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Annex-4: Climate Change Mitigation

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Abbreviations Used in this Annex

BE	Beech
BI	Silver birch and birch
$C_{10}H_{16}$	Monoterpenes
C_5H_8	Compound isoprene
CCF	Continuous Cover Forestry
CCN	Cloud Condensation Nuclei
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
Confor	Confederation of Forest Industries
DF	Douglas fir
DOC	Dissolved Organic Carbon
ERAMMP	Environment and Rural Affairs Monitoring & Modelling Programme
ESC	Ecological Site Classification
ET	Evapotranspiration
GHG	Greenhouse Gas
GWP	Global Warming Potentials
iLUC	Indirect Land Usage Change
IPCC	Intergovernmental Panel on Climate Change
ktC	Kilo-tonnes carbon
LCA	Life Cycle Assessment
LIIB	Low Indirect Impact Biofuel
LULUCF	Land Use, Land Use Change and Forestry
MDF	Medium Density Fibreboard
$MtCO_2$	Million tonnes of carbon dioxide [sometimes with '-eq' = equivalent]
N_2O	Nitrous Oxide
NO	Nitric Oxide
NO_X	Nitrogen Oxides (generic, i.e. NO or NO_2)
NRW	Natural Resources Wales
O_3	Ozone
odt	Oven dry tonnes - wood quantity without moisture content
OH	Hydroxyl Radical
OK	Oak
PO	Aspen and black poplar
POC	Particulate Organic Carbon
SOA	Secondary Organic Aerosol
SP	Scots pine
SRF	Short Rotation Forestry
SS	Sitka spruce
$tC\ ha^{-1}$	Tonnes carbon per hectare
$tC\ ha^{-1}\ yr^{-1}$	Tonnes carbon per hectare per year
$tCO_2\ ha^{-1}\ yr^{-1}$	Tonnes carbon dioxide per hectare per year
tCO_2-eq.	Tonnes CO_2 equivalent
UKCEH	UK Centre for Ecology & Hydrology
UNFCCC	United Nations Framework Convention on Climate Change
UKFS	UK Forestry Standard
VOC	Volatile Organic Compound
WCC	Woodland Carbon Code
WID	Waste Incineration Directive

Abbreviations and some of the technical terms used in this report are expanded on in the programme glossaries: https://erammp.wales/en/glossary (English) and https://erammp.cymru/geirfa (Welsh)

Contents

1. Introduction to Annex-4

This annex presents an assessment of the potential roles of woodlands in Wales in contributing towards climate change objectives, in particular, the achievement of reductions in greenhouse gas (GHG) emissions and the possible attainment of net-zero emissions in Wales. The assessment covers how woodlands in Wales may contribute directly as reservoirs and sinks of carbon and also indirectly as a sustainable source of wood-based products and bioenergy. The possible options for enhancing these contributions by Welsh woodlands are also discussed and assessed.

1.1 Purpose

The purpose of this annex comes directly from the brief given: "*Explore how woodland creation and management can increase carbon sequestration and reduce Wales' carbon footprint. [To include] carbon sequestration, GHG reduction, carbon abatement, substitution effects, soil carbon*".

1.2 Structure of this annex

The discussion in this annex is structured to first describe some essential concepts, followed by a description and assessment of options for woodland-based activities relevant to climate change mitigation.

The discussion of essential concepts in Section 2 is important because the processes of woodland carbon sequestration and the contributions made by wood-based products can be quite complicated. Sometimes this leads to misunderstandings amongst stakeholders and erroneous claims being made, whilst in some subject areas there is significant controversy. The essential concepts discussed in Section 2 form the basis for assessing the impacts of different interventions based on woodlands, as measures for mitigating climate change. A more detailed discussion of important background concepts, including some relevant example results, is provided in Appendix A1.

The main types of intervention measures, described in Section 3, consist of woodland creation, the protection of existing woodland areas and interventions in the management of existing woodlands to increase wood production. A quantitative assessment of these measures is given in Section 4. An interpretation of this assessment and key conclusions are presented in Section 5, along with the identification of a number of gaps in knowledge, evidence and tools.

1.3 Main sources of evidence

Much of the evidence base for this assessment has been presented in previous reports and papers produced by Forest Research and collaborators, and material from several of these reports has been drawn upon for the content of this annex and Appendix A1 (see Matthews and Robertson 2006; Matthews et al. 2007, 2014ab, 2015, 2017, 2018; background reports to Kuikman et al. 2010; Morison et al. 2012; Fritsche et al. 2020). Where appropriate, estimates presented in previous reports have been updated based on more current data and results or with estimates more relevant to woodlands in Wales. For the quantitative assessment in Section 4, the main data source referred to consists of a more substantial and consistent set of results produced as part of modelling in support of ERAMMP. These were supplemented with estimates of long-term carbon stocks in woodlands, published as part of the UK Woodland Carbon Code Carbon Calculation Spreadsheet (Woodland Carbon Code 2020).

The estimates and results derived from Forest Research reports and particularly the results of Forest Research models referred to in this assessment have been verified through comparison with those from the wider scientific literature (Matthews et al. 2020a).

1.4 Reporting results for different greenhouse gases

The main GHG concerned in woodland GHG balances is carbon dioxide (CO_2) from woodland carbon stock changes (in vegetation, deadwood, litter, soil and, where relevant, wood products). Usually in this assessment, results for carbon stocks in woodlands are reported in units of tonnes carbon per hectare (tC ha^{-1}). Results for carbon stock changes are reported in units of tonnes carbon per hectare per year (tC ha^{-1} yr^{-1}) or, to indicate the implied equivalent quantity of CO_2 removed from (or emitted to) the atmosphere, in units of tonnes carbon dioxide per hectare per year (tCO_2 ha^{-1} yr^{-1}). The conventions generally adopted when reporting such results are:

- A positive result expressed in tC ha^{-1} yr^{-1} implies net carbon sequestration (or a net carbon sink), a negative result implying a net loss of carbon (or a net emission or carbon source).
- A positive result expressed in tCO_2 ha^{-1} yr^{-1} implies a net loss of carbon to the atmosphere as CO_2 (or a net CO_2 source), a negative result implying a net removal of CO_2 from the atmosphere as carbon (or a net carbon sink).

A stock of 1 tonne carbon is equivalent to 44/12 (3.67) tonnes CO_2. The fraction of carbon in carbon dioxide is the ratio of their weights; the atomic weight of carbon is 12 atomic mass units, while the weight of carbon dioxide is 44.

Other relevant GHGs include nitrous oxide (N_2O) from, for example, nitrogen inputs (when fertilising woodlands, currently not common practice in the UK), and methane (CH_4) which is involved in the GHG balances of woodlands growing on highly organic soils such as peatlands. Non-CO2 GHG emissions can also occur as part of the process of manufacturing wood products and alternative non-wood products, and when wood and non-wood products are destroyed, through combustion or decay.

Where relevant to reporting results in this annex, to enable comparison, and to permit an appreciation of the combined impact of different GHGs, emissions of methane (CH_4) and nitrous oxide (N_2O) are expressed in units of equivalent carbon dioxide (CO_2). This is achieved by referring to quoted values of global warming potentials (GWP) for these GHGs. GWP values are reported for a range of GHGs in Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, and generally these are updated as each new Assessment Report is produced. Results derived from different studies, presented at evidence in this annex, will refer to different values of GWPs for non-CO_2 GHGs. However, the GWP for CO_2 is always 1 and those for the key non-CO_2 GHGs of methane and nitrous oxide are typically of the order 20 and 300 tonnes CO_2 equivalent (tCO2-eq.), respectively, with successive reported values changing only slightly. Hence, for example, 1 tonne of CH_4 equals roughly 20 tonnes equivalent (20 tCO_2-eq.). These GWP values are usually based on modelling of the relative warming potentials of CO_2, CH_4 and N_2O over a 100-year time horizon.

2. Essential Concepts

2.1 International policy context

Under the United Nations Framework Convention on Climate Change (UNFCCC 1992) participating countries are committed to avoiding dangerous levels of climate change. The Paris Agreement (UNFCCC 2015) identifies a specific target of achieving, "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century", sometimes referred to achieving "net zero emissions". The Paris Agreement also recognizes the need to strengthen the capacity of countries to adapt in the face of climate change, as an important element of sustainable development.

The question thus arises as to how woodlands and woodland management might support these goals of climate change mitigation and adaptation, including the specific goal of "net zero emissions", noting the wider context of sustainable development.

An essential first step in addressing this question is to understand the contributions of woodlands in the cycles of atmospheric greenhouse gases (GHGs), notably carbon dioxide (CO_2). It is also necessary to understand the potential impacts of woodland management on levels of atmospheric GHGs, in particular those management activities that support the goals of climate change mitigation and climate change adaptation. It is also critical to recognize where particular management activities can support both of these goals, or where they may support one goal whilst frustrating the achievement of the other. Other potential climate impacts of woodland and woodland management may also need to be considered.

2.1.1 What is meant by "net zero emissions?"

Although the Paris Agreement sets the goal of achieving net zero emissions in the second half of this century (or rather, more vaguely, a "balance"), the exact technical goal is not defined. The following definition is adopted as representing the goal, for the purposes of this annex:

By some point in the second half of this century, global atmospheric concentrations of GHGs should at least not be increasing.

Achieving this outcome implies that emissions of GHGs (both anthropogenic and non-anthropogenic) must not exceed the sequestration of GHGs (both anthropogenic and non-anthropogenic), also allowing for feedbacks that may occur in terrestrial and marine systems (e.g. responses in the naturally occurring ocean sink). This in turn requires that either existing levels of GHG emissions are reduced, or existing sinks ("negative emissions") are increased, or that a combination of both is achieved.

2.2 Scope of assessment

Whilst recognising the international policy context as outlined above, the scope of the assessment in this annex obviously covers the climate impacts related to woodlands and their management in Wales. However, it is important to clarify exactly which climate impacts are included or alternatively not considered. The assessment's main focus is on the interactions between woodlands and atmospheric CO_2. However, non-CO_2 GHGs are also discussed as are potential non-GHG climate impacts of woodlands.

When evaluating GHG balances, the scope and "system boundary" (specified in both *spatial* and *temporal* terms) can be defined narrowly or widely, as illustrated for the spatial system boundary in Figure 2-1.

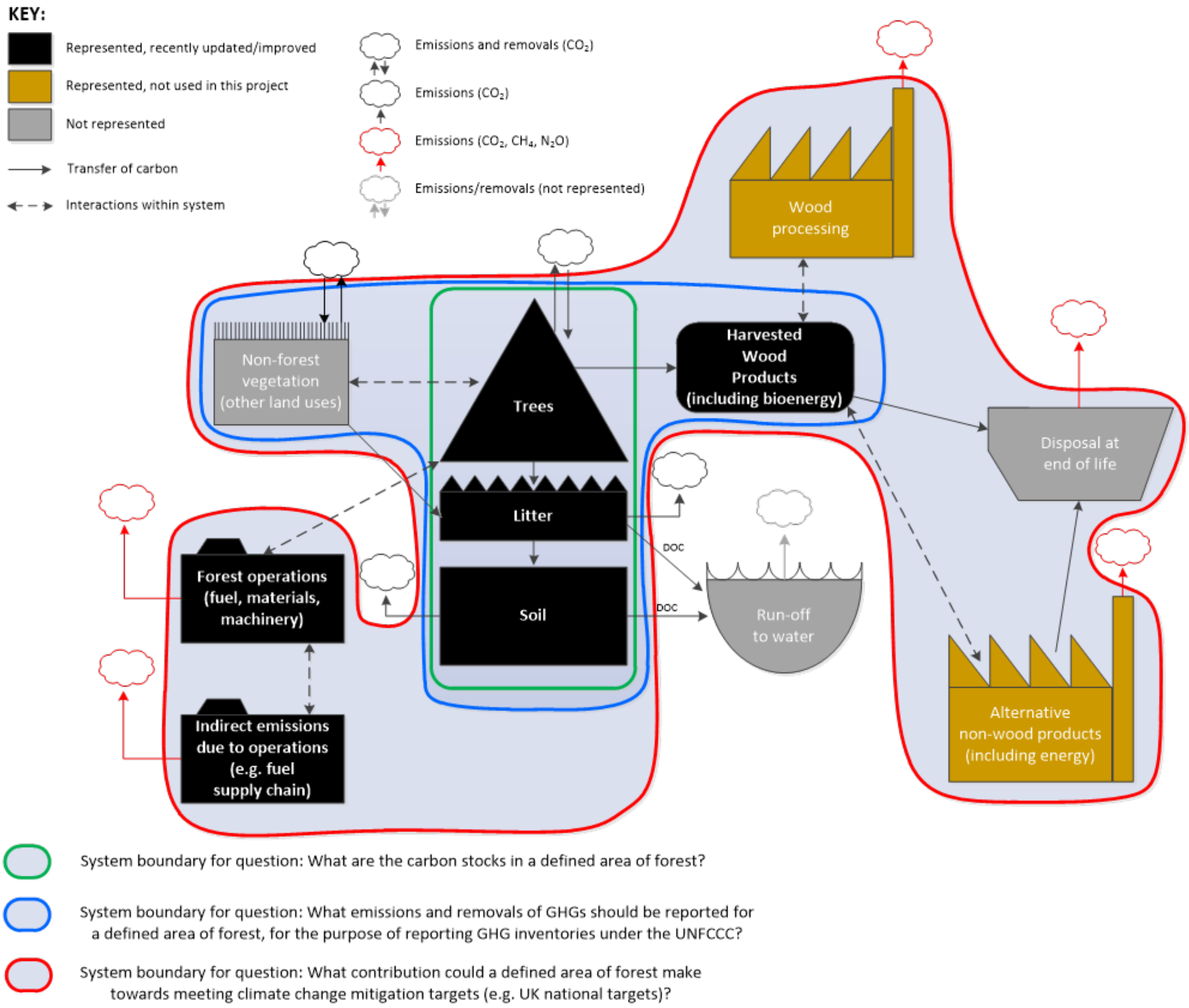

Figure 2-1 Determining the scope and system boundary appropriate for this assessment. The figure illustrates how different system boundaries will capture different impacts on GHG emissions related to woodlands and their management. The red boundary is most appropriate for addressing the stated brief. After Matthews et al. (2017, 2020a).

