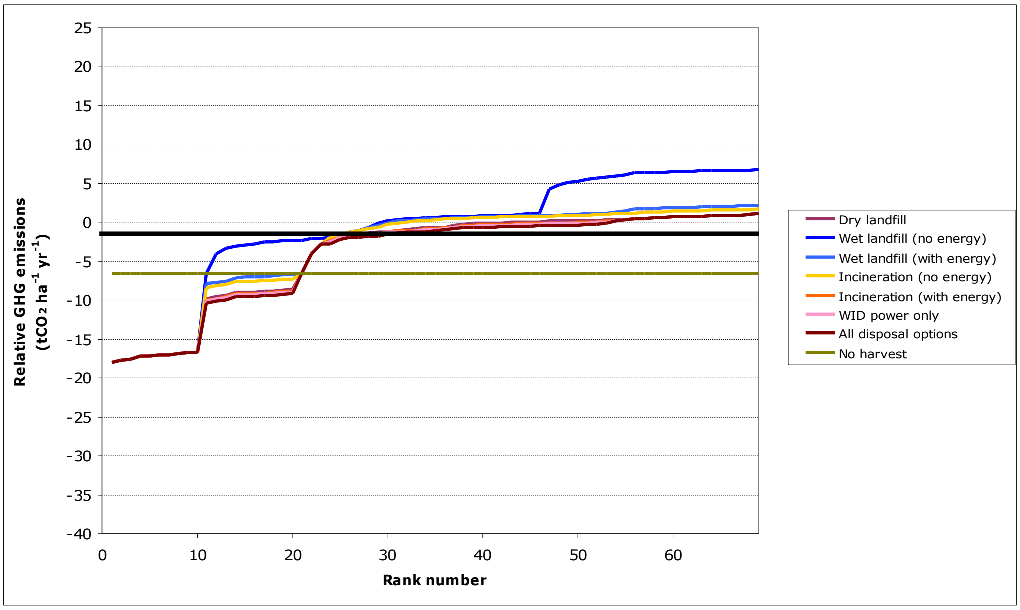


Figure A1.26. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 20 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

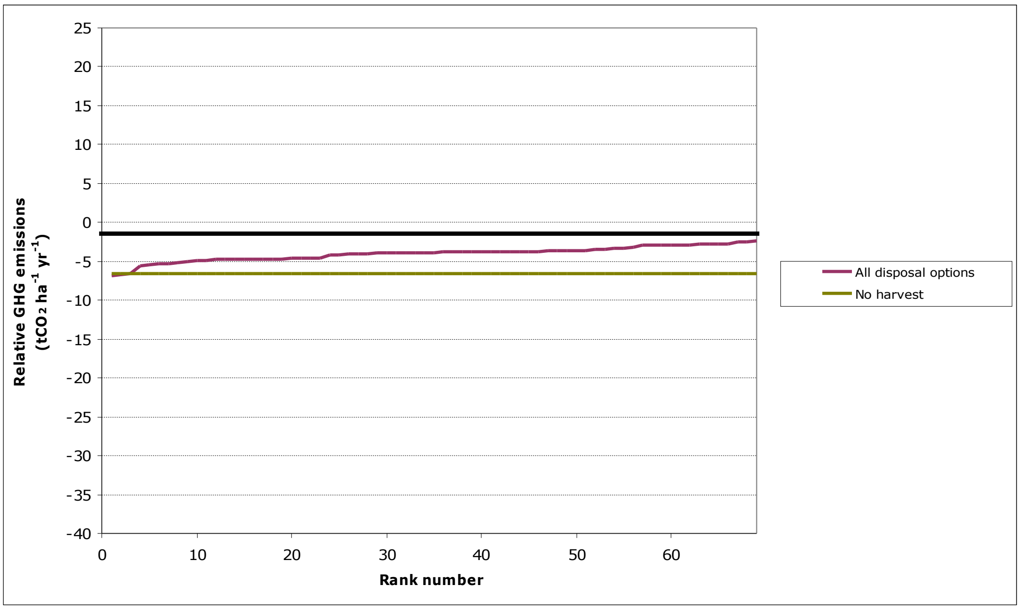


Figure A1.27. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 20 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

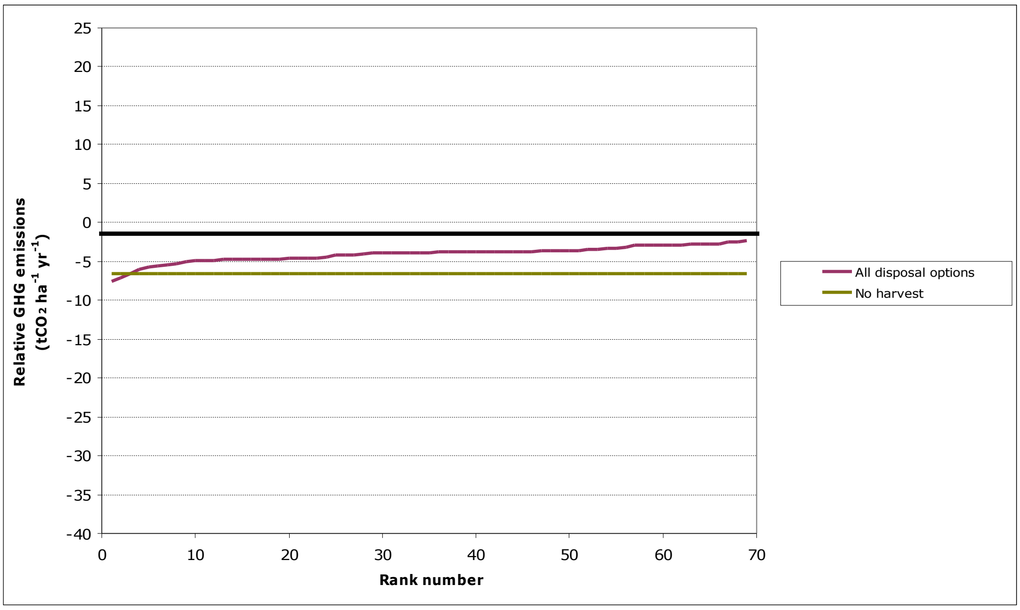


Figure A1.28. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 20 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

Similar to the case with managed UK broadleaf forests, extension to a 40 year time horizon enables distinctions between disposal options to continue to emerge for the restoration of neglected UK broadleaf forest with assumed non-wood counterfactuals (Figures A1.29 and A1.30). One significant change is that the profile of wood products is increased for restored broadleaf forests over this time period. In particular, sawlogs are now available and this increases the production scenarios from 69 back up to 215. However, over a 40 year time horizon, this has no effect on GHG emissions outcomes since it has been assumed that sawlogs will be used to provide hardwood window frames which have longer lives than this time period. With a 40 year time horizon and non-wood counterfactuals, there are still many scenarios which have lower relative GHG emissions than those for the reference line of not restoring production, either without the relevant application of CCS (Figure A1.29) or with CCS application (Figure A1.30). With a 40 year time horizon and assuming imported wood counterfactuals, there are no production scenarios with lower relative GHG emissions than those of the reference line, either without CCS application (Figure A1.31) or without CCS application (Figure A1.32).