For example, at one extreme, just carbon sequestration and losses occurring in trees may be considered, perhaps also encompassing the carbon balances of closely related carbon "pools" (carbon reservoirs) such as deadwood, litter and soils. At the other extreme, the potential impacts of woodlands on a wide range of GHG emissions can be included, such as carbon retained in wood-based products, GHG emissions from woodland operations and wood processing chains, and emissions potentially "saved" by using wood-based products and bioenergy in place of (generally) more GHG-intensive non-wood products. Certain other market-mediated effects may also be considered, for example, changes in agricultural land use in response to an expansion or contraction of woodland areas. Some of these impacts may occur outside Wales.

In setting the system boundary, this assessment draws on the ideas of systems analysis and, in particular, life cycle assessment (LCA) and its precursor energy analysis (Chapman 1975; Boustead and Hancock 1979; Socolow et al. 1994; Bringezu et al. 1997; den Hond 2000; Rebitzer et al. 2004; ISO 2006:14040; ISO 2006:14044). An absolutely critical step in LCA involves clearly defining the goal, and inferring the scope and system boundary for LCA calculations from this goal.

Given the stated brief for this assessment (Section 1.1), in particular the potential for “increasing carbon sequestration and reducing Wales’ carbon footprint”, the scope and system boundary for this assessment need to be wide, in order to capture the full impacts of decisions about woodland creation and/or management in Wales. This suggests a *spatial* system boundary such as illustrated by the red boundary line in Figure 2-1. Exchanges of carbon between the pools included in the assessment, and GHG emissions arising from certain wider but related processes or activities, are shown as arrows crossing this system boundary.

The *temporal* system boundaries for this assessment of GHG emissions and carbon stocks/sequestration have been selected for consistency with those referred to in the ERAMMP project. Three “time horizons”, from present day (2020) to 2030, 2050 and 2100 are considered. These time horizons are relevant for near-term policy goals and for longer-term goals, such as achieving net zero emissions in the second half of this century, as referred to in the Paris agreement. Results for a time horizon of 200 years (2020 to 2220) are also considered, so as to assess the very long-term implications of decisions taken now about woodland creation and management.

2.3 Carbon balances in woodlands

As illustrated by the green boundary in Figure 2-2, the carbon balance directly associated with woodland covers the carbon pools of living biomass of trees (above and below ground), dead organic matter (dead wood and litter) and organic soil carbon under woodland. Where relevant, emissions of methane and nitrous oxide may be considered as well as those of carbon dioxide (see Section 2.10).

Woodland carbon dynamics involve “sequestration” (or “sinks”) of carbon 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 trees and other vegetation grow or organic matter accumulates in the soil) as well as the release of GHGs to the atmosphere (e.g. when vegetation respires, decays or burns, or when microbes break down soil organic matter).These various exchanges of carbon are illustrated in Figure 2-2. Vegetation and soil carbon dynamics thus involve a balance between emissions and sequestration, depending on specific circumstances, and the net result can be an emission to the atmosphere or removal from it. Estimating these emissions and sequestration requires an understanding of how natural processes affecting greenhouse gas dynamics interact in response to the interventions of humans.

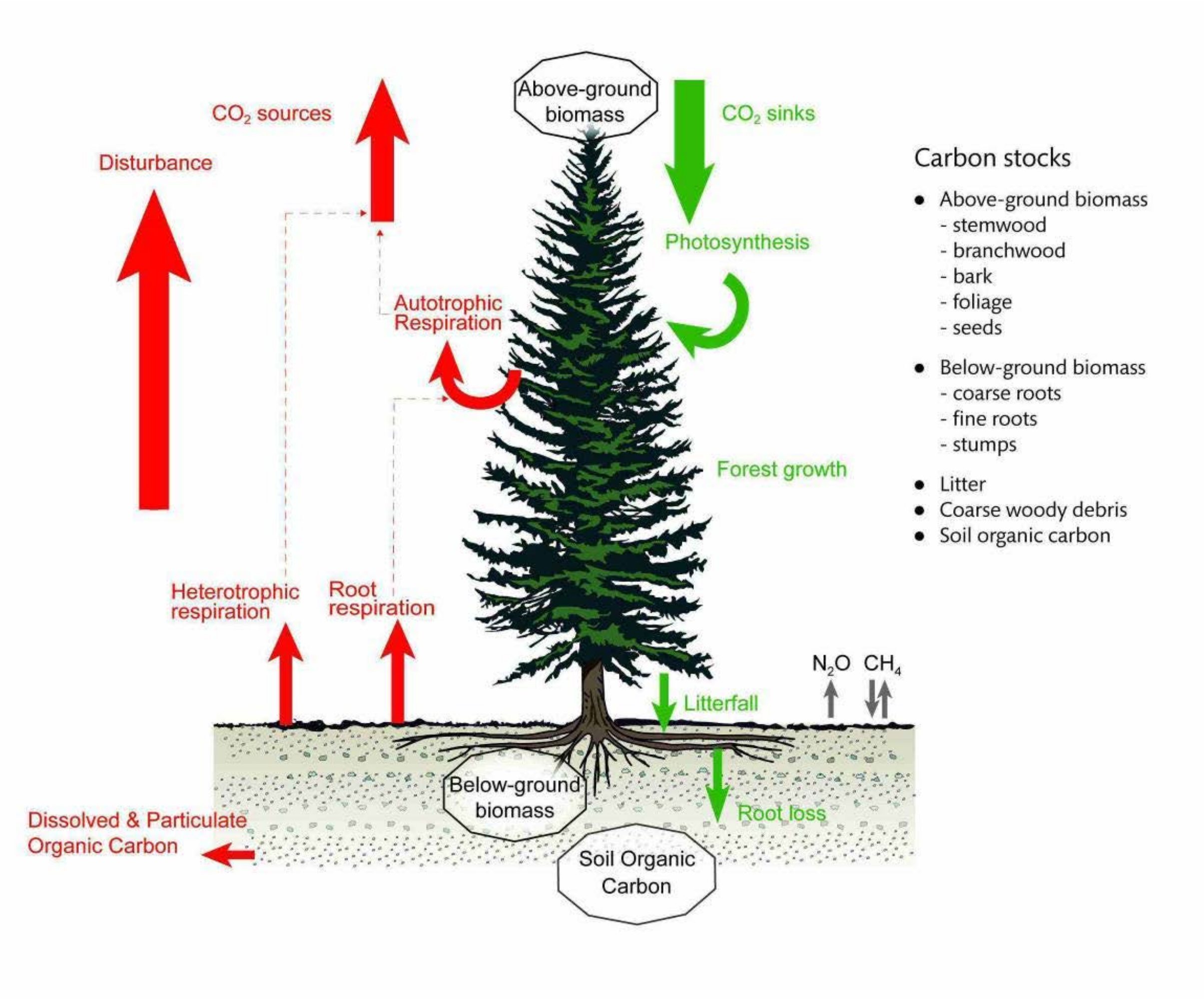

Figure 2-2. Illustration of the carbon pools and naturally occurring GHG dynamics associated with woodlands. After Morison et al. (2012).

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

2.4 Understanding woodland carbon balances as stock changes

The range of carbon pools involved in woodland GHG balances and the types of issues raised in the preceding discussion can lead to the impression that woodland GHG balances are difficult to understand and quantify, particularly in terms of the impacts of changes to woodland management. However, as has been pointed out by Maclaren (2000), for most purposes, woodland carbon or GHG balances can be understood and modelled more simply by considering changes in carbon stocks.

Maclaren uses the example of the carbon budget of a pig (Figure 2-3) to illustrate this point.

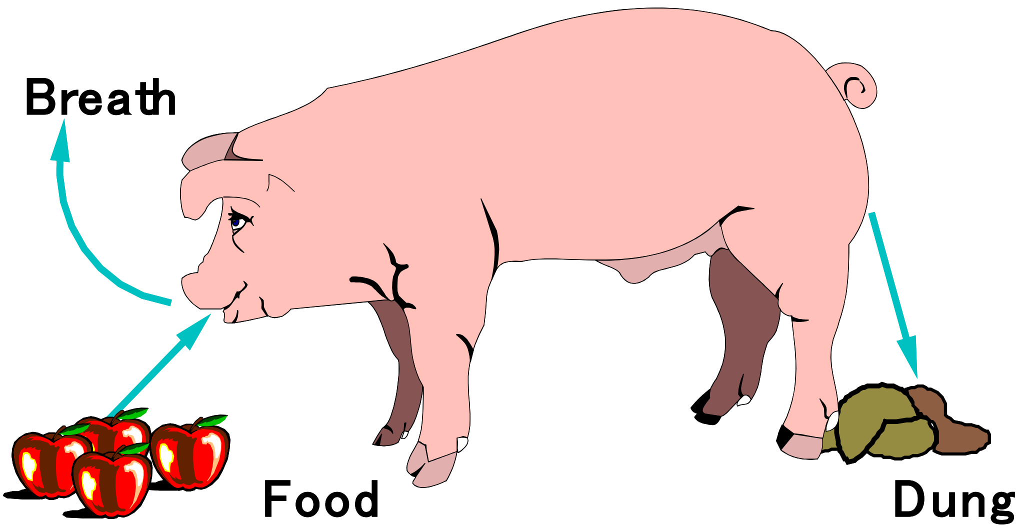

Figure 2-3 The carbon balance of a pig can be worked out by estimating all the flows of carbon into and out of the pig, or by working out how the weight of the pig (its carbon stock) is changing. After Maclaren (2000).

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 (or otherwise modelled), requiring complex apparatus and the chances of error. Alternatively, the pig's carbon balance can be estimated by monitoring or modelling its change in carbon stock over time, i.e. by weighing the pig and seeing how its weight changes over time. The principle behind this approach applies equally to woodland carbon balances – woodland GHG emissions and sequestration are directly associated with changes in vegetation and soil carbon stocks on land. Net carbon sinks or sources may thus be understood as net changes in vegetation and soil carbon stocks. This principle has been adopted extensively in this assessment. The principle is widely understood and is the basis of the "Stock-Difference" method specified in IPCC Good Practice Guidance on the compilation of National Greenhouse Gas Inventories (IPCC 2006). It is important to note that estimates of emissions and sequestration associated with woodlands, as given in this assessment, follow the reporting conventions of IPCC Good Practice Guidance. This has some implications for the interpretation and understanding of results for different woodland types and woodland management options, as misunderstandings and confusion can sometimes occur. Relevant points are discussed further in Sections 2.15 and 2.16.

It must be stressed that the main relevance of the pig analogy and of the consideration of carbon stock changes in this assessment is to *assist with the illustration and understanding* of the net results of sometimes complex changes of carbon between the atmosphere and a number of carbon pools associated with woodlands. As already noted, methods based on the quantification of carbon stock changes have also been developed for *estimating* the net carbon sinks and sources of actual woodlands (and other vegetation systems). These methods can be applied with quite high accuracy in situations where it is relatively easy to directly assess carbon stocks and stock changes. For example, this is usually the case for individual trees and populations of trees, where tree biomass can be assessed periodically using established protocols and these estimates can be converted to carbon stocks (and stock changes) using published values for the carbon content of tree biomass. However, not all of the components of woodland systems are so straightforward to measure. For example, this is the case for soil carbon stocks, which require quite complicated and expensive measurements, and for which results may have relatively high associated uncertainty. This is particularly evident for the measurements of carbon stocks in peatlands, where the organic soils may be very deep and it is practically impossible to measure down to the full depth. The situation is further complicated by the exchanges of non-CO_2 GHGs in soils, involving CH_4 and N_2O as well as CO_2, again particularly in the case of peatlands. Nevertheless, it is suggested here that considering the carbon stock changes in woodland systems is useful for the purposes of illustration and for aiding an understanding of a number of essential features of the carbon and GHG dynamics of woodland systems, including the potential impacts of decisions about woodland creation and management.

2.5 Woodland carbon dynamics – essential features

Figure 2-4 illustrates how the carbon stocks in vegetation biomass 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 possibly by assisting natural regeneration. Before the trees are established, the existing vegetation carbon stocks might typically comprise no more than 20 tonnes carbon per hectare (20 tC ha^{-1}). The small initial loss of carbon stocks as a result of removal of existing vegetation is not shown in Figure 2-4. The results in Figure 2-4 were produced using the Forest Research CARBINE forest carbon accounting model (Thompson and Matthews 1989; Matthews 1994, 1996; Matthews and Broadmeadow 2009; Matthews et al. 2020a) and represent the carbon stock changes resulting from planting a 1 hectare stand of mixed broadleaf trees (birch and oak) with a mean growth rate (over about 50 years) of 4 cubic metres stem volume per hectare per year (4 m^3 ha^{-1} yr^{-1}). The stand is assumed to be managed without any harvesting (either through thinning or clearfelling), effectively being allowed to develop into a very dense woodland composed of very mature trees. Results such as this example were produced using the CARBINE model as part of analysis undertaken for the ERAMMP project, covering a range of tree species, growth rates and different possible management regimes (see Appendix A1 for more examples and Section 4 and Appendix A2 for examples of summary results used for ERAMMP).

It must be stressed that this example mixed broadleaf stand is not suggested as representative of all tree species or of tree growth grates in general for woodlands in Wales. Rather, this example illustrates in general terms the pattern with which carbon stocks can be accumulated over time in a stand of newly-planted or regenerated trees, which is not subjected to any disturbance, either from harvesting or from natural processes such as fires, storms, pests and diseases and so on.