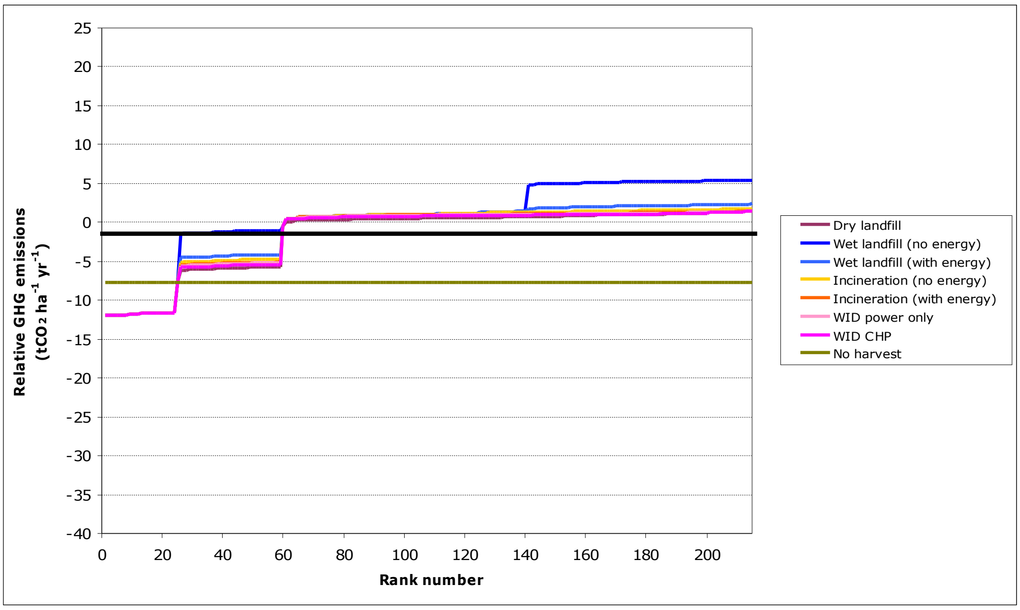


Figure A1.29. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 40 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

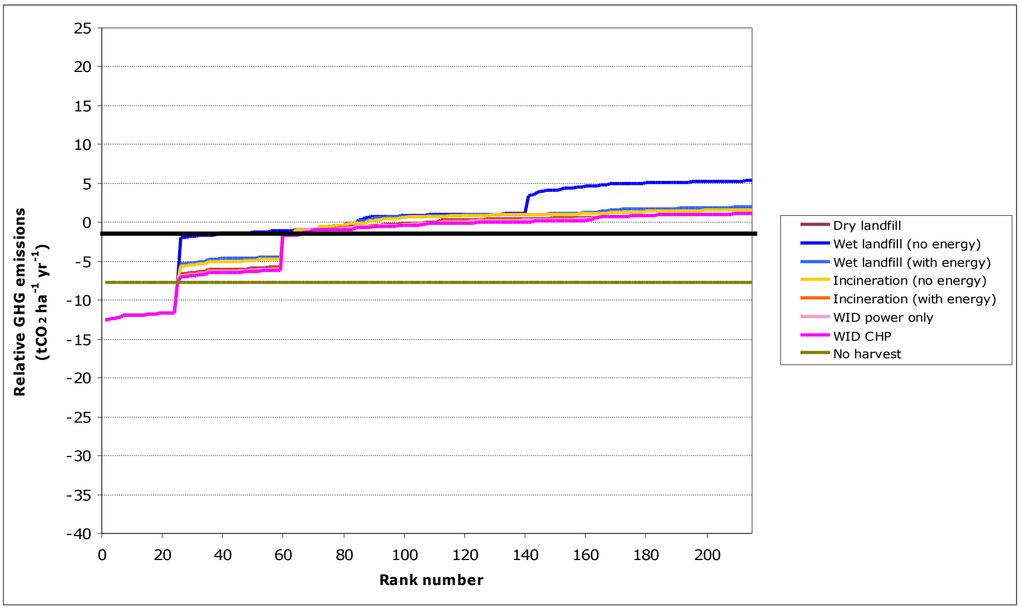


Figure A1.30. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 40 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

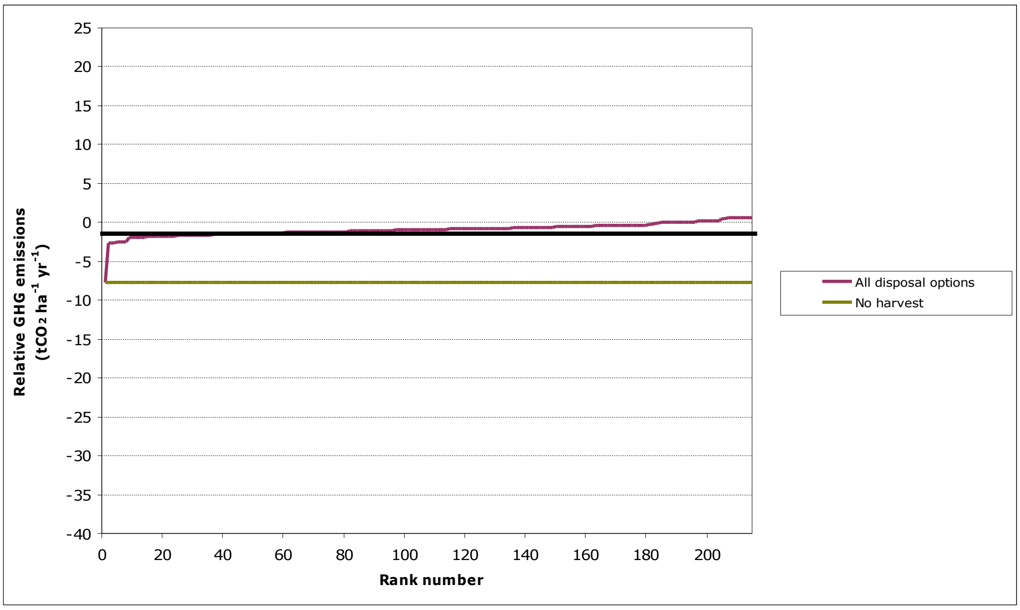


Figure A1.31. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 40 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

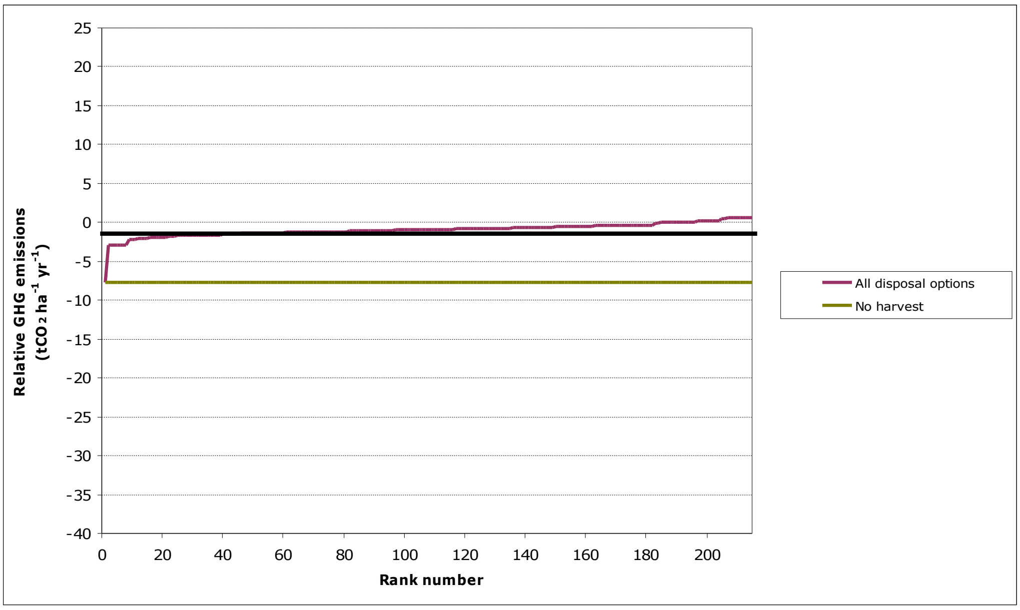


Figure A1.32. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 40 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

Extending the time horizon to 100 years again brings out distinctions between disposal options with non-wood counterfactuals for restored UK neglected broadleaf forests as with managed UK broadleaf forests (Figures A1.33 and A1.34). This means that disposal to wet landfill without energy recovery should be avoided and that the same GHG emissions hierarchy for wood product disposal applies. For certain end-of-life disposal options, there are still many scenarios over a 100 year time horizon and assuming non-wood counterfactuals which have lower relative GHG emissions than those of the reference line, either without the relevant application of CCS (Figure A1.33) or with relevant CCS application (Figure A1.34). As before, with a 100 year time horizon and assuming imported wood counterfactuals, there are still no production scenarios with lower relative GHG emissions than those of the reference line, either without CCS application (Figure A1.35) or with CCS application (Figure A1.36).

As for results for UK conifer and broadleaf forests in production, options for wood utilisation from restored production in neglected UK broadleaf forests, when scenarios are placed in ranked order (Figures A1.25 to A1.36), they do not form distinctly separate groups in terms of relative GHG emissions. Rather, successive results for relative GHG emissions, placed in ranked order, form a continuous progression. However the occasional steps in the sequence are more pronounced.