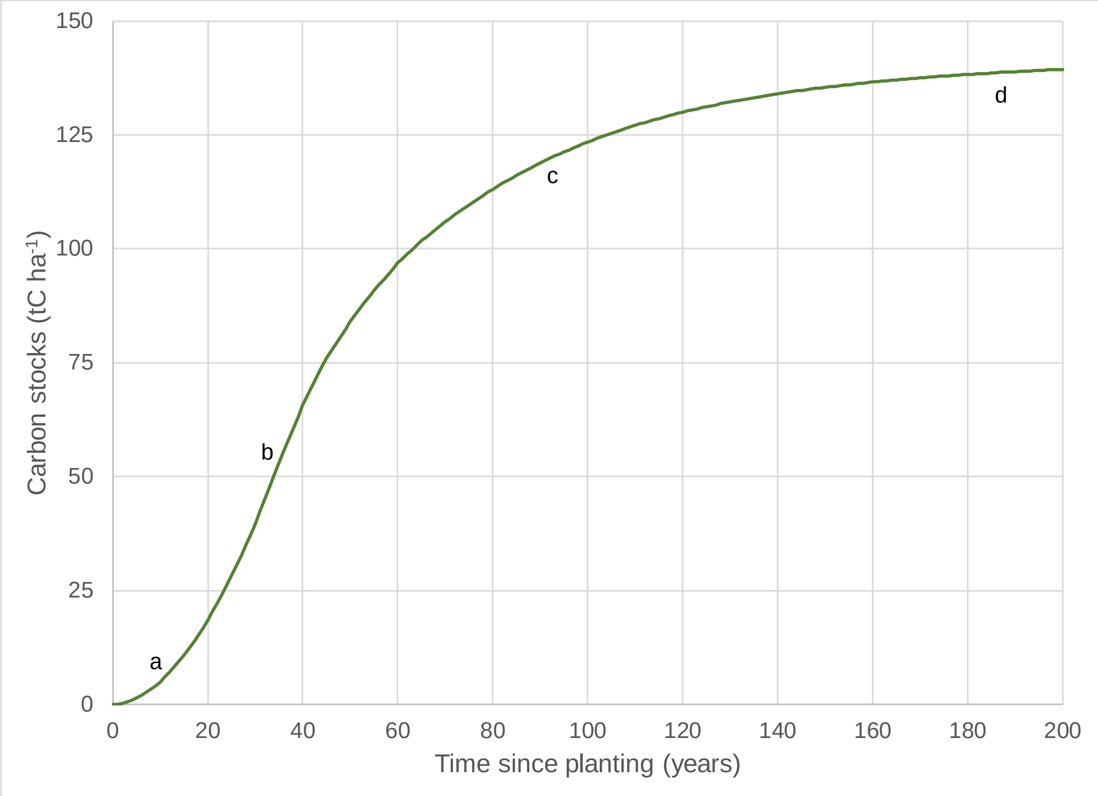

Figure 2-4 An illustration of the change in vegetation (tree) carbon stocks that can occur on an area of land by planting a stand of conifer trees. a: establishment phase; b: full-vigour phase; c: mature phase; d: long-term equilibrium phase. After Matthews et al. (2014).

The model results shown in Figure 2-4 describe the development of carbon stocks in the biomass of living trees (consisting of foliage, branches, stem and coarse roots). Carbon in the biomass of fine roots is not included.

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 2-4)
2. The full-vigour phase (denoted ‘b’ in Figure 2-4)
3. The mature phase (denoted ‘c’ in Figure 2-4) and
4. The long-term equilibrium phase (denoted ‘d’ in Figure 2-4).

The rate of carbon sequestration in the biomass of trees (the slope of the curve in Figure 2-4) can be significant in the full-vigour phase, for example a maximum rate of nearly 3 tonnes carbon per hectare per year (3 tC ha^{-1} yr^{-1}) is observed in Figure 2-4. However, after about 150 years, rates of carbon sequestration have declined to less than 0.5 tC ha^{-1} yr^{-1}, as a result of the phenomenon of ‘saturation’ as discussed further in Section 2.7. As is clear from Figure 2-4, the ultimate result of planting 1 hectare of land with trees is not the continuous sequestration of carbon in trees, rather (in this example) there is a one-off change (increase) in vegetation carbon stocks of about 140 tC ha^{-1}, which takes place over a number of decades. (This ultimate carbon stock will vary with tree species, site conditions and other factors) It is this property of the carbon dynamics of a woodland stand that has led to the suggestion sometimes made that planting trees to sequester carbon and “offset” GHG emissions resulting from 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 as a result of other activities directly). However, this conclusion could be considered to depend on how the carbon sink of vegetation systems (including woodland) is defined, as discussed further in Section 2.15.

The above discussion has been based on the consideration of a single stand of trees. The carbon dynamics in individual stands determine those of populations of stands (i.e. woodlands) and have implications for the impacts of management decisions on the carbon dynamics of woodlands. A more detailed discussion of these points is provided in Appendix A1.

The general pattern of carbon sequestration in stands of trees illustrated in Figure 2-4 is widely accepted (see for example, Maclaren 2000; Morison et al. 2012). This understanding is the basis of “Tier 1” methods for estimating carbon stock changes in Forest Land (and other vegetation systems) as described in IPCC Good Practice Guidance on methods for estimating and reporting national GHG emissions inventories. Specifically, methods are included in IPCC Guidance that represent land-use change as involving a change in carbon stocks from one constant level to another, over a specified period of years. The pattern shown in Figure 2-4 is also a feature of the estimates of woodland carbon stocks and rates of carbon stock changes over time produced by the other main internationally applied forest carbon models (Dewar 1990, 1991; Mohren and Klein Goldewijk 1990; Cannell and Dewar 1995; Marland and Schlamadinger 1995; Nabuurs 1996; Beets et al. 1999; Schlamadinger and Marland 1996; Mohren et al. 1999; Richards 2001; Kindermann et al. 2006, 2008; Schelhaas et al. 2007; Kurz et al. 2009; Böttcher et al. 2012; Waterworth et al. 2012). Generally, these models rely on underlying forest growth models, calibrated using data on the forest growth patterns exhibited by trees and stands of trees, which have been the subject of centuries of research (see for example Chapman and Meyer 1949; Prodan 1968; Assmann 1970; Philip 1994; Husch et al. 2003; Pretzsch et al. 2009, 2019; Matthews et al. 2016).

Many studies have estimated the magnitudes of carbon stocks and stock changes associated with different types of woodland creation, conservation and management. The main estimates referred to in this assessment are based on modelling undertaken for the ERAMMP project, supplemented where needed by results reported as part of the UK Woodland Carbon Code (UK Woodland Carbon Code 2020), as described in Section 4.1. These results are discussed and assessed in detail in Sections 4.2 to 4.6, and a complete set of the ERAMMP project results referred to in this assessment is given in Appendix A2 of this annex.

2.6 Influence of disturbance events on tree carbon stocks

It is very important to note that the relatively large carbon stock accumulated in the stand of trees after about 100 years, as indicated in the example in Figure 2-4, involves the assumption that the stand is not subject to significant incidents of natural disturbance such as fire, storms, and infestations of pests and diseases. Such disturbance events disrupt woodland carbon stocks with the result that the long-term levels of carbon stocks actually observed will be lower than suggested by Figure 2-4 (see for example Figure 2 in Matthews and Robertson 2006). In the case where major disturbance occurs regularly, the long-term equilibrium carbon stocks may be less than half of the level that would be achieved in the absence of disturbance.

Hence, high uncertainty should be attached to theoretical carbon sequestration achieved by low-management or no-management forestry options such as shown in Figure 2-4.

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 (Schelhaas et al. 2003). This implies that the risks of significant, large-scale disturbance events could be mitigated by the systematic control of levels of growing stock in woodland stands associated with management involving harvesting. However, so far, disturbance processes and their effects have not been represented adequately in the assessment of woodland management options, although some studies have made initial steps to address this issue (Lindroth et al. 2009).

In cases where there is significant, large-scale incidence of woodland disturbance, perhaps as a result of a major storm or disease outbreak, the affected trees can be left on-site to decay or they can be harvested, an activity referred to in this context as "salvage logging". The harvested wood can be used for solid-wood products and/or as a bioenergy feedstock. Decisions about whether or not to carry out salvage logging, at what scale and over what period following the original disturbance event, can have both beneficial and detrimental consequences for GHG emissions and carbon sequestration, the latter occurring as the woodland areas recover and re-grow, and will also strongly influence the timing of GHG emissions and carbon sequestration (see for example Thurig et al. 2005; Köster et al. 2011). Some forms of disturbance can sometimes preclude salvage logging (e.g. when a forest fire burns wood beyond the point that salvage logging can be used), and can cause relatively immediate release of carbon stocks, which would act against the objective of conserving carbon stocks in woodlands.

2.7 "Carbon saturation" or "eternal sequestration"?

The capacity for terrestrial vegetation and soil to remove carbon from the atmosphere 'saturates' because ultimately (in unchanging environmental conditions) a steady state will occur in the balance of emissions and removals for a given area of land. The magnitude and stability of the carbon stock at this saturation point, and the time taken to reach it, depend on various factors including soil type, vegetation type, long-term management, disturbance events and climate, also including environmental changes such as atmospheric pollution. The phenomenon of saturation is very clear in the example described earlier in Figure 2-4.

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

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

Technical saturation occurs when vegetation attains a maximum long-term average, subject to both the biological capacity of the land and vegetation and also the way in which the land is being managed. For example, consider the case of a new woodland area created by planting trees on an area that was previously grassland, in which the woodlands are subsequently managed for production involving periodic clearfelling and replanting. After the initial planting of trees, vegetation carbon stocks will most likely increase, however harvesting will reduce carbon stocks in individual stands of trees, with the consequence that overall carbon stocks in the woodland will be limited to a long-term average level (see for example Maclaren 1996; see also the detailed discussion in Appendix A1). This long-term average carbon stock will be determined in large part by the balance between the (re)growth of individual stands of trees and the rate of harvesting (in particular the rotation period for clearfelling). Generally, the magnitude of this long-term average carbon stock will be smaller than that attained under biological saturation (i.e. in the absence of harvesting), although there may be cases where the magnitudes are comparable (e.g. where management includes the moderating of disturbance events).

In this assessment, generally the term saturation is used in both the biological and technical senses.

The notion that woodland creation, or a change in woodland management, ultimately results in a one-off change in carbon stocks (generally from a relatively low level to a higher level in the case of woodland creation), is widely accepted (see the discussion and references at the end of Section 2.5). However, recently, some researchers have been suggesting a contrary view, i.e. that, if left unharvested and unmanaged, woodlands have the potential to sequester carbon in perpetuity (or, at least over very long timescales). So far, there is limited evidence to support this idea, obtained from data in quite site-specific circumstances (see for example Stephenson et al. 2014). A weakness in some of the evidence appears to lie in the fact that relevant studies consider the growth of individual old and very large trees, and so assess the potential *carbon sequestration of an individual tree*, rather than that of stands formed of populations of trees (i.e. *carbon sequestration per hectare*). Numerous studies have shown that the numbers of trees that can be supported on an area of land decrease according to the inverse of the size of the trees (e.g. the inverse of mean stem diameter or mean stem biomass; see for example Reineke 1933; Yoda et al. 1963; Kizukawa 1999; Luyssaert et al. 2008). This interaction between the size of individual trees and the number that can be supported on an area of land may explain why estimates of carbon sequestration obtained in some studies of old, large individual trees may appear to be at odds with the carbon dynamics generally observed at the scale of a stand of trees. Luyssaert et al. (2008) point out that high woodland carbon stocks suggested by theoretical potentials may only rarely be achieved because of natural disturbance events. However, the authors observe that conserving high carbon stocks in existing long-established very mature woodlands is a sensible measure, where this is occurring.

As highlighted previously (Section 2.5), the assessment presented above could be viewed as depending on how the carbon sink of vegetation systems (including woodland) is defined, as discussed further in Section 2.15.

2.8 Potential impermanence of woodland carbon sequestration

The issue of impermanence is related to the physical reversibility of carbon sequestration and GHG emissions in woodlands (and other vegetation). Both sequestration and emissions related to vegetation and soil carbon dynamics are potentially reversible. For example, on the one hand, an area of woodland can be felled and not replanted or destroyed by fire while, on the other hand, an area of woodland that has been felled or has burned down can regenerate or can be replanted. While this property of reversibility might be viewed as imparting a certain flexibility in woodland management, there are significant implications for the role of woodland management activities in contributing to GHG emissions reduction or carbon sequestration (see for example Matthews and Robertson 2006). In essence, a given human activity (such as supplying heat or constructing a new building) involves a certain level of GHG emissions. When acting to mitigate these emissions, there is a choice to be made between directly reducing the emissions associated with the activity, or offsetting some or all of the emissions through management of an area of vegetation or soil to achieve carbon sequestration.

If the emissions associated with the activity are reduced directly, then in principle the emissions reductions achieved for a specific activity cannot be reversed. For example, suppose fossil fuels are being used in a power station to generate electricity. If improvements are introduced that increase the efficiency of the energy conversion process, then GHG emissions will be reduced. The GHG emissions reductions associated with generating the energy cannot be “undone”. Moreover, it is very unlikely that the power station would go back to using a less energy-efficient conversion process in the future, which would otherwise increase GHG emissions again. In contrast, if the option of sequestering the emissions in vegetation or soil is pursued, then the sequestered carbon is always potentially at risk of being emitted again as a result of future disturbance. Natural disturbances such as fires, storms, drought or pest and disease infestations may cause carbon sequestered in vegetation or soil to be released back to the atmosphere. Climate change itself could alter the suitability of land in certain locations for sustaining certain types of vegetation and compromise sequestered (or sequestering) stocks of carbon.