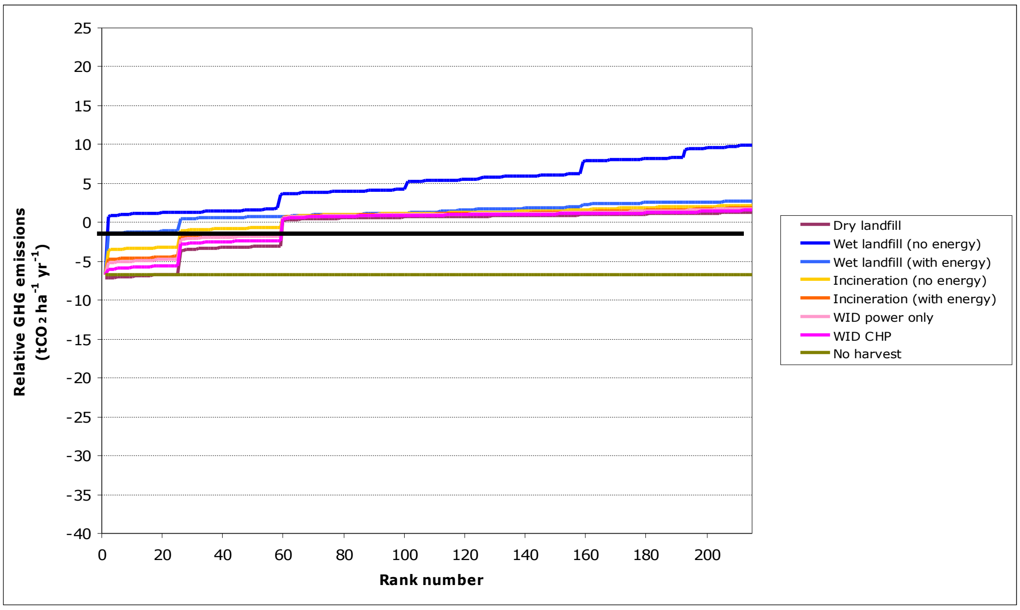


Figure A1.33. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 100 year time horizon, non-wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

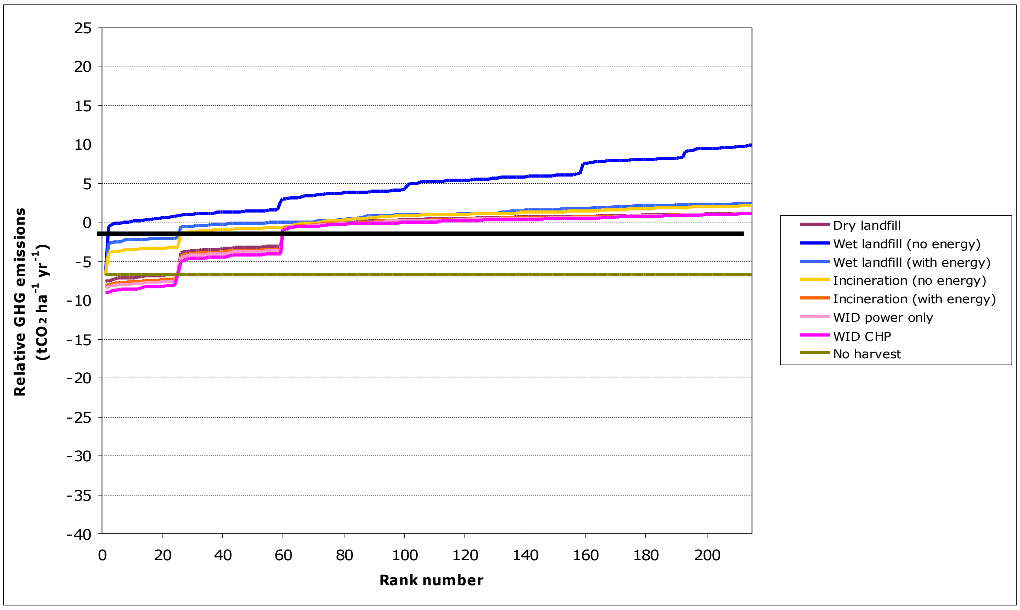


Figure A1.34. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 100 year time horizon, non-wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are shown separately but may overlap and obscure.

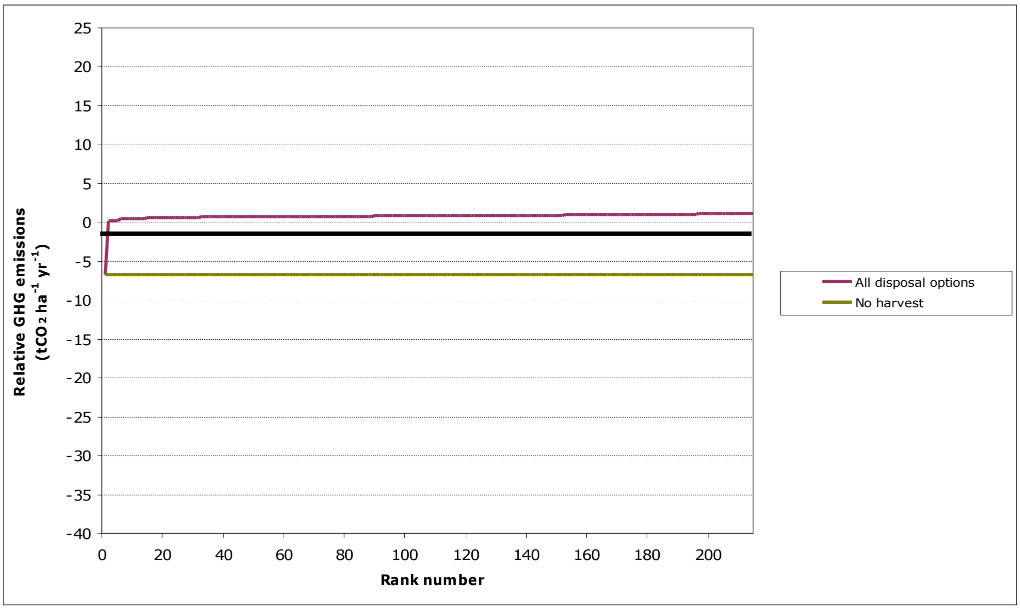


Figure A1.35. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 100 year time horizon, imported wood counterfactuals, CCS not applied. Results involving different options for disposal of wood at end-of-life are the same.

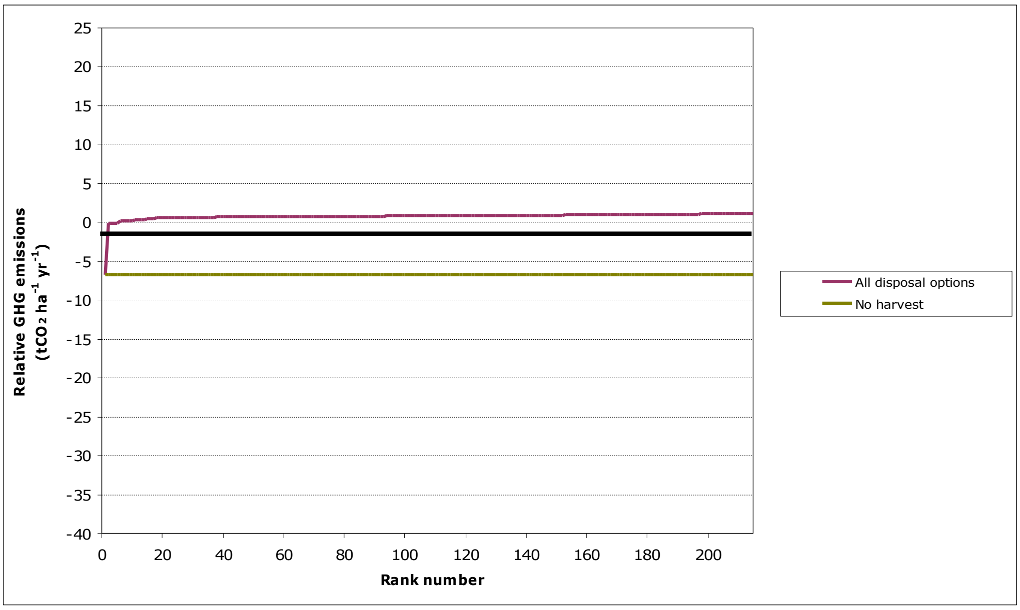


Figure A1.36. Relative greenhouse gas emissions plotted against rank number for scenarios involving restoration of UK broadleaf forests managed for production: 100 year time horizon, imported wood counterfactuals, CCS applied. Results involving different options for disposal of wood at end-of-life are the same.

A1.3 Summary analysis of ranked results

Key outcomes of the graphical analysis of ranked results considered in Section A1.1 can be summarised as a set of indicators, as presented in Tables A1.1 to A1.12. These tables consider each combination of forest type (managed conifer, managed broadleaf and 'neglected' broadleaf), and each counterfactual type (non-wood or imported wood) either with or without application of carbon capture and storage. Each table gives:

- The number of scenarios for which the relative GHG emissions are less than for the 'reference' level of suspended production (e.g. '268 results from 282')
- The lowest observed value for relative GHG emissions (in units of $kgCO_2$-equivalent ha^{-1} yr^{-1})
- Details of the scenario with the lowest observed value for relative GHG emissions (e.g. scenario code number and a short description in footnotes to each table).

Results are presented in Tables A1.1 to A1.12 for each time horizon considered in the project (i.e. 20, 40 and 100 years) and also separately for each possible end-of-life disposal option (where relevant).

Self-evidently, these results can be referred to in order to gain a rapid appreciation of the extent to which scenarios involving wood production and utilisation involve lower relative GHG emissions compared to leaving wood in the forest, the 'best' scenario involving wood production and utilisation (where one exists) and the magnitude of relative GHG emissions associated with this 'best' scenario. However, any consideration of the results in Tables A1.1 to A1.12 should bear in mind the explanatory remarks about the interpretation of carbon impacts made in Section 6 of this report, notably in Section 6.2. Sensitivities to time horizon considered and end-of-life disposal option can also be determined from the tables.

Table A1.1 Managed UK Conifer Forests; Non-Wood Counterfactuals; Without Carbon Capture and Storage

Outcome	Time Horizon	End-of-Life Disposal Option						
		Dry Landfill	Wet Landfill without Energy Recovery	Wet Landfill with Energy Recovery	Waste Incineration without Energy Recovery	Waste Incineration with Energy Recovery	WID Compliant Power Only Generation	WID Compliant Combined Heat and Power Generation
Number of Scenarios with Relative GHG Emissions Less than Suspended Production [a]	20	93 from 282	93 from 282	93 from 282	93 from 282	93 from 282	93 from 282	93 from 282
	40	117 from 282	93 from 282	117 from 282	117 from 282	117 from 282	117 from 282	117 from 282
	100	269 from 282	0 from 282	84 from 282	139 from 282	208 from 282	239 from 282	269 from 282
Lowest Relative GHG Emissions ($kgCO_2$-eq. ha^{-1} yr^{-1})	20	-30,713	-30,713	-30,713	-30,713	-30,713	-30,713	-30,713
	40	-30,713	-30,713	-30,713	-30,713	-30,713	-30,713	-30,713
	100	-30,913	-8,223	-12,961	-19,620	-23,463	-24,621	-27,223
Scenario with Lowest Relative GHG Emissions [b]	20	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	40	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	100	04.03	00.00	04.03	04.03	04.03	04.03	04.03

(a) Relative GHG emissions for suspended production: -16,694 $kgCO_2$-eq. ha^{-1} yr^{-1} (20 years); -13,928 $kgCO_2$-eq. ha^{-1} yr^{-1} (40 years); -8,223 $kgCO_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 04.03 = sawn timber from sawlogs, particleboard from sawlogs and roundwood, and CHP with wood chips from bark and branchwood.

Table A1.2 Managed UK Conifer Forests; Non-Wood Counterfactuals; With Carbon Capture and Storage

Outcome	Time Horizon	End-of-Life Disposal Option						
		Dry Landfill	Wet Landfill without Energy Recovery	Wet Landfill with Energy Recovery	Waste Incineration without Energy Recovery	Waste Incineration with Energy Recovery	WID Compliant Power Only Generation	WID Compliant Combined Heat and Power Generation
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	98 from 282	93 from 282	94 from 282	95 from 282	98 from 282	99 from 282	100 from 282
	40	125 from 282	102 from 282	125 from 282	125 from 282	127 from 282	127 from 282	127 from 282
	100	271 from 282	2 from 282	135 from 282	171 from 282	271 from 282	271 from 282	271 from 282
Lowest Relative GHG Emissions ($kgCO_2$-eq. ha^{-1} yr^{-1})	20	-31,377	-31,377	-31,377	-31,377	-31,377	-31,377	-31,377
	40	-31,377	-31,377	-31,377	-31,377	-31,377	-31,377	-31,377
	100	-31,577	-9,653	-16,414	-20,284	-33,230	-34,180	-36,165
Scenario with Lowest Relative GHG Emissions (b)	20	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	40	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	100	04.03	01.05	04.03	04.03	04.03	04.03	04.03

(a) Relative GHG Emissions for suspended production: -16,694 $kgCO_2$-eq. ha^{-1} yr^{-1} (20 years); -13,928 $kgCO_2$-eq. ha^{-1} yr^{-1} (40 years); -8,223 $kgCO_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 04.03 = sawn timber from sawlogs, particleboard from sawlogs and roundwood, and CHP with wood chips from bark and branchwood; Scenario 01.05 = CHP with wood chips from sawlogs, roundwood, bark and branchwood.

Table A1. 3 Managed UK Conifer Forests; Imported Wood Counterfactuals; Without Carbon Capture and Storage

Outcome	Time Horizon	All End-of-Life Disposal Options
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	2 from 282
	40	0 from 282
	100	0 from 282
Lowest Relative GHG Emissions ($kgCO_2$-eq. ha^{-1} yr^{-1})	20	-16,844
	40	-13,928
	100	-8,223
Scenario with Lowest Relative GHG Emissions (b)	20	21.05
	40	00.00
	100	00.00

(a) Relative GHG Emissions for suspended production: -16,694 $kgCO_2$-eq. ha^{-1} yr^{-1} (20 years); -13,928 $kgCO_2$-eq. ha^{-1} yr^{-1} (40 years); -8,223 $kgCO_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 21.05 = sawn timber from sawlogs, paper and card from roundwood, and CHP with wood chips from sawlogs, roundwood, bark and branchwood; Scenario 00.00 = suspended production.

Table A1.4 Managed UK Conifer Forests; Imported Wood Counterfactuals; With Carbon Capture and Storage

Outcome	Time Horizon	All End-of-Life Disposal Options
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	4 from 282
	40	0 from 282
	100	0 from 282
Lowest Relative GHG Emissions (kgCO$_2$-eq. ha^{-1} yr^{-1})	20	-17,957
	40	-13,928
	100	-8,223
Scenario with Lowest Relative GHG Emissions (b)	20	01.05
	40	00.00
	100	00.00

(a) Relative GHG Emissions for suspended production: -16,694 kgCO$_2$-eq. ha^{-1} yr^{-1} (20 years); -13,928 kgCO$_2$-eq. ha^{-1} yr^{-1} (40 years); -8,223 kgCO$_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 01.05 = CHP with wood chips from sawn timber, roundwood, bark and branchwood;

Scenario 21.05 = sawn timber from sawlogs, paper and card from roundwood, and CHP with wood chips from sawlogs, roundwood, bark and branchwood;

Scenario 00.00 = suspended production.