Equally, it is very unlikely that guarantees can be secured to ensure that future generations will maintain measures to conserve carbon sequestered on a specified area of woodland – circumstances and priorities may change the way the land is managed in the future. In the UK, strong regulation limits deforestation but there is still a modest but registerable level of woodland area loss. Perhaps more pertinently in a European/UK/Welsh context, the issue of impermanence is not restricted to deforestation activities. For example, if areas of previously unmanaged woodlands with high carbon stocks are brought into active management, including harvesting for wood production, often this will result in some reduction of carbon stocks in the woodlands, even if the management meets sustainability standards. Hence, some of the carbon sequestration that occurred historically in the woodlands will be reversed by the introduction of management in what were previously unmanaged woodlands. The same outcome is likely to occur when management is intensified (to increase levels of sustainable wood production) in woodlands already under active but less intensive management. Further explanation of relevant points is provided in Section 2.16.1.

There is a corollary to the risks of reversal of woodland carbon sequestration because of the issue of impermanence as described above. Specifically, suppose actions are taken now to sequester and conserve carbon in woodland areas. This would effectively commit future generations to recognise the status of the sequestered carbon and not to take any actions that would lead to its loss. (For example, in the future, there may be interest in managing the woodland resource that has been created by conservation measures more intensively, to supply products and fuel). Assuming the carbon stocks created by activities taken now were registered and recognised in some way, either the options for the management of the woodlands would be significantly constrained in the future, or any emissions arising from decisions to change woodland management would need to be compensated for by deeper cuts in emissions and/or enhanced carbon sequestration elsewhere. It follows that, in effect, in such a context, the impermanence issue “locks in” future generations to manage woodland areas in certain specific ways, that do not negatively affect woodland carbon stocks and sequestration rates, or to undertake additional climate change mitigation activities.

The risks of impermanence of net emissions reductions in the woodlands require that any framework for supporting and implementing climate change mitigation measures would need to be able to account for incidents where net emissions reductions are subsequently reversed, and to support remediation where appropriate. For example, a recent EU Regulation (EU 2018/841) on the inclusion of greenhouse gas emissions and removals from land use, land-use change and forestry in the 2030 climate and energy framework includes accounting rules that directly address this issue with regard to human activities in woodlands that have impacts on carbon stocks and sequestration. Relevant provisions are also included to cover natural disturbances, Guidance on methods for assessing and allowing for the effects of disturbance events has also been included in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019a).

2.9 Soil carbon

2.9.1 Soil carbon stocks in forests

Soil can contain a substantial amount of organic carbon, and this carbon stock depends on many factors, in particular the soil type and the vegetation cover and therefore the land use history (see for example Wiesmeier et al. 2019). Soil carbon content varies with depth, changing in both amount and chemical composition in the different soil horizons. Although not strictly part of the soil, the litter layer on the surface under woodlands also contains a substantial amount of organic carbon, consisting of dead biomass in various states of decomposition.

A global assessment of forests shows that the soil can be the major component of the total carbon stock; in boreal and temperate forests it represents approximately 70% and 60% respectively, of the total carbon stock (Pan et al. 2011). At the stand scale, results from the BioSoil study of 166 woodland sites in Great Britain produced total soil carbon stocks for seven different broad soil types with mean values ranging from 108 tC ha^{-1} to 539 tC ha^{-1} down to 1m depth (Vanguelova et al. 2013, see Table 2.1 below). Values of carbon stock in the above ground biomass in a woodland are typically 50 – 170 tC ha^{-1} so it is evident that the soil carbon stock can be at least as large as that in the above ground biomass, and in some cases considerably more. In the Biosoil survey, mineral soil types had a carbon stock of 108 – 173 tC ha^{-1}, (so broadly similar to the stock in trees) but organo-mineral and organic soils had considerably higher stocks (mean of 36 peaty gleys = 362 tC ha^{-1}, and 14 deep peats = 539 tC ha^{-1} (Vanguelova et al. 2013). Therefore, the management of the soil carbon stock can have an important impact on the overall woodland carbon balance, particularly for organo-mineral and organic soils.

In addition to this soil carbon stock, the litter layers (including both the true litter layer, and the fermentation or F layer, consisting of partially decomposed matter), may contain an additional 12-20 tC ha^{-1} (the mean for the BioSoil survey sites is 16 tC ha^{-1}). The litter layers are also key to the nutrient cycling in woodlands and thus affect growth and productivity.

Vanguelova et al. (2013) assessed the area occupied by different soil types in Wales and under coniferous and broadleaved woodland and, using the BioSoil measurements of carbon stock per area, estimated the total woodland soil carbon stock (Table 2.1) at 35 and 16 MtC (million tonnes carbon) for the two woodland types (total = 51 MtC). The majority of the existing woodland area (in 2003) was on brown earths, podsols and peaty gleys/podsols. The areas of coniferous woodland on peaty gleys/podsols and deep peats, although only 21% of the area, contributed 42% of the woodland soil carbon stock because of the high carbon stock of these organo-mineral and organic soil types. The additional carbon stock in the litter layer in woodlands was estimated for Wales to be 4.6 MtC (Morison et al. 2012).

Table 2.1 Estimates of long-term equilibrium carbon stocks in living tree biomass in three example woodland types, for typical rotation ages

Soil type	Area (km^2)			GB mean soil carbon stock (tC ha^{-1})	Total soil carbon stock (MtC)	
	All Wales	Conifer forest	Broadleaf forest		Conifer forest	Broadleaf forest
Rankers and rendzinas	21	0	2	108	0.0	0.0
Brown earths	10,987	790	691	152	12.0	10.5
Podzols and ironpans	2,013	434	6	154	6.7	0.1
Surface-water gleys	3,476	92	183	167	1.5	3.1
Groundwater gleys	605	8	21	173	0.1	0.4
Peaty gleys/podsols	1,624	228	41	362	8.2	1.5
Deep peats	697	118	5	539	6.4	0.3
Total carbon stock (MtC)					**35.0**	**15.8**

As a comparison, soil carbon stocks in the topsoil (0-15 cm) of other UK vegetation types were compiled for the 2007 Countryside Survey (Table 2.2). They indicate that woodland topsoil carbon stocks are substantially higher than arable and horticultural land, but similar to other habitat types. However, this information is only for topsoil, and is likely to severely underestimate the total carbon stock which in many habitats can be substantial at depths up to 1m (Shi et al. 2013); it also averages across different soil types.

Other grassland soil carbon stock estimates are similar to those in the table: 97 tC ha^{-1} for rough pasture on a surface-water gley in Ireland (to 30 cm depth, compared to 102-205 tC ha^{-1} in 30-47 year-old spruce stands; Black et al. 2009) and 64.9 tC ha^{-1} for a permanent pasture in Denmark (to 25 cm depth, compared to 81 tC ha^{-1} in a 200 year-old deciduous stand; Vesterdal, Ritter and Gundersen 2002). A recent survey of soil carbon stocks in 180 English grasslands (Ward et al. 2016) under different management intensities illustrate the soil carbon stock at different depths: to 20 cm the average was 82.9 tC ha^{-1} (a little higher than the Countryside Survey figure for 15 cm depth), but 229 tC ha^{-1} over 1m depth. The latter is larger than the mean carbon stocks in woodland mineral soils (Table 2.1), but is an average across different soil types, and presumably includes organo-mineral and organic soils.

Table 2.2 Topsoil (0-15 cm) carbon stocks across broad habitat types in the Countryside Survey 2007. Data from Emmett et al. (2010).

Habitat type	***Mean topsoil C stocks (tC ha^{-1})***
Broadleaved, mixed and yew woodland	72.9
Coniferous woodland	81.4
Arable and horticulture	47.3
Improved grassland	67.2
Neutral grassland	68.6
Acid grassland	90.6
Bracken	84.7
Dwarf shrub heath	89.9
Fen, marsh and swamp	82.8
Bog	85.6
All habitat types	69.3

2.9.2 Soil carbon dynamics and change with afforestation

The soil carbon stock is the result of the balance between inputs of organic matter from dead plant material and rhizodeposition and the losses from decomposition, leaching and erosion. The bulk of the soil carbon content usually changes slowly over time (decades or centuries), although there are components (or 'soil fractions') that change more rapidly on time scales of months, years or decades.

Where land use and climate remain constant over an extended period, (many decades or centuries), the soil carbon stock tends to reach a dynamic equilibrium between the rate of carbon input from litter and roots, and loss from emissions of CO_2, leaching and erosion. (Some small amount of carbon may be lost as methane, CH_4, emitted from saturated, anaerobic soils, but although this is significant in the greenhouse gas balance, it is not significant in the carbon balance and most woodland soils are small sinks for CH_4). However, change of land use or climate and other environmental conditions like natural or pollutant deposition may lead to changes in soil carbon over a period ranging from several years to many decades (e.g. Poeplau et al. 2011), before any new equilibrium may be restored, if at all. The magnitude and time course of these changes in soil carbon depend on the details of the land use changes involved, the initial and final vegetation cover, the soil type and initial organic matter content, and the type of land management activities involved.

Afforestation of land previously under non-woodland vegetation usually results in a change in soil carbon stocks. These changes are usually slow and can be difficult to assess particularly given the high carbon stock and variability normally observed in soil carbon contents (e.g. Kravchneko & Robertson 2011; Upson et al. 2016). Nevertheless, there is a substantial literature on soil carbon changes with afforestation, although results vary considerably because of the range of soil and woodland types, prior land use and climate conditions. Some studies have only measured the upper part of the soil (e.g. 15, 20 or 30 cm) which may not capture the full change, particularly as trees root deeply and can input carbon through exudations and root death deep in the profile (Shi et al. 2013). Although mature woodland is generally associated with higher soil carbon stocks than many other land uses (Table 2.2), the initial impact of the change to woodland may involve a reduction in stocks, especially where the soil initially had a high level of organic matter, and dependent on any ground preparation practices used.

Several recent meta-analyses of afforestation studies in different environments and regions have been carried out (e.g. Laganiere et al. 2010; Li et al. 2012; Barcena et al. 2014). The latest review by Mayer et al. (2020) summarises the consensus as "*afforestation on former cropland may result in a significant increase in soil carbon stocks over 100 years. In some studies no new steady-state levels were reached within 100 years… while in others, modest decadal increases culminated in a ~15% net increase in soil carbon stock by the end of the first century. In contrast, following afforestation of grasslands mean soil carbon stocks may increase less, remain unchanged or even decrease*." When soil carbon stocks increase after tree planting the main change particularly early on is the accumulation of a deeper litter layer and carbon increases in the surface organic layers under the woodland, particularly in coniferous woodlands. The carbon accumulation in the mineral soil is usually slower, requiring several decades (Mayer et al. 2020). In a new study of woodlands established in central English and central Scottish agricultural areas, the rate of accumulation in the surface layers was 0.49 tC ha-1 yr^{-1} (Ashwood et al. 2019). The oft-cited long-term study of the natural establishment of an acid woodland on arable land at Rothamsted in SE England has produced a similar estimate of 0.38 tC ha^{-1} yr^{-1} (Poulton 2006; see also Section A1.3.2 in Appendix 1). In the Ashwood et al. study, woodlands approx. 110 years old had similar soil C stocks as woodlands older than 400 years, while a German study of beech woods (Leuschner et al. 2014) showed that 230-year-old stands had 47% more soil C than stands between 50 and 128 years old. These example studies emphasise that the timescale for carbon accumulation and thus soil carbon sequestration after afforestation is several decades to a century or more in temperate climates.

The long timescale of soil carbon stock changes is similar to or longer than the timescales of woodland stand growth and it is important to consider the impact on soil carbon of multiple cycles of tree planting and harvesting such as in high-productivity coniferous plantations (e.g. Zerva and Mencuccini 2005; Jarvis et al. 2009). In the British Isles much of the afforestation over the last century has been establishment of such conifer plantations in upland areas, where the cooler, wetter climate is frequently associated with organo-mineral and organic soils (peaty-gleys and deep peats). In order to establish stands successfully on these wet soils drainage and some type of soil cultivation is necessary, and frequently fertilisation. The resulting vegetation disturbance, lower soil moisture and higher aeration has resulted in some loss of the carbon in the peat layer in these soils (see reviews in Vanguelova et al. 2018 and Sloan et al. 2019). In deep peat soils the drainage results in consolidation and compression of the peat (which does not result in a loss of carbon) and oxidation (which does result in carbon loss). There may also be increased carbon loss in leaching (dissolved organic carbon (DOC)) and particulate erosion (particulate organic carbon (POC)) (Sloan et al. 2019). The rates of carbon loss that have been measured are highly variable but a recent review (Evans et al. 2017) to assess emission factors for greenhouse gas inventory purposes in the UK has suggested the total soil carbon loss for afforested deep peats should be estimated as 2.4 tC ha^{-1} yr^{-1} during the first rotation of trees. Best practice would be to follow the UK Forestry Standard (UKFS) for all woodland establishment, noting the differentiation made between deep and shallow peats. UKFS states *'...there is a specific presumption against the conversion of some priority habitats, such as deep peat or active raised bogs' and 'avoid establishing new forests on soils with peat exceeding 50 cm in depth and on sites that would compromise the hydrology of adjacent bog or wetland habitats.*'

In organo-mineral soils (peaty-gleys and podsols), tree planting and the associated ground preparation and any drainage will also cause some soil carbon loss. This is evident after the initial planting (i.e. the first rotation), and particularly in the first half of the rotation. However, recent evidence shows that initial losses can be recovered later in response to the substantial input of carbon from the tree growth and the increase in litter and organic surface layers (reviewed in Vanguelova et al. 2018 & 2019; Mayer et al. 2020). Using a chronosequence of 40 spruce stands planted on organo-mineral soils in Kielder Forest in N. England, Vanguelova et al. (2019) showed that there was a loss of carbon from the peat layer over the first 30 years of the first rotation. However, by the end of a second rotation (i.e. approx. 100 years after original afforestation) the input of carbon during the tree growth and from harvest residues had compensated so that total soil carbon stock was similar to adjacent unforested moorland (Vanguelova et al. 2019). This study also noted that although the major changes to soil carbon were in the organic layers, there was some evidence of a slow increase in carbon content of the deeper mineral layers, agreeing with some other studies that have suggested that after afforestation carbon may accumulate in lower layers and be in more stable forms combined with the clay fraction (e.g. Swain et al. 2010; Villada 2013). In summary, afforested drained organo-mineral soils are likely to be net carbon sinks, as carbon loss from the peat layer is compensated by accumulation of litter and fermentation layers. The net carbon change over any time period will depend on the forest stand growth and productivity and the number of planting-harvest-restock cycles.