Table A1.5 Managed UK Broadleaf Forests; Non-Wood Counterfactuals; Without Carbon Capture and Storage

Outcome	Time Horizon	End-of-Life Disposal Option						
		Dry Landfill	Wet Landfill without Energy Recovery	Wet Landfill with Energy Recovery	Waste Incineration without Energy Recovery	Waste Incineration with Energy Recovery	WID Compliant Power Only Generation	WID Compliant Combined Heat and Power Generation
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	74 from 215	47 from 215	55 from 215	71 from 215	72 from 215	72 from 215	72 from 215
	40	35 from 215	34 from 215	33 from 215	34 from 215	34 from 215	34 from 215	34 from 215
	100	71 from 215	0 from 215	0 from 215	10 from 215	34 from 215	34 from 215	34 from 215
Lowest Relative GHG Emissions (kgCO$_2$-eq. ha^{-1} yr^{-1})	20	-15,102	-15,102	-15,102	-15,102	-15,102	-15,102	-15,102
	40	-15,102	-15,102	-15,102	-15,102	-15,102	-15,102	-15,102
	100	-15,131	-6,771	-6,771	-8,717	-10,900	-11,553	-13,035
Scenario with Lowest Relative GHG Emissions (b)	20	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	40	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	100	04.03	00.00	00.00	04.03	04.03	04.03	04.03

(a) Relative GHG Emissions for suspended production: -6,541 kgCO$_2$-eq. ha^{-1} yr^{-1} (20 years); -7,717 kgCO$_2$-eq. ha^{-1} yr^{-1} (40 years); -6,771 kgCO$_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 04.03 = sawn timber from sawlogs, particleboard from sawlogs and roundwood, and CHP with wood chips from bark and branchwood; Scenario 00.00 = suspended production.

Table A1.6 Managed UK Broadleaf Forests; Non-Wood Counterfactuals; With Carbon Capture and Storage

Outcome	Time Horizon	End-of-Life Disposal Option						
		Dry Landfill	Wet Landfill without Energy Recovery	Wet Landfill with Energy Recovery	Waste Incineration without Energy Recovery	Waste Incineration with Energy Recovery	WID Compliant Power Only Generation	WID Compliant Combined Heat and Power Generation
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	72 from 215	48 from 215	65 from 215	75 from 215	85 from 215	87 from 215	87 from 215
	40	47 from 215	39 from 215	40 from 215	41 from 215	48 from 215	51 from 215	55 from 215
	100	78 from 215	0 from 215	2 from 215	12 from 215	87 from 215	96 from 215	96 from 215
Lowest Relative GHG Emissions ($kgCO_2$-eq. ha^{-1} yr^{-1})	20	-15,617	-15,617	-15,617	-15,617	-15,617	-15,617	-15,617
	40	-15,617	-15,617	-15,617	-15,617	-15,617	-15,617	-15,617
	100	-15,646	-6,771	-7,034	-9,232	-16,585	-17,120	-18,251
Scenario with Lowest Relative GHG Emissions (b)	20	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	40	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	100	04.03	00.00	04.03	04.03	04.03	04.03	04.03

(a) Relative GHG Emissions for suspended production: -6,541 $kgCO_2$-eq. ha^{-1} yr^{-1} (20 years); -7,717 $kgCO_2$-eq. ha^{-1} yr^{-1} (40 years); -6,771 $kgCO_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 04.03 = sawn timber from sawlogs, particleboard from sawlogs and roundwood, and CHP with wood chips from bark and branchwood; Scenario 00.00 = suspended production.

Table A1.7 Managed UK Broadleaf Forests; Imported Wood Counterfactuals; Without Carbon Capture and Storage

Outcome	Time Horizon	All End-of-Life Disposal Options
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	16 from 215
	40	0 from 215
	100	0 from 215
Lowest Relative GHG Emissions (kgCO$_2$-eq. ha^{-1} yr^{-1})	20	-8,561
	40	-7,717
	100	-6,771
Scenario with Lowest Relative GHG Emissions (b)	20	01.05
	40	00.00
	100	00.00

(a) Relative GHG Emissions for suspended production: -6,541 kgCO$_2$-eq. ha^{-1} yr^{-1} (20 years); -7,717 kgCO$_2$-eq. ha^{-1} yr^{-1} (40 years); -6,771 kgCO$_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 01.05 =CHP with wood chips from sawlogs, roundwood, bark and branchwood;

Scenario 00.00 = suspended production.

Table A1.8 Managed UK Broadleaf Forests; Imported Wood Counterfactuals; With Carbon Capture and Storage

Outcome	Time Horizon	All End-of-Life Disposal Options
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	19 from 215
	40	0 from 215
	100	0 from 215
Lowest Relative GHG Emissions (kgCO_2-eq. ha^{-1} yr^{-1})	20	-9,183
	40	-7,717
	100	-6,771
Scenario with Lowest Relative GHG Emissions (b)	20	01.05
	40	00.00
	100	00.00

(a) Relative GHG Emissions for suspended production: -6,541 kgCO_2-eq. ha^{-1} yr^{-1} (20 years); -7,717 kgCO_2-eq. ha^{-1} yr^{-1} (40 years); -6,771 kgCO_2-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 01.05 =CHP with wood chips from sawlogs, roundwood, bark and branchwood;

Scenario 00.00 = suspended production.

Table A1.9 Restored UK Neglected Broadleaf Forests; Non-Wood Counterfactuals; Without Carbon Capture and Storage

Outcome	Time Horizon	End-of-Life Disposal Option						
		Dry Landfill	Wet Landfill without Energy Recovery	Wet Landfill with Energy Recovery	Waste Incineration without Energy Recovery	Waste Incineration with Energy Recovery	WID Compliant Power Only Generation	WID Compliant Combined Heat and Power Generation
Number of Scenarios with Relative GHG Emissions Less than Suspended Production [(a)]	20	20 from 69	20 from 69	14 from 69	20 from 69	20 from 69	20 from 69	20 from 69
	40	25 from 215	24 from 215	24 from 215	24 from 215	24 from 215	24 from 215	24 from 215
	100	37 from 215	0 from 215	0 from 215	0 from 215	0 from 215	0 from 215	0 from 215
Lowest Relative GHG Emissions (kgCO$_2$-eq. ha^{-1} yr^{-1})	20	-17,207	-17,207	-17,207	-17,207	-17,207	-17,207	-17,207
	40	-11,996	-11,996	-11,996	-11,996	-11,996	-11,996	-11,996
	100	-7,210	-6,771	-6,771	-6,771	-6,771	-6,771	-6,771
Scenario with Lowest Relative GHG Emissions [(b)]	20	03.05/04.03	03.05/04.03	03.05/04.03	03.05/04.03	03.05/04.03	03.05/04.03	03.05/04.03
	40	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	100	04.03	00.00	00.00	00.00	00.00	00.00	00.00

(a) Relative GHG Emissions for no restoration of production: -6,541 kgCO$_2$-eq. ha^{-1} yr^{-1} (20 years); -7,717 kgCO$_2$-eq. ha^{-1} yr^{-1} (40 years); -6,771 kgCO$_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 03.05/04.03 = particleboard from roundwood, and CHP with wood chips from bark and branchwood;

Scenario 04.03 = sawn timber from sawlogs, particleboard from sawlogs and roundwood, and CHP with wood chips from bark and branchwood;

Scenario 00.00 = no restoration of production.

Table A1.10 Restored UK Neglected Broadleaf Forests; Non-Wood Counterfactuals; With Carbon Capture and Storage

Outcome	Time Horizon	End-of-Life Disposal Option						
		Dry Landfill	Wet Landfill without Energy Recovery	Wet Landfill with Energy Recovery	Waste Incineration without Energy Recovery	Waste Incineration with Energy Recovery	WID Compliant Power Only Generation	WID Compliant Combined Heat and Power Generation
Number of Scenarios with Relative GHG Emissions Less than Suspended Production [(a)]	20	20 from 69	10 from 69	20 from 69	20 from 69	20 from 69	20 from 69	20 from 69
	40	24 from 215	24 from 215	24 from 215	24 from 215	24 from 215	24 from 215	24 from 215
	100	20 from 215	0 from 215	0 from 215	0 from 215	24 from 215	24 from 215	24 from 215
Lowest Relative GHG Emissions ($kgCO_2$-eq. ha^{-1} yr^{-1})	20	-17,938	-17,938	-17,938	-17,938	-17,938	-17,938	-17,938
	40	-12,519	-12,519	-12,519	-12,519	-12,519	-12,519	-12,519
	100	-7,545	-6,771	-6,771	-6,771	-8,078	-8,379	-9,024
Scenario with Lowest Relative GHG Emissions [(b)]	20	03.05/04.03	03.05/04.03	03.05/04.03	03.05/04.03	03.05/04.03	03.05/04.03	03.05/04.03
	40	04.03	04.03	04.03	04.03	04.03	04.03	04.03
	100	04.03	00.00	00.00	00.00	04.03	04.03	04.03

(a) Relative GHG Emissions for no restoration of production: -6,541 $kgCO_2$-eq. ha^{-1} yr^{-1} (20 years); -7,717 $kgCO_2$-eq. ha^{-1} yr^{-1} (40 years); -6,771 $kgCO_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 03.05/04.03 = particleboard from roundwood, and CHP with wood chips from bark and branchwood;
Scenario 04.03 = sawn timber from sawlogs, particleboard from sawlogs and roundwood, and CHP with wood chips from bark and branchwood;
Scenario 00.00 = no restoration of production.