2.9.3 Soil carbon stocks and forest management

As noted above, the extent of any ground preparation required to allow planting and successful stand establishment will have a large impact on the change in soil carbon stocks. The site preparation treatments used will depend upon the site conditions and the previous vegetation cover and will involve different degrees of soil disturbance (Mayer et al. 2020). The essential need is to improve tree seedling growth by reducing competition with existing vegetation and by improving soil moisture and nutrient availability. Although some ground preparation in the past has been intensive, the UKFS Guidelines are that managers should "minimise the soil disturbance necessary to secure management objectives, particularly on organic soils". Broadly, the degree of soil disturbance and probably soil carbon loss depends on the ground preparation methods, the intensity and the depth of peat layers (if any are present). The impact ranges from a minimum with hand planting and increases with various mechanised methods from scarification through to ploughing of different intensities which causes the greatest impact (see review by Mayer et al. 2020). Revisions to the guidance on ground preparation and cultivation are presently [Summer 2020] under discussion in Scotland, which could be helpful in planning future afforestation practice more widely. The guidance has examined the available evidence on the disturbance and likely loss of carbon with different ground preparation techniques and concludes that mounding is the preferred method on organo-mineral soils in order to minimise disturbance, while ploughing should not be used with peat layers of 30 cm or more deep. One point to note about the effect of soil disturbance on soil carbon stocks is that measurements of change only in the topsoil or upper layers (which are the most disturbed) may overestimate the relative effect on the whole carbon stock of the profile; in addition, some carbon from the upper layers may be redistributed deeper (see above).

When woodlands are managed, thinning of tree stands at intervals is a routine operation. As this reduces the number of stems and therefore tree carbon inputs to the soil it might be expected to reduce the soil carbon stock. It may also modify the microclimate under the stand which may increase decomposition rates, which could also reduce carbon stocks in the important litter layer. However, most studies report little or no effect on carbon stock of mineral soil (see review of Mayer et al. 2020). In some studies there is a short-term increase in soil carbon only for the first 2 years after thinning (see meta-analysis by Zhang et al. 2018), although this will depend on thinning intensity. It is likely that the effect of thinning on soil carbon stocks will be highly dependent on the climate conditions and stand productivity in a similar way to the effect of different tree densities. In high productivity, cooler conditions with high moisture availability, thinning impacts are probably only limited (provided soil is protected from physical damage during operations). Conversely, in low productivity, low density stands in warmer, dry conditions soil carbon stocks may be reduced by thinning.

Clearfell harvesting of a stand has several obvious effects that could have impacts soil carbon stocks. The above ground biomass is felled and while most stemwood is removed from site, some branches and foliage may be left on site. The material left on site contributes to the litter and will gradually break down over subsequent years, with some contributing to the soil carbon stock, and some decomposing. In addition, ground disturbance associated with the harvesting process and subsequent ground preparation for planting the next crop, will also lead to loss of soil carbon. Clearfell harvesting has usually been found to cause a reduction in soil carbon stocks, although the effect is not large. The meta-analysis of Nave et al. (2010) of studies from temperate forests found an average reduction of only 8% in the total carbon stock, although the loss in the litter layer averaged 30%. The recovery of carbon stocks may take several decades (Mayer et al. 2020). It might be expected that lower-impact harvesting methods such as selection, continuous cover, shelterwood, etc. would show less effect on soil carbon stocks than clearfelling, but the evidence is variable (Mayer et al. 2020).

After harvesting, the residues (poor quality stems, branches, twigs, leaves or needles and sometimes bark) may be removed, for example, for biomass energy generation. Tree stumps may also be removed, although because of the high soil disturbance this is usually only practiced in the UK for phytosanitary reasons. The review of Mayer et al. (2020) suggests that the influence of residue removal on soil carbon stocks is variable with both reductions and no effects being reported in different studies comparing residue removal treatments over decadal timespans. Usually, if an effect was found, it was a small reduction (5-15%) in soil carbon, and mainly evident in losses in the litter and surface organic layers (Achat et al. 2015; Mayer et al. 2020). Interestingly, on a peaty-gley soil in Kielder Forest, Vanguelova et al. (2010) found that removal of the spruce trees and their residues ('whole tree harvesting') led to an increase in soil carbon stocks in the second rotation after 28 years, which they attributed to reduced mineralisation of the soil organic layer after brash removal. However, there were negative effects on the balance of some soil nutrients, which would reduce growth and thus carbon sequestration benefits. Until there is more evidence, on a range of soil types, the influence of residue removal on soil carbon will have to be assessed for each site.

2.10 Non-CO_2 greenhouse gases and non-GHG impacts

2.10.1 Non-CO_2 greenhouse gases

The climate effects of this biological CO_2 sequestration need to be considered alongside the exchange of other greenhouse gases, particularly methane (CH_4) and nitrous oxide (N_2O), and the emission of volatile organic compounds (VOCs), which also have an influence on the atmosphere and climate. The factors influencing the GHG balance of woodlands and woodland management interventions are quite well understood, although some components are not well quantified (Morison et al. 2012). In brief, most woodlands on mineral soils are a small sink for methane, while woodlands on wet organic soils can be significant sources of methane, particularly deep peats with poor drainage.

N_2O emissions from woodlands are usually low, and much lower than from most agricultural land uses, although they may rise briefly during and after harvesting and thinning operations.

2.10.2 Albedo effects of afforestation

Albedo refers to the proportion of solar radiation reaching the surface of the earth that is reflected back to the atmosphere (and space). The absorption of solar radiation at the earth's surface results in a warming effect on the atmosphere. Hence, lower albedo implies more surface absorption and a bigger warming effect (a positive radiative forcing).

There is an extensive scientific literature about albedo, land cover and land-use change, because albedo can be a critical variable in quantifying the effect of land surface on the atmosphere and hence on climate.

Woodlands typically have lower albedo than short crops and grassland, and the difference is substantial for conifers, less so for broadleaf trees. The difference between conifers and broadleaves is partly a result of leaf colour, but also a consequence of the canopy structure, as denser, more branched canopies absorb more solar radiation, resulting in lower albedo. Climate regimes have a small influence, as in cloudy conditions the more diffuse radiation results in lower albedo, but the effect does not differ much for different land covers.

The change in land surface albedo after afforestation is sometimes raised as a counter-argument to the assumption of benefits of afforestation or woodland expansion in climate change mitigation. There is wide acceptance that more solar radiation is absorbed at the earth's surface in a forest compared to crops and grassland, resulting in a warming effect. However, there is uncertainty about the size of the effect. Published albedo values vary with methodology, sky conditions and the time period considered. For example, averaging daily albedo values over the year will overestimate albedo compared to a calculation based on the annual total radiation received and reflected (i.e. weighted for the peak solar input). Furthermore, albedo values measured at the surface can differ from those estimated from satellite instruments. Forest Research has undertaken a review of published albedo values relevant for British conditions and other temperate regions, also drawing on data from two woodland research sites managed by Forest Research. This review indicates that typical values are:

- 20%-25% for arable crops (but over a year including a bare soil period 15%-20% is more appropriate)
- 15%-21% for grasslands
- 13%-18% for deciduous broadleaf woodlands and 8%-12% for evergreen coniferous woodlands.

These results have been confirmed by a recent synthesis of data from the "FluxNet" international network of research sites (Cescatti et al. 2012) and by a large-scale analysis of satellite data (Leonardi et al. 2014). This indicates that the albedo difference will be approximately 5% lower for broadleaf woodlands and 10% lower for conifer woodlands, when compared to grassland. The review suggested a rather smaller difference for comparisons between woodlands and moorland, although the figure for that vegetation cover is not well defined. The exact difference will depend on vegetation differences and location. In continental and boreal climates, the presence of evergreen conifers can have a substantial effect on albedo in winter and spring compared to grass or cropped land when there is snowfall (unless the snow is held on the tree canopy), and can influence snowmelt timing (e.g. Manninen et al. 2019). However, Britain has a temperate oceanic climate, and the duration of lying snow is short (average 20-40 days in upland areas), is usually in mid-winter, and is declining as the climate warms (Brown 2019; Morison and Matthews 2016). The level of radiation input at those times is also relatively low. Hence, while the albedo effect is a component of the net climate change mitigation effect of afforestation, in British conditions the effect is unlikely to negate the cooling effect of carbon sequestration, and much smaller than the effect that has been estimated for boreal regions.

Several relatively simple models to estimate the effect have been used recently, and recent work on influence of land use change and afforestation (or deforestation) on albedo and radiative forcing confirms the relatively small effect in oceanic British conditions compared to boreal continental regions (Jones et al. 2015).

The woodland growth rate is key in assessing the balance between the warming effect of a reduction in albedo (from the original vegetation) and the cooling effect of enhanced CO_2 removal. At the extreme of very poor growth, then neither carbon uptake nor albedo change will be large. At the other extreme, very high growth rates will result in rapid carbon uptake and change in albedo. Considering variations with stand growth, the change in albedo may be expected to increase approximately linearly as the stand grows up to full canopy cover, after which albedo should then stay constant, whilst the rate of carbon sequestration will peak sometime after this, and then may decline. This implies that there may apparently be an optimum time for harvest, where the net benefit is maximal. However, the complete benefit also depends on the whole carbon uptake pattern including soil, and the subsequent uses of the timber including the mix of products, sizes and longevity. Some papers have looked at such 'time optimisation' of this balance (see e.g. Lutz and Howarth 2015; Lutz et al. 2016; Mykleby et al. 2017).

2.10.3 Other effects of afforestation on climate

Evapotranspiration

It should also be noted that alteration of albedo is not the only change that occurs after a land use change. In general, woodlands have higher rates of evapotranspiration (ET) than grasslands and crops. This is particularly the case in seasonally drier conditions, where the larger rooting depth of trees means that transpiration can continue for longer at a higher rate. Even in wet conditions, woodlands usually evaporate more water, because the larger canopies usually hold more rainfall than crops and grasslands, and this then evaporates readily during and after rainfall because of the better air flow. While the evaporation of more water does not change the overall *global* energy balance (because the water condenses elsewhere, releasing the same amount of heat), more moisture in the air can lead to more cloud formation, causing a cooling effect. Forest cover may even contribute to more local or regional rainfall, but whether changes to cloud and rainfall occur depends on local meteorological conditions. IPCC (2019b) reviewed modelling work on deforestation and afforestation impacts and stated: "*There is high agreement that forestation in North America or in Europe cools surface climate during summer time, especially in regions where water availability can support large evapotranspiration rates. In temperate regions with water deficits, the simulated change in evapotranspiration following forestation will be insignificant while the decreased surface albedo will favour surface warming*".

As noted earlier, a change in vegetation is likely to alter emissions of VOCs from vegetation which may affect the climate. More of these types of hydrocarbons are emitted into the atmosphere by plants than by human activity, particularly in warm conditions (Sharkey et al. 2008). Globally, most of this flux is the compound isoprene (C_5H_8), although there are many others. Conifer woodlands emit mainly monoterpenes ($C_{10}H_{16}$) with their characteristic scents (e.g. pinene). Broadleaved woodlands (dependent on species) emit isoprene in particular. Temperate tree genera that emit isoprene include oaks, poplars, willows, eucalypts, but there are many others, and many more in the tropics. However, at the species level there is apparently a wide diversity. In general, isoprene emission is associated with perennial plant species; crop species do not emit isoprene, nor do grasses. Therefore, replacing croplands with isoprene-emitting tree species will cause an increase in isoprene concentrations (e.g. Ashworth et al. 2012; Rosenkranz et al. 2015). VOCs are produced by leaves, stems, litter and soils; some may also be broken down by microbes on or in these surfaces.

Emitted VOCs can oxidise rapidly in the atmosphere and can result in the formation of tropospheric ozone (O_3) particularly where air pollution results in high NOx concentrations. In addition, VOCs also influence the atmospheric lifetime of the strong GHG methane (CH_4) through their reactions with the hydroxyl radical (OH), which otherwise forms a key mechanism for CH_4 removal. VOCs can also be involved in the formation of secondary organic aerosols (SOAs). These aerosols produce the blue hazes often seen in vegetated landscapes; monoterpenes are more effective than isoprene in blue haze formation. SOAs scatter or absorb solar radiation, so can have both direct cooling and warming effects, but their radiative properties are not well characterised. The present view is that they probably have a direct negative radiative forcing (i.e. cooling) effect (e.g. Scott et al. 2014), although analysis for the forthcoming IPCC 6th Assessment will provide a more up to date view. However, SOAs can then grow to form cloud condensation nuclei (CCN). Higher VOC amounts can contribute to faster aerosol particle and thus CCN growth, which may lead to cloud formation, so that they contribute an indirect negative radiative forcing. Few analyses of these complex interactions exist. In one, Spracklen et al. (2008) showed that in warmer conditions VOC production associated with boreal woodlands increased cloud and resulted in cooling (negative radiative forcing), whereas in colder conditions the snow-albedo influence dominated, resulting in warmer conditions with woodlands. More recent modelling studies have suggested the indirect cooling effect of aerosols is substantial (Scott et al. 2014 & 2018).