Table A1.11 Restored UK Neglected Broadleaf Forests; Imported Wood Counterfactuals; Without Carbon Capture and Storage

Outcome	Time Horizon	All End-of-Life Disposal Options
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	2 from 69
	40	0 from 215
	100	0 from 215
Lowest Relative GHG Emissions ($kgCO_2$-eq. ha^{-1} yr^{-1})	20	-6,291
	40	-7,717
	100	-6,771
Scenario with Lowest Relative GHG Emissions (b)	20	01.05/02.05/05.05/08.05
	40	00.00
	100	00.00

(a) Relative GHG Emissions for no restoration of production: -6,541 $kgCO_2$-eq. ha^{-1} yr^{-1} (20 years); -7,717 $kgCO_2$-eq. ha^{-1} yr^{-1} (40 years); -6,771 $kgCO_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 01.05/02.05/05.05/08.05 = CHP with wood chips from roundwood, bark and branchwood;

Scenario 00.00 = no restoration of production.

Table A1.12 Restored UK Neglected Broadleaf Forests; Imported Wood Counterfactuals; With Carbon Capture and Storage

Outcome	Time Horizon	All End-of-Life Disposal Options
Number of Scenarios with Relative GHG Emissions Less than Suspended Production (a)	20	2 from 69
	40	0 from 215
	100	0 from 215
Lowest Relative GHG Emissions (kgCO$_2$-eq. ha^{-1} yr^{-1})	20	-7,596
	40	-7,717
	100	-6,771
Scenario with Lowest Relative GHG Emissions (b)	20	01.05/02.05/05.05/08.05
	40	00.00
	100	00.00

(a) Relative GHG Emissions for no restoration of production: -6,541 kgCO$_2$-eq. ha^{-1} yr^{-1} (20 years); -7,717 kgCO$_2$-eq. ha^{-1} yr^{-1} (40 years); -6,771 kgCO$_2$-eq. ha^{-1} yr^{-1} (100 years).

(b) Scenario 01.05/02.05/05.05/08.05 = CHP with wood chips from roundwood, bark and branchwood;

Scenario 00.00 = no restoration of production.

Annex 2 General conclusions

The main results are reported as annualised relative GHG emissions (kgCO_2-equivalent ha^{-1} yr^{-1}), taking into account full life cycle emissions and also accounting for forest carbon stock changes and temporary sequestration in wood products using consequential LCA, for specified scenarios for the management of conifer (282 production scenarios), the management of broadleaf forests (215 production scenarios) and the restoration of neglected broadleaf forests (between 69 and 215 production scenarios) in the UK over time horizons of 20, 40 and 100 years.

A number of general observations can be made about these results:

- The results are spread over a very wide range of values stretching from negative values (indicating a net removal of GHGs from the atmosphere) with a magnitude of 10^4 kgCO_2-equivalent ha^{-1} yr^{-1} to positive values (indicating a net addition of GHGs from the atmosphere) with a magnitude of 10^4 kgCO_2-equivalent ha^{-1} yr^{-1}, depending on assumptions about time horizons, counterfactuals, end-of-life disposal options and the application of carbon capture and storage (CCS).
- These results can be ranked in order of increasing relative GHG emissions in order to draw specific conclusions about their relative benefits or disbenefits.
- Although the full ranges of ranked results are substantial, differences between specific results can be quite small, suggesting that absolute distinctions cannot be made between neighbouring scenarios in the rankings since possible changes in fundamental values of parameters (transport distances, energy efficiencies, etc.) can cause overlapping and re-ranking of similar results.
- Despite the likely effects of such sensitivities, clear trends can be established on which to base firm conclusions about the preferential uses of conifer and broadleaf forests in the UK in the context of global climate change mitigation and the selected counterfactuals for wood products and bioenergy.
- Trends can be articulated by comparing any scenario individually with others (see Section 6).
- A systematic approach to interpreting the results has to recognise the importance of the time horizons adopted in national policy analysis; short-term (20 year time horizon), medium term (40 year time horizon) and long-term (100 year time horizon) in relation to forest carbon stock changes, the lifetime of wood products, their end-of-life disposal options and chosen counterfactuals.

For managed UK conifer forests (in their second rotation) in the short-term (20 year time horizon) with *non-wood counterfactuals*:

- There are very many scenarios which have lower relative GHG emissions than the option of suspending production in managed conifer forests, regardless of the end-of-life options assumed for the disposal of wood products.
- The irrelevance of disposal options is obviously due to the fact that the lifetimes of many of the wood products exceed the chosen time horizon of 20 years.
- The numerous scenarios below the reference line (-16,694 kgCO_2-equivalent ha^{-1} yr^{-1}) of suspended production in managed conifer forests consist of a diverse utilisation of forest products in which sawlogs and roundwood are used in wood products, and bark and branchwood are used for bioenergy generation.
- The lowest relative GHG emissions are achieved, regardless of end-of-life disposal options, for the scenario (Scenario 04.03) in which sawlogs are used 60% for sawn timber (wooden flooring displacing concrete screed) and 40% used for particleboard with 100% roundwood (wooden external walling displacing blockwork), and bark and branchwood are used for wood chips in commercial and industrial CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- Other scenarios give higher, yet similar relative GHG emissions based on the combination of wood product uses for sawlogs and roundwood, and various bioenergy options, including power only generation, for bark and branchwood.
- The use of sawlogs, roundwood, bark and branchwood exclusively for bioenergy feature prominently amongst those scenarios which have higher relative GHG emissions than those for the reference line of suspending production in the forest (-16,694 kgCO_2-equivalent ha^{-1} yr^{-1}).

For managed UK conifer forests (in their second rotation) in the short-term (20 year time horizon) with *imported wood counterfactuals*:

- There are few scenarios (2 from 282), not involving the application of CCS, which have lower relative GHG emissions than the option of suspending production in managed conifer forests, for any end-of-life disposal options (since the effects of this cancel out due to fact that wood products are being disposed in all instances).
- The scenarios below the reference line (-16,694 kgCO_2-equivalent ha^{-1} yr^{-1}) of suspended production in managed conifer forests consist of a diverse utilisation of forest products in which sawlogs and roundwood are used in wood products, bark used either for bioenergy generation or as a horticultural mulch, and branchwood used for bioenergy generation.
- The lowest relative GHG emissions (-16,844 kgCO_2-equivalent ha^{-1} yr^{-1}) are achieved, regardless of end-of-life disposal options, for the scenario (Scenario 21.05) in which sawlogs are used 60% for sawn timber, 100% of roundwood is used for paper and card, and 40% of sawn timber, 100% of bark and 50% of branchwood are used as wood chips in commercial and industrial CHP generation.
- With the application of CCS, slightly more scenarios (4 from 282) have lower relative GHG emissions than those for the baseline of suspending production in

the forest (-16,694 $kgCO_2$-equivalent ha^{-1} yr^{-1}), regardless of the end-of-life disposal option.

- With the application of CCS, the lowest relative GHG emissions (-17,957 $kgCO_2$-equivalent ha^{-1} yr^{-1}) are achieved by the scenario (Scenario 01.05) in which 100% of sawlogs, 100% of roundwood, 100% of bark and 50% of branchwood are used directly as wood chip in CHP generation, regardless of the end-of-life disposal option.