Primary biogenic aerosols

Woodlands and other vegetation also produce “primary biogenic aerosols” – plant debris, spores, pollen, soil dust etc., which may have a role in cloud formation and radiative forcing, although very little is known and it is unclear how the amounts or characteristics differ between vegetated land uses. Forest fires and other wildfires produce aerosols which can contribute a negative radiative forcing (Landry & Ramankutty 2015), but production of black carbon has a positive forcing effect.

While several papers have recognized the need to include the additional influence of differences in VOC emissions, changes in ET and the other effects described above, taking the next step to estimate their combined effects has hardly been attempted, and results will be highly dependent on location and specific circumstances.

2.10.4 Overall assessment of non-CO_2 and non-GHG effects

Current understanding of the combined impacts of woodland carbon sequestration and the factors considered in this section that arise from afforestation may be summarised *qualitatively* as follows:

1. Increased CO_2 absorption (carbon sequestration), resulting in cooling (well accepted)
2. Reduced albedo, reflecting less sunlight, thus contributing to warming (well accepted)

3. Increased VOC emission, so increasing aerosols and cloud formation, which reflects more solar radiation, and thus has a cooling influence (conflicting evidence)
4. Increased evapotranspiration, increasing cloud cover and contributing to cooling (well accepted).

The first two can be substantial effects, although the change in albedo is probably a small effect in British conditions, while the latter two are probably smaller, but much harder to quantify as they will depend on scale, species and local and regional climate. It should be noted that only the first effect is included in international emissions reporting and emissions reduction agreements.

Two recent papers (Luyssaert et al. 2018; Grassi et al. 2019) have considered the impacts of biophysical climate factors alongside those of CO_2 and non-CO_2 GHGs, but come to slightly different conclusions. They both agree that the effects of biophysical impacts of forest management options are complex, hard to quantify but can be of significant magnitude. The conclusion Luyssaert et al. draw is that using Europe's forests to achieve climate amelioration entails trade-off between carbon sink and biophysical effects and so "*Europe should not rely on forest management to mitigate climate change*". Grassi et al. are more nuanced and conclude that "*the net annual biophysical climate impact of forest management in Europe remains more uncertain than the net CO_2 impact*", however "*the seasonal and local impacts are less uncertain and more relevant*". Grassi et al. (2019) therefore conclude that the conclusions of Luyssaert et al. (2018) are premature and that countries should assess the local biophysical effects of different forest management scenarios which requires the development of accessible tools.

Grassi et al. (2019) consider that it is important to identify the country-specific mix of conserving and/or enhancing the sink and using more wood for energy and material substitution to reduce GHG emissions. Although biophysical effects may counteract the benefits achievable, Grassi et al. recommend that this should not deter forest management strategies that try to achieve these better quantified GHG benefits, or to remove disincentives to over-use of forest resources, potentially depleting the current carbon sink. It is, however, important that the biophysical effects of forest management are considered in national policies.

2.11 Wood product carbon dynamics

Wood products represent a reservoir (or "pool") of carbon originally sequestered from the atmosphere by woodlands. It follows that, when trees are cut down, not all of the carbon in the wood is released immediately. Rather, the release of the carbon back to the atmosphere is delayed, for the period during which the various wood products are in use (i.e. for the duration of the "service lives" of the different products). Even some wood used as fuel may be retained for 1 or 2 years before being combusted, whilst some wood products, such as construction timber, can remain in use for many decades. In terms of the carbon stock dynamics of woodlands, it is this role of wood products in potentially delaying the return to the atmosphere of carbon originally sequestered by trees that is critical. It may be noted that there would be no need to consider the role of wood products in woodland carbon stock dynamics, were it not for this role. (However, there are other impacts potentially associated with the utilisation of wood products which would still be important to consider, as discussed in Section 2.12.)

This understanding of the role of wood products in carbon stock balances is well understood and widely accepted but can lead to some confusion about the implications for the best use of harvested wood. For example, a conclusion frequently drawn is that harvested wood is best utilised for long-lived products in preference to short-lived products (see for example, Eriksson et al. 2007; Brunet-Navarro et al. 2017; Nabuurs et al. 2018). Whilst there is certainly some validity to such a notion, it is important to understand the full implications of pursuing interventions in the wood products sector such as suggested here. In this context, it must be recognised that the dynamics of carbon in wood products are fundamentally different to those of woodlands, litter and soil, as illustrated by the example below.

Figure 2-5, repeated from Matthews et al. (2007), shows a simplified representation of the stocks and flows of carbon in wood products which illustrates the potential impacts of human activity. Wood is assumed to be harvested from a woodland to maintain three wood products: a log cabin, a sled and a reserve of fuel logs. Each product is taken to contain an annual average stock of carbon in wood: 15 tonnes carbon (tC), 0.5 tC and 15 tC respectively (assuming fuel log stocks are replenished once a year and their consumption is linear through the year). Each product has an average service life (50 years, 1 year and 2 years, respectively), as determined by oxidation, attrition and, perhaps least understood, fashion. It follows by simple arithmetic that, to maintain these carbon stocks, each product requires an average annual in-flow of carbon in wood: 0.3 tC yr^{-1}, 0.5 tC yr^{-1} and 7.5 tC yr^{-1}, respectively, as shown in the figure. So long as the stock (i.e. the requirement for a particular product) is unchanged the average annual out-flow must be balanced by the average annual in-flow and, conversely, if the average annual in-flow is equal to the average annual out-flow, the stock is unchanged.

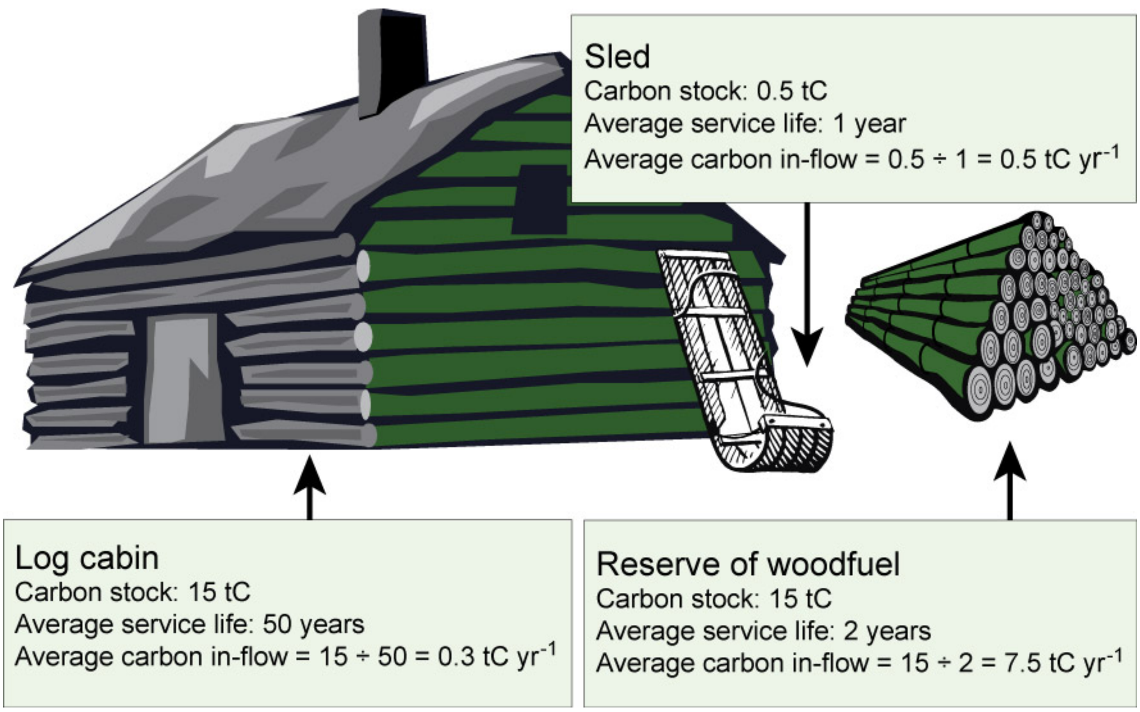

Figure 2-5 A log cabin, a sled, and a stock of fuel wood illustrate the relationships among carbon stocks, flows, and the service lives of wood products. After Matthews et al. (2007).

Figure 2-5 illustrates that there are a large variety of wood products and that the size of the stock and the length of the service life are independent decisions (e.g. it is possible to choose to have large stocks with short service lives, large stocks with long service lives, small stocks with short service lives), but that the decisions on stocks and service lives will determine the flow rates from forests to products and to disposal. Increasing the service life of a particular product may not increase the stock but may simply decrease the average annual in-flow and out-flow. Similarly, increasing the in-flow may simply decrease the service life (e.g. if the supply of a particular product exceeds demand, its price may drop to the point where people may replace the product more frequently than suggested by its full potential service life). The only way to increase the carbon stock in log cabins, sleds or fuel reserves is to increase the number of cabins or sleds or the size of the fuel reserves. When maintaining the log cabin, the sled and the fuel reserve, the average annual in-flow of carbon must not exceed the productivity of the woodland, otherwise the carbon stocks of the woodland would be depleted over time.

The above analysis suggests the following conclusions about the potential roles of wood products as a component of woodland carbon stock dynamics:

- Carbon stocks in wood products are increased (and additional carbon is sequestered) if more of a given wood product is used (and in use) at any time, compared with previous levels of use; this is true regardless of whether the product is relatively long-lived or short-lived.
- If the use of long-lived products is increased, this is likely to involve lower requirements for harvested wood when compared with increasing the use of short-lived products (because the long-lived products should require replacing less frequently), although this will also depend on other factors (e.g. the total amount of wood required to make different types of products). Lower requirements for wood imply less requirements for harvesting in woodlands, which will have consequences for woodland carbon stocks (see Sections 3.3 and 4.5).

These rather subtle conclusions about the role of wood products are not always recognised. Nevertheless, these conclusions still suggest a role for wood products as a pool of sequestered carbon, with a particular role for long-lived products. This suggests that consideration should be given to expanding the use of such products, for example in the construction sector. The importance of re-using, re-purposing and recycling wood products (regardless of their lifespans) is also apparent, as a way of extending the time with which carbon in harvested wood is retained out of the atmosphere in products.

The illustration in Figure 2-5 and the above analysis do not, however, tell the full story of the potential impacts of wood products on GHG emissions. The analysis does not describe, for example, how much fuel was used for the chain-saw that cut the logs or the truck that transported them; and it does not consider what sort of cabin would have been built if trees were not harvested to produce logs or how the cabin would be heated in the absence of fuel wood (see Section 2.12).

2.12 Cross-sectoral impacts of wood products

As discussed in the previous section, when a decision is taken to manufacture a certain product from wood, this has consequences for the carbon stocks and stock changes in the wood product carbon pool (and also for carbon stocks and stock changes in the woodlands where the wood is harvested to manufacture the product). However, this does not tell the full story of the potential impacts of such a decision on GHG emissions. A decision to make and use a wood product also implies that:

- The option of reducing (or avoiding) the use of the particular product has been discounted
- The option of manufacturing the product from some other material has not been pursued.

These choices also have impacts on GHG emissions.

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

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

All of these possible consequences imply changes in GHG emissions.

The potential impacts on GHG emissions of marginal changes in the levels of the production of wood products are usually estimated by comparing the GHG emissions of an alternative non-wood product with those of the wood product, and expressing the result as a ratio with respect to a unit quantity of wood product, so as to derive an “emissions displacement factor”. Hence, this is calculated as:

$$\text{Emissions displacement factor} = \frac{\text{GHG emissions to manufacture equivalent non-wood product} - \text{GHG emissions to manufacture a given wood product}}{\text{Mass of wood in wood product}}$$

(Note that the formulation of the above equation assumes that the non-wood product does not include any wood as a component of its manufacture.)

Generally, the GHG emissions in the above equation are expressed in units of tonnes carbon equivalent (tC-eq.) and the mass of wood is expressed in units of tonnes carbon (i.e. the carbon content of the wood composing the product, with units tC). Thus, emissions displacement factors are frequently reported with units of tC-eq. tC^{-1}.

For example, an emissions displacement factor for a wood product of 1.5 tC-eq. tC^{-1} would imply that:

- Either 1 tonne carbon of “additional” production of a specified wood product leads to the displacement (or “saving”) of 1.5 tC-eq. of GHG emissions that would have been associated with the manufacture of an equivalent non-wood product
- Or 1 tonne carbon of “reduced” production of a specified wood product leads to an increase in GHG emissions of 1.5 tC-eq. as a consequence of the increased manufacture of an equivalent non-wood product.

A key reference in the estimation of such emissions factors has been the review of Sathre and O’Connor (2010), which has suggested a generic value for an emissions displacement factor for wood products of 2.1 tC-eq. tC^{-1}. However, a more recent review (Leskinen et al. 2018), covering a wider range of wood products, reports a lower value of 1.2 tC-eq. tC^{-1}. Leskinen et al. suggest that the main reasons for the differences are the inclusion of a greater number of studies and more diverse products in the more recent review, and methodological differences between individual studies. Both reviews note that estimates of GHG emissions displacement factors produced by different studies show considerable variability.

GHG emissions factors for solid woody biomass energy products (e.g. wood chips and pellets) are generally lower than the generic value for material products suggested above. Calculations based on data and results presented in Matthews et al. (2014b, see Table 1.1) and Matthews et al. (2015, see Tables 5.3 and 5.4) suggest GHG emissions displacement factors for wood pellets in the range 0.4 to 1.1 tC-eq. tC^{-1}. The variability in the factor depends on the type of fossil fuel displaced and the efficiency of the wood pellet supply chain.

It is very important to highlight that the GHG emissions factors for wood products discussed in this section do not include any allowances for impacts on carbon stocks or carbon stock changes in woodland areas, as a result of increased or decreased harvesting associated with changes in the supply of products. When net CO_2 emissions occur as a consequence of carbon stock changes in woodlands, in turn resulting from management for increased wood production, this is frequently referred to as a “carbon debt” (see for example Searchinger et al. 2009; Zanchi et al. 2010). Such impacts on carbon stock changes are also relevant when considering the impacts of changes in the supply of material wood products. In general, when assessing different options for woodland management in support of climate change mitigation efforts that involve changes in the levels of supply of wood products, it is necessary to allow for these impacts in addition to those represented by simple GHG emissions displacement factors for wood products.

A further note of caution must be sounded with regard to assumptions about GHG emissions displacement achieved through the use of wood products, including wood fuel. It may be possible and defendable to make reasonable assumptions about the kinds of commodities that wood products displace under current conditions (e.g. fossil fuels, grid electricity and products made from steel, plastic or concrete using current manufacturing processes). However, this becomes more challenging the further projections are made into the future. Assuming that efforts are made to decarbonise across all economic sectors, it may be expected that the GHG emissions associated with the manufacture of non-wood products will decrease in the future. Furthermore, the consumption of fossil fuels is likely to decline significantly in the future, assuming that fossil fuel reserves will become depleted, if for no other reason. This highlights the very high uncertainty that should be attached to estimates of GHG emissions displaced by wood fuel and wood products in the longer term. Amongst the implications of this point, this emphasises a requirement for the forestry and wood processing sectors to minimise GHG emissions from woodland management and wood product supply chains (including those contributed by carbon stock changes in woodlands).

2.12.1 GHG emissions at end of life of wood products

For material wood products, GHG emissions on disposal at end of life, including those related to the release of the carbon physically contained in the wood, can be significant and show strong dependence on the approach to disposal, as illustrated in Figure 2-6. The results in Figure 2-6, which are repeated from Matthews et al. (2014a), illustrate the GHG emissions arising from the disposal of wood products supplied from a managed even-aged coniferous woodland representative of UK conditions, considering forest management and production over a period of 100 years. The harvested wood is assumed to be used principally to manufacture structural timber and particleboard. Emissions in the form of non-CO_2 GHGs (notably methane) are included, where relevant.

The results in Figure 2-6 show annualised GHG emissions from disposal of wood products supplied from a notional 1 hectare of woodland over the 100 year period, and so have units of tCO_2-eq. ha^{-1} yr^{-1}.

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-eq. ha^{-1} yr^{-1}) or for Combined Heat and Power (CHP) generation (about 4 tCO_2-eq. 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-eq. ha^{-1} yr^{-1}). Estimates of methane emissions from disposal of wood to landfill are highly uncertain. It should also be noted that energy recovery from landfill gas is frequently but not universally practiced.

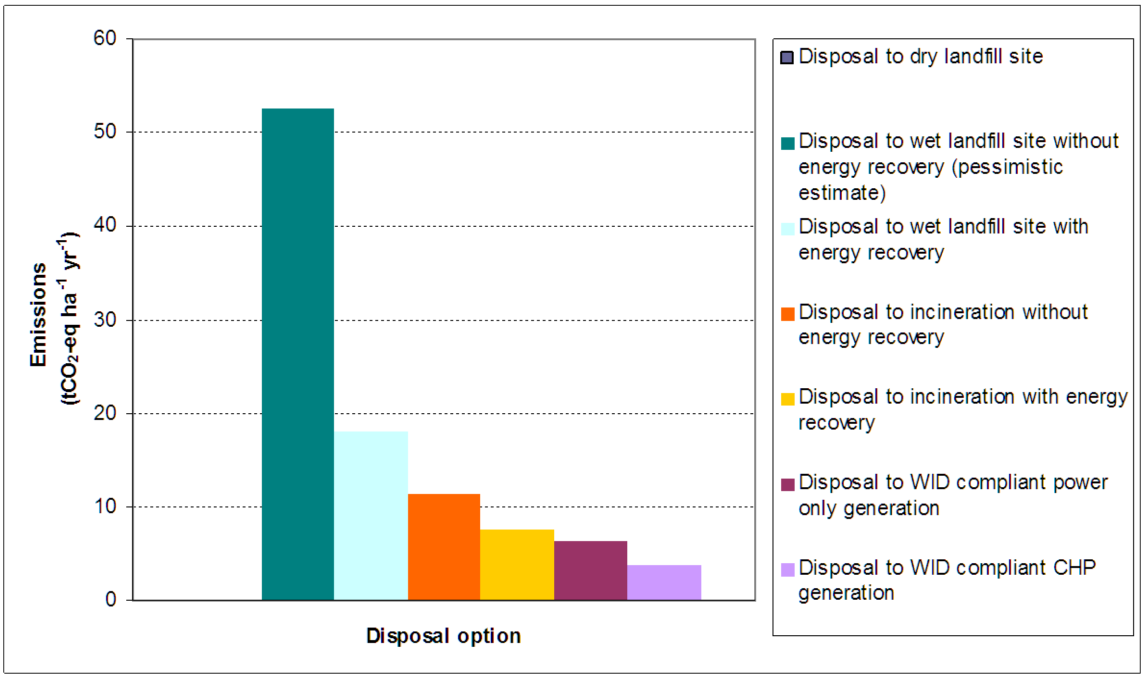

Figure 2-6 Examples of GHG emissions associated with disposal of solid wood products at end-of-life. The results are based on the same scenario involving wood supply from a coniferous woodland typical of UK conditions, considering a period of 100 years. Results are shown for different disposal options. Emissions resulting from disposal to dry landfill are small and do not register in the graph. After Matthews et al. (2014a).

2.13 Sequester or substitute?

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

1. As is clear from most of the discussion in this annex and from the additional information in Appendix A1, the carbon stocks in woodland biomass, litter and soil represent a natural reservoir of carbon sequestered from the atmosphere. In principle, this process of carbon sequestration could be “managed”.
2. As discussed in Sections 2.11 and 2.12, woodland biomass can be harvested and used to manufacture a range of solid wood products (e.g. sawn timber, wood-based panels, card and paper) which also represent a reservoir of sequestered carbon (although, arguably, a mainly temporary reservoir) and can be used in place of (i.e. to “substitute” for or “displace”) generally GHG-intensive non-wood materials; wood harvested for use as fuel can replace fossil energy sources.

Several critical issues arise from the fact that the management of woodlands can make these two contributions. First of all, it follows that woodlands can be managed to conserve or enhance carbon stocks and/or to produce wood products to displace GHG-intensive materials and fossil fuels. There are certain specific situations in which efforts to increase the supply of wood products can also involve increased carbon stocks (see Section 3). The most obvious example is when non-woodland with low initial carbon stocks is converted to woodland through afforestation activities.

In many situations, however, there is a trade-off in terms of carbon stocks (and resultant GHG emissions) between activities aimed at extracting wood to produce wood products, and activities aimed at sustaining or enhancing carbon stocks within woodlands. Essentially, attempting to enhance one of the twin contributions of woodlands to climate change mitigation tends to act in antagonism to the other function, and there is consequently a trade-off between them.

When considering options for the management of woodland areas to increase the supply of wood products whilst sustaining carbon stocks, it may be appropriate to consider the potential for a "package" of measures undertaken in a population of stands on a site-by-site basis across large scales (Nabuurs et al. 2008, 2018). This might involve, for example, a systematic and coordinated programme of management across woodland areas involving a combination of increased harvesting in some areas, conservation or enrichment of carbon stocks in other areas, and possibly also the creation of new woodland areas. Currently, there has been limited exploration of the potential for developing such a package of measures for a significant country or region. Such an exercise would require evidence on the estimated overall impacts on GHG emissions of different options for woodland management, relevant for the region or country. This is the main purpose of the assessment in Sections 3 and 4 (see also Sections 5.1 and 5.2).

2.14 Market-mediated (indirect) land-use change (iLUC)

The phenomenon of iLUC has been presented by some scientists and commentators as a crucial influence on the overall GHG impacts of certain land use and land management options aimed at mitigation of GHG emissions (Searchinger et al. 2008; Fargione et al. 2008; Al-Riffai et al. 2010; Kim and Dale 2011; Pena et al. 2011). The focus of the discussion tends to be on the agriculture sector and in particular the potential impacts of converting land used for production of food over to production of biomass crops for energy use. Questions regarding iLUC can also occasionally arise when considering woodland creation activities.

Although potential risks related to iLUC are recognised in the forest sector, iLUC is identified primarily as an issue in the agriculture sector and is, therefore, not regarded as a key subject for consideration in this annex. The issue of iLUC is most likely to arise in scenarios involving land-use change as an essential theme, such as a very significant programme of woodland creation. It may be worth noting that an operational methodology for implementing such measures so as to avoid risks of iLUC has been proposed in LIIB (2012).

2.15 Definition of carbon sink

At several points in this annex so far (Sections 2.5 and 2.7), it has been stressed that certain statements depend on how the carbon sink associated with woodlands is defined. The achievement of substantive GHG emissions reductions, and potentially net zero emissions, requires a very clear and commonly understood definition of the carbon sink associated with woodland. It is equally critical to understand how different types of climate change mitigation activities can affect carbon sinks and losses in woodland. Equally, an appreciation is needed of how efforts to maintain or enhance woodland carbon sinks can interact with carbon exchanges and emissions associated with products derived from biomass harvested from woodlands.

The sinks, exchanges and emissions of carbon associated with woodlands are illustrated in simplified form in Figure 2-7, which is repeated from Fritsche et al. (2020). As an important example of simplification, the illustration does not represent production, trade and consumption of biomass-derived products between different countries. Figure 2-7 illustrates how the role of woodland carbon in climate change mitigation can be considered as exchanges of carbon between the "woodland system" and the atmosphere. These exchanges can occur *directly* between the trees, litter and soil of woodlands and the atmosphere, or *indirectly*, when carbon in the biomass of wood products is combusted or decays or is disposed of at end of life. These emissions from wood products are sometimes referred to as "biogenic carbon emissions". This term can be defined as referring to *carbon released as carbon dioxide or methane from combustion or decomposition of biomass or biobased products*.

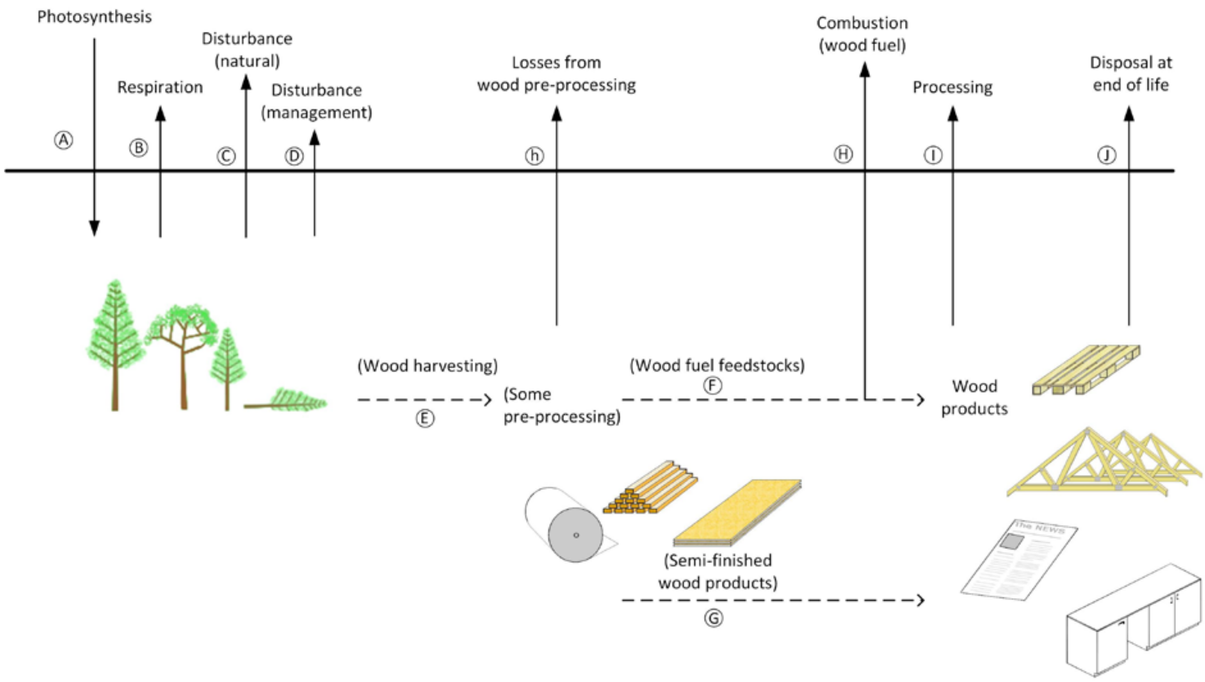

Figure 2-7 Simplified illustration of carbon exchanges (sinks and sources) associated with vegetation (woodlands in this example) and products derived from harvested biomass. The net carbon sink/source consists of the combined exchanges of carbon between vegetation, biomass products and the atmosphere indicated by the sold black arrows crossing the black system boundary line. Other transfers of carbon (dashed lines) are represented implicitly. After Fritsche et al. (2020).