For managed UK conifer forests (in their second rotation) in the medium-term (40 year time horizon) with *non-wood counterfactuals*:

- There are again many scenarios which have lower relative GHG emissions than the option of suspending production in managed conifer forests, regardless of the end-of-life options assumed for the disposal of wood products.
- The irrelevance of disposal options is obviously due to the fact that the lifetimes of many of the wood products also exceed the chosen time horizon of 40 years.
- The numerous scenarios below the reference line (-13,928 $kgCO_2$-equivalent ha^{-1} yr^{-1}) of suspended production in managed conifer forests consist of a diverse utilisation of forest products in which sawlogs and roundwood are used in wood products, and bark and branchwood are used for bioenergy generation.
- The lowest relative GHG emissions are achieved, regardless of end-of-life disposal options, for the scenario (Scenario 04.03) in which sawlogs are used 60% for sawn timber (wooden flooring displacing concrete screed) and 40% used for particleboard with 100% roundwood (wooden external walling displacing blockwork), and bark and branchwood are used for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- Other scenarios again give higher, yet similar relative GHG emissions based on the combination of wood product uses for sawlogs and roundwood, and various bioenergy options, including power only generation, for bark and branchwood.
- The use of sawlogs, roundwood, bark and branchwood exclusively for bioenergy again feature prominently amongst those scenarios which have higher relative GHG emissions than those for the reference line of suspending production in managed conifer forests (-13,928 $kgCO_2$-equivalent ha^{-1} yr^{-1}).

For managed UK conifer forests (in their second rotation) in the medium-term (40 year time horizon) with *imported wood counterfactuals*:

- There are no scenarios, not involving the application of CCS, which achieve lower relative GHG emissions than the option of suspending production in managed conifer forests, for any end-of-life disposal options (since the effects of this cancel out due to fact that wood products are being disposed in all instances).
- With the application of CCS, there are also no scenarios that have lower relative GHG emissions than those for the reference line of suspending production in the

forest (-13,928 kgCO$_2$-equivalent ha^{-1} yr^{-1}), regardless of the end-of-life disposal option.

For managed UK conifer forests (in their second rotation) in the long-term (100 year time horizon) with *non-wood counterfactuals*:

- For all end-of-life disposal options for wood products, apart from disposal to wet landfill without energy recovery, there are many scenarios which achieve lower relative GHG emissions than the reference line of suspending production in managed conifer forests.
- However, the full impact of end-of-life disposal options does affect all the results as the time horizon of 100 years encompasses the assumed lifetimes of all wood products.
- In particular, ultimate disposal of wood products to wet landfill without energy recovery is to be avoided as no scenarios have lower relative GHG emissions than suspending production in managed conifer forests (-8,223 kgCO$_2$-equivalent ha^{-1} yr^{-1}).
- For all other end-of-life disposal options for wood products, the lowest relative GHG emissions are achieved for the scenario (Scenario 04.03) in which sawlogs are used 60% for sawn timber (wooden flooring displacing concrete screed) and 40% used for particleboard with 100% roundwood (wooden external walling displacing blockwork), and bark and branchwood are used for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- The clear majority of scenarios below the reference line (-8,223 kgCO$_2$-equivalent ha^{-1} yr^{-1}) consist of a diverse utilisation of forest products in which sawlogs and roundwood are used in wood products, and bark and branchwood are used for bioenergy generation.
- The use of sawlogs, roundwood, bark and branchwood exclusively for bioenergy feature prominently amongst those scenarios which have higher relative GHG emissions than those for the reference line of suspending production in managed conifer forests (-8,223 kgCO$_2$-equivalent ha^{-1} yr^{-1}).

For managed UK conifer forests (in their second rotation) in the long-term (100 year time horizon) with *imported wood counterfactuals*:

- There are no scenarios (0 from 282), either involving or not involving the application of CCS, which achieve lower relative GHG emissions than the reference line of suspending production in managed conifer forests, for any end-of-life disposal options (since the effects of this cancel out due to fact that wood products are being disposed in all instances).

For managed UK broadleaf forests (in their third rotation) in the short-term (20 year time horizon) with *non-wood counterfactuals*:

- There are many scenarios which achieve lower relative GHG emissions than the reference line of suspending production in managed broadleaf forests, regardless of the end-of-life options assumed for the disposal of wood products.
- Again, the irrelevance of disposal options is obviously due to the fact that the lifetimes of many of the wood products exceed the chosen time horizon of 20 years.
- The clear majority of scenarios below the reference line (-6,541 kgCO_2-equivalent ha^{-1} yr^{-1}) of suspended production in managed broadleaf forests consist of a diverse utilisation of forest products in which sawlogs and roundwood are used in wood products, and bark and branchwood are used for bioenergy generation.
- The lowest relative GHG emissions are achieved, regardless of end-of-life disposal options, for the scenario (Scenario 04.03) in which sawlogs are used 50% for sawn timber (wooden window frames displacing uPVC window frames) and 50% used for particleboard with 100% roundwood (wooden external walling displacing blockwork), and bark and branchwood are used for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- Other scenarios give higher, yet similar relative GHG gas emissions based on the combination of wood product uses for sawlogs and roundwood, and various bioenergy options, including power only generation, for bark and branchwood.
- The use of sawlogs, roundwood, bark and branchwood exclusively for bioenergy feature prominently amongst those scenarios which have higher relative GHG emissions than those for the reference line of suspending production in the forest (-6,541 kgCO_2-equivalent ha^{-1} yr^{-1}).

For managed UK broadleaf forests (in their third rotation) in the short-term (20 year time horizon) with *imported wood counterfactuals*:

- There are several scenarios (16 from 215), not involving the application of CCS, which achieve lower relative GHG emissions than the reference line of suspending production in managed broadleaf forests, for any end-of-life disposal options (since the effects of this cancel out due to fact that wood products are being disposed in all instances).
- Those below the reference line (-6,541 kgCO_2-equivalent ha^{-1} yr^{-1}) of suspended production in managed broadleaf forests consist of a diverse utilisation of forest products in which sawlogs and roundwood are used in wood products, and bark and branchwood are used for bioenergy generation.
- The lowest relative GHG emissions (-8,561 kgCO_2-equivalent ha^{-1} yr^{-1}) are achieved, regardless of end-of-life disposal options, for the scenario (Scenario 01.05) in which sawlogs, roundwood, bark and branchwood are used exclusively for CHP generation.
- With the application of CCS, very slightly more scenarios (19 from 215) have lower relative GHG emissions than those for the reference line of suspending

production in the forest (-6,541 kgCO_2-equivalent ha^{-1} yr^{-1}), regardless of the end-of-life disposal option.
- With the application of CCS, the lowest relative GHG emissions (-9,183 kgCO_2-equivalent ha^{-1} yr^{-1}) are achieved by the scenario (Scenario 01.05) in which sawlogs, roundwood, bark and branchwood are used exclusively for CHP generation.

For managed UK broadleaf forests (in their third rotation) over the medium-term (40 year time horizon) with *non-wood counterfactuals*:
- There are many scenarios which achieve lower relative GHG emissions than the option of suspending production in managed broadleaf forests, regardless of the end-of-life options assumed for the disposal of wood products.
- Again, the irrelevance of disposal options is obviously due to the fact that the lifetimes of many of the wood products exceed the chosen time horizon of 40 years.
- The clear majority of scenarios below the reference line (-7,717 kgCO_2-equivalent ha^{-1} yr^{-1}) of suspended production in managed broadleaf forests consist of a diverse utilisation of forest products in which sawlogs and roundwood are used in wood products, and bark and branchwood are used for bioenergy generation.
- The lowest relative GHG emissions are achieved, regardless of end-of-life disposal options, for the scenario (Scenario 04.03) in which sawlogs are used 50% for sawn timber (wooden window frames displacing uPVC window frames) and 50% used for particleboard with 100% roundwood (wooden external walling displacing blockwork), and bark and branchwood are used for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- Other scenarios give higher, yet similar relative GHG emissions based on the combination of wood product uses for sawlogs and roundwood, and various bioenergy options, including power only generation, for bark and branchwood.
- The use of sawlogs, roundwood, bark and branchwood exclusively for bioenergy generation feature prominently amongst those scenarios which have higher relative GHG emissions than those for the baseline of suspending production in the forest (-7,717 kgCO_2-equivalent ha^{-1} yr^{-1}).

For managed UK broadleaf forests (in their third rotation) in the medium-term (40 year time horizon) with *imported wood counterfactuals*:
- There are no scenarios which achieve lower relative GHG emissions than the reference line of suspending production in managed broadleaf forests (-7,717 kgCO_2-equivalent ha^{-1} yr^{-1}), regardless of the end-of-life disposal option either with or without the application of CCS.

For managed UK broadleaf forests (in their third rotation) over the long-term (100 year time horizon) with *non-wood counterfactuals*:

- For all end-of-life disposal options for wood products, apart from disposal to wet landfill without energy recovery, there are many scenarios which achieve lower relative GHG emissions than the reference line of suspending production in managed conifer forests.
- However, the full impact of end-of-life disposal options does affect all the results as the time horizon of 100 years encompasses the assumed lifetimes of all wood products.
- In particular, ultimate disposal of wood products to wet landfill without energy recovery is to be avoided as there are no scenarios with lower relative GHG emissions than the reference line of suspending production in managed broadleaf forests (-6,771 $kgCO_2$-equivalent ha^{-1} yr^{-1}).
- For all other end-of-life disposal options for wood products, the lowest relative GHG emissions are achieved for the scenario (Scenario 04.03) in which sawlogs are used 50% for sawn timber (wooden window frames displacing uPVC window frames) and 50% used for particleboard with 100% roundwood (wooden external walling displacing blockwork), and bark and branchwood are used for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- The clear majority of scenarios below the reference line consist of a diverse utilisation of forest products in which sawlogs and roundwood are used in wood products, and bark and branchwood are used for bioenergy generation.
- The use of sawlogs, roundwood, bark and branchwood exclusively for bioenergy generation again feature prominently amongst those scenarios which have higher relative GHG emissions than those for the reference line of suspending production in managed broadleaf forests (-6,771 $kgCO_2$-equivalent ha^{-1} yr^{-1}).

For managed UK broadleaf forests (in their third rotation) in the long-term (100 year time horizon) with *imported wood counterfactuals*:

- Either without or with the application of CCS, there are no scenarios which achieve lower relative GHG emissions than the reference line of suspending production in managed broadleaf forests (-6,771 $kgCO_2$-equivalent ha^{-1} yr^{-1}), regardless of the end-of-life disposal option.

For the restoration of production in neglected UK broadleaf forests over the short-term (20 year time horizon) with *non-wood counterfactuals*:

- There are several scenarios which have lower relative GHG emissions than the reference line (-6,541 $kgCO_2$-equivalent ha^{-1} yr^{-1}) of not restoring neglected broadleaf forests to production, regardless of the end-of-life option for assumed wood product disposal.
- The irrelevance of disposal options is obviously due to the fact that the lifetimes of many of the wood products exceed the chosen time horizon of 20 years.
- In all cases, the scenario (Scenario 03.05/04.03; these are equivalent as no sawlogs are produced over a 20 year time horizon) with the lowest relative GHG

emissions consists of using roundwood for particleboard (wooden external walling displacing blockwork), and bark and branchwood for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).

- Other scenarios with similar, yet higher relative GHG emissions involve combinations of using roundwood for particleboard and fencing, bark for horticultural mulch and bioenergy applications, and branchwood for bioenergy generation.
- With CCS application, there are also several scenarios which have lower relative GHG emissions than the reference line (-6,541 kgCO_2-equivalent ha^{-1} yr^{-1}) of not restoring neglected broadleaf forests to production, regardless of the end-of-life option for assumed wood product disposal.

For the restoration of production in neglected UK broadleaf forests over the short-term (20 year time horizon) with *imported wood counterfactuals*:

- There are a few scenarios (2 from 69), not involving the application of CCS, which achieve lower relative GHG emissions than the reference line of not restoring production in neglected broadleaf forests (-6,541 kgCO_2-equivalent ha^{-1} yr^{-1}), for any end-of-life disposal options (since the effects of this cancel out due to fact that wood products are being disposed in all instances).
- The lowest relative GHG emissions (-6,291 kgCO_2-equivalent ha^{-1} yr^{-1}) for a scenario (Scenario 01.05/02.05/05.05/08.05; these are equivalent as no sawlogs are produced over a 20 year time horizon) which involves all roundwood, bark and branchwood used as wood chips for CHP generation.
- With the application of CCS, there are is the same number of scenarios (2 from 69) which achieve lower relative GHG emissions than the reference line of not restoring production in neglected broadleaf forests (-6,541 kgCO_2-equivalent ha^{-1} yr^{-1}), for any end-of-life disposal options (since the effects of this cancel out due to fact that wood products are being disposed in all instances).
- With CCS, the lowest relative GHG emissions (-7,596 kgCO_2-equivalent ha^{-1} yr^{-1}) for a scenario (Scenarios 01.05/02.05/05.05/08.05; these are equivalent as no sawlogs are produced over a 20 year time horizon) which involves all sawlogs, roundwood, bark and branchwood used as wood chips for CHP generation.

For the restoration of production in neglected UK broadleaf forests over the medium-term (40 year time horizon) with *non-wood counterfactuals*:

- There are a few scenarios which have lower relative GHG emissions than the reference line (-7,717 kgCO_2-equivalent ha^{-1} yr^{-1}) of not restoring neglected broadleaf forests to production, regardless of the end-of-life option for assumed wood product disposal.
- The irrelevance of disposal options is obviously due to the fact that the lifetimes of many of the wood products exceed the chosen time horizon of 40 years.

- In all cases, the scenario (Scenario 04.03) with the lowest relative GHG emissions consists of using 50% of sawlogs for sawn timber (wooden window frames displacing uPVC window frames), 50% sawlogs and all roundwood for particleboard (wooden external walling displacing blockwork), and all bark and branchwood for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- Other scenarios with similar, yet higher relative GHG emissions involve combinations of using sawlogs for sawn timber and particleboard, roundwood for particleboard and bioenergy applications, bark for horticultural mulch and bioenergy generation, and branchwood for bioenergy generation.
- With CCS applications, there are also a few scenarios which have lower relative GHG emissions than the reference line (-7,717 kgCO_2-equivalent ha^{-1} yr^{-1}) of not restoring neglected broadleaf forests to production, regardless of the end-of-life option for assumed wood product disposal.
- With CCS, the scenario (Scenario 04.03) with the lowest relative GHG emissions consist of using 50% of sawlogs for sawn timber (wooden window frames displacing uPVC window frames), 50% sawlogs and all roundwood for particleboard (wooden external walling displacing blockwork), and all bark and branchwood for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).

For the restoration of production in neglected UK broadleaf forests over the medium-term (40 year time horizon) with *imported wood counterfactuals*:

- There are no scenarios which achieve lower relative GHG emissions than the reference line of suspending production in managed broadleaf forests (-7,717 kgCO_2-equivalent ha^{-1} yr^{-1}), regardless of the end-of-life disposal option or the application of CCS.

For the restoration of production in neglected UK broadleaf forests over the long-term (100 year time horizon) with *non-wood counterfactuals*:

- For all end-of-life disposal options apart from dry landfill, there are no scenarios which have lower relative GHG emissions than the reference line (-6,771 kgCO_2-equivalent ha^{-1} yr^{-1}) of not restoring neglected broadleaf forests to production.
- For the end-of-life disposal option of dry landfill, the scenario (Scenario 04.03) with the lowest relative GHG emissions consists of using 50% of sawlogs for sawn timber (wooden window frames displacing uPVC window frames), 50% sawlogs and all roundwood for particleboard (wooden external walling displacing blockwork), and all bark and branchwood for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- With CCS application and for most end-of-life disposal options, there are a few scenarios (typically 20 from 215) which have lower relative GHG emissions than

the reference line (-6,771 $kgCO_2$-equivalent ha^{-1} yr^{-1}) of not restoring neglected broadleaf forests to production.
- With CCS application and all end-of-life disposal options apart from wet landfill without energy recovery, the scenario (Scenario 04.03) with the lowest relative GHG emissions consist of using 50% of sawlogs for sawn timber (wooden window frames displacing uPVC window frames), 50% sawlogs and all roundwood for particleboard (wooden external walling displacing blockwork), and all bark and branchwood for wood chips in CHP generation (displacing natural gas heating and UK grid electricity in 2004).
- With CCS and end-of-life disposal to wet landfill with or without energy recovery and disposal to waste incineration without energy recovery, there are no scenarios which achieve lower relative GHG emissions than the reference line of suspending production in managed broadleaf forests (-6,771 $kgCO_2$-equivalent ha^{-1} yr^{-1}).

For the restoration of production in neglected UK broadleaf forests over the long-term (100 year time horizon) with *imported wood counterfactuals*:
- There are no scenarios which achieve lower relative GHG emissions than the reference line of suspending production in managed broadleaf forests (-6,771 $kgCO_2$-equivalent ha^{-1} yr^{-1}), regardless of the end-of-life disposal option or the application of CCS.