According to the representation in Figure 2-7, the *direct* net carbon sink or source of woodland consists of the combined balance of carbon inputs from photosynthesis (A, positive contribution), and losses from respiration and disturbance (B, C and D, negative contributions), that is:

Direct woodland carbon sink/source = A – B – C – D (Equation 2.1)

Note that the disturbance term C represents losses from tree mortality whilst the term D represents the decay of waste wood left behind after harvesting activities. However, losses of carbon in the form of wood extracted to make products are not included in the balance defined by Equation 2.1. This way of measuring the woodland carbon sink is very similar to how the forest sector monitors forest growth and productive potential, using a metric known as "net increment". Net increment is defined in a quite similar way to Equation 2.1, although not identically. Strictly when calculating net increment, losses in the form of waste wood left behind after harvesting, represented by the term D, are not included. Net increment is usually expressed in units of stem volume, rather than tonnes carbon in trees, litter and soil.

The *overall* balance of all the *direct* and *indirect* carbon exchanges associated with woodland and harvested products consists of the combined exchanges of carbon between the atmosphere, vegetation and products, as illustrated in Figure 2-7 by the arrows crossing the black system boundary line, that is:

Overall carbon sink/source = A – B – C – D – h – H – I – J   (Equation 2.2)

Exchanges of carbon between components of the system in Figure 2-7 (woodlands, wood feedstocks, wood products), represented by dashed lines are implicitly linked to the carbon exchanges to and from the atmosphere. The introduction of changes to woodland management activities, and decisions about the utilisation and disposal of different harvested wood products can change the magnitude of the direct net carbon sink/source of woodland and can also lead to changes in all of the carbon exchanges shown in Figure 2-7 and Equation 2.2. As a relatively simple example, "intensifying" the management of woodlands to produce more biomass for use as an energy source will increase the magnitude of the term H in Equation 2.2, but will also have a variable impact on the contribution made by direct woodland carbon sink/source (Equation 2.1). In some situations, a direct woodland carbon sink may be reduced by increased woodland management including harvesting but changes in forest management can also be designed to ensure that the sink is enhanced. A common complication can be that the impact of intensified woodland management on the direct net carbon sink can be variable and time-dependent, e.g. a net emission (or sink reduction) initially followed by an eventual enhanced net sink.

If the goal of climate change mitigation is to be achieved, ideally, as a *minimum requirement*, the *overall* carbon balance as illustrated in Figure 2-7 and defined in Equation 2.2 must be at least zero and ideally a net sink. Hence, ensuring that forest management sustains or enhances the *direct* woodland carbon sink (Equation 2.1) is not a sufficient test for guaranteeing that the carbon impacts of forest management are consistent with the goal of climate change mitigation.

It is very important to recognize that the definition of the carbon sink/source associated with woodlands, as illustrated in Figure 2-7 and expressed in Equation 2.2, is not universally understood or accepted by all stakeholders. Other definitions are possible and different stakeholders can refer to different definitions when discussing the role of the woodland carbon balance in climate change mitigation, which can lead to confusion and misunderstanding.

The representation of the carbon balance associated with woodlands in Figure 2-7 may be referred to here as the "atmospheric exchange representation". An important example of an alternative way of representing the carbon balance of woodlands is illustrated in Figure 2-8. This can be referred to as the “sectoral exchange representation”. This alternative way is significant because it is the approach currently applied as part of reporting GHG emissions in national GHG inventories under the UNFCCC. It is also the representation frequently used by forest carbon researchers and analysts.

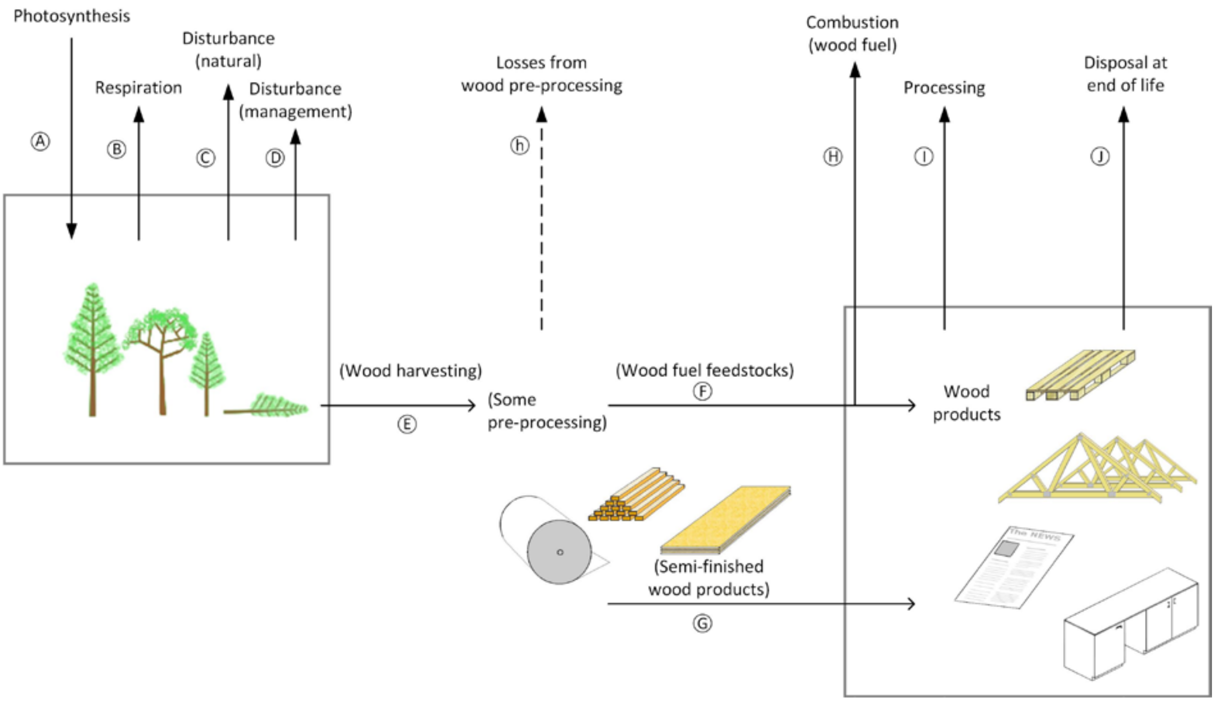

Figure 2-8 Simplified illustration of carbon exchanges (sinks and sources) associated with vegetation (woodlands in this example) and products derived from harvested biomass according to an alternative scheme. The net carbon sink/source consists of the combined exchanges of carbon between vegetation, biomass products and the atmosphere indicated by the sold black arrows crossing the grey system boundary boxes. However, the flows of carbon directly associated with woodlands, and those associated with carbon in wood products, are represented distinctly (i.e. by considering carbon exchanges across the boundaries defined by the two separate boxes). Some transfers of carbon (dashed lines) are represented implicitly.

As with Figure 2-7, Figure 2-8 is simplified, notably by not showing production, trade and consumption of harvested biomass between different countries. In Figure 2-8, the overall net carbon sink or source is still ultimately represented as the exchanges between the atmosphere and the woodland-wood products system, with the same result as given by Equation 2.2. However, the exchanges of carbon directly associated with woodland, and those associated with harvested biomass and products, are treated as two distinct components, as represented by the system boundaries shown as two grey boxes.

According to this “sectoral exchange representation”, the net carbon sink or source associated directly with woodland is represented by the flows of carbon (black arrows) across the system boundary line of the left-hand grey box in Figure 2-8. This is calculated as

Direct woodland carbon sink/source = A – B – C – D – E (Equation 2.3)

In other words, the net carbon balance of the woodlands is defined as the net sequestration (or loss) of carbon in woodlands resulting from biological and natural processes (the balance between A, B and C), minus all the losses arising from the harvesting and extraction of biomass for utilisation for products (D and E). Hence, it is evident that the carbon sink/source directly associated with woodland is defined differently in the two representations of carbon exchanges in Figure 2-7 and Figure 2-8.

Carbon exchanges associated with the fate of harvested wood are represented distinctly from the woodland carbon sink/source. The net carbon sink or source associated with harvested wood is calculated as:

Wood product carbon sink/source = F + G – H – I – J (Equation 2.4)

Because losses of carbon from woodlands as a result of harvesting and extraction of products are included in the calculation of the direct woodland carbon balance, i.e. as an *output* from the “woodland system box” (E), it is necessary to allow for the input of carbon in products into the “wood products system box” (F and G). Otherwise, losses of carbon associated with wood products (energy and materials) would be double counted, the first time as losses from (exchanges of carbon out of) the woodland system box (E) and a second time as exchanges of carbon out of the wood products system box (H, I and J).

Emissions from losses of wood during pre-processing of raw harvested wood into semi-finished wood products (h) are included implicitly, as the difference between the losses from the woodland system box (E) and the gains into the wood products system box (F and G).

The ultimate result for the *overall* balance of all the *direct* and *indirect* carbon flows associated with woodland and harvested products is the same under the “sectoral exchange representation” (Figure 2-8) as for the “atmospheric exchange representation” described in Figure 2-7, i.e. in principle Equation 2.2 still applies. In practice, under the “sectoral exchange representation”, Equation 2.2 is decomposed into the two contributions given in Equations 2.3 and 2.4, which involves the introduction of the terms additional E, F and G.

2.15.1 The challenge of balancing carbon sinks and sources

When considering options for vegetation (including woodland) management to mitigate climate change, it is important to recognise the likely saturation of land-based carbon sinks, even if this may occur in the very long term. This point appears to have received relatively little attention in discussions of how to meet a target of net zero emissions, for the second half of this century and thereafter. The implication appears to be that, at some point, there must be very deep cuts in GHG emissions or significant deployment of other technological measures introduced to sequester carbon. This situation is highlighted by the current approach to defining and reporting vegetation carbon sinks under the UNFCCC (see preceding discussion of the “sectoral exchange representation” and Figure 2-8). Part of the way of addressing this (longer-term) problem may be to view the vegetation carbon sink in a different way, i.e. define it differently. It is already the case that some stakeholders in the agriculture and forestry sectors, and some researchers, habitually refer to the vegetation carbon sink as consisting of just the terms A – B – C as suggested by the representation in Figure 2-7, i.e. literally the net sink of carbon into vegetation, before subtracting losses of carbon resulting from harvesting of biomass (D and E). If the carbon sink is defined in this way (or as something very similar, e.g. A – B – C – D), then it is possible to argue that vegetation carbon sinks can be sustained indefinitely – indeed this is particularly true for managed vegetation. However, this does not alter the need to achieve an overall balance, and ideally net sequestration, as expressed fully by the overall carbon balance as described in the complete versions of both representations as illustrated in Figure 2-7 and Figure 2-8 and defined fully in Equation 2.2. Given this aim, the equation implies that several of the terms contributing losses to the carbon balance in Equation 2.2 (e.g. from combustion of biomass energy sources or the disposal of biomass products at end of life) need to be significantly reduced or mitigated in some way. The problem is essentially the same as already discussed, but the different approach to describing and representing the problem may assist stakeholders of gaining a common understanding of the challenges involved.

2.16 Misunderstandings arising from different representations of the woodland carbon balance

The potential complexity of woodland and wood product carbon cycles, and the different ways of representing them, as discussed in the previous section, can lead to misunderstandings and misleading conclusions about how best to work with woodlands to mitigate climate change. These are fuelling debates and sometimes arguments amongst stakeholders, who occasionally have arrived at opposing positions on this subject. Occasionally, this appears to be a result of partial understanding of the carbon impacts of possible interventions involving woodland creation and/or management. Some of the claims consequently being made by stakeholders could potentially lead to misguided or significantly sub-optimal policies addressing woodland management and climate change mitigation. It is important to identify the main examples of misleading conclusions currently in circulation and to clarify where evidence may support alternative, qualified or modified conclusions. Key cases are discussed below and, in each case, an attempt at clarification is offered. Six examples are considered:

1. “Managing trees on rotations that maintain fast growth will maximise woodland carbon sequestration” (Section 2.16.1)
2. “Avoiding tree harvesting will maximise woodland carbon sequestration” (Section 2.16.2)
3. “Allowing land to regenerate to a wilderness-woodland by natural succession is the best option for woodland creation to mitigate climate change” (Section 2.16.3)
4. “Bioenergy produced from woodlands (wood fuel) is carbon-neutral” (Section 2.16.4)
5. “Bioenergy produced from woodlands (wood fuel) releases more CO_2 emissions than burning coal” (Section 2.16.5)
6. “Wood products (including wood fuel) are carbon-neutral as long as the carbon harvested from woodlands in harvesting does not exceed the woodland carbon sink” (Section 2.16.6).

The discussions of these cases are supported by example results illustrating the development of woodland carbon stocks, either included directly or provided in Appendix A1.

2.16.1 “Managing trees on rotations that maintain fast growth will maximise woodland carbon sequestration”

This idea comes from a consideration of the characteristic pattern of growth and carbon sequestration in a stand of trees, as described in Section 2.5 and illustrated in Figure 2-4. It is evident from Figure 2-4 that (in the case of this example) managing the woodland on rotations between about 45 and 50 years will keep the stand of trees young and maximise the time the trees are growing through their “full-vigour” phase, i.e. their period of highest growth rate, averaged over the rotation. It is true that such a form of woodland management should keep the mean rate of CO_2 absorption by the woodland close to the maximum possible rate.

When considered in terms of the “atmospheric exchange representation” system diagram in Figure 2-7, in effect, managing the woodland on these relatively short rotations to maintain a high increment ensures that the balance between photosynthesis (A) and respiration (B) results in a relatively high carbon sink. Actively managed stands are also likely to be protected against natural disturbance events and incidents of tree mortality, or otherwise there is likely to be active remediation of the impacts of such events. Hence, losses of woodland carbon from these processes (C in Figure 2-7) are likely to be minimised or at least reduced. However, whilst it is generally true that the type of management considered here will ensure a relatively strong and continuous carbon sink into the woodland system, it is also clear from Figure 2-7 that carbon is also *lost* from the system as a result of tree harvesting (D and E in Figure 2-7).

The idea of an optimal carbon sink thus comes from focussing on the carbon sink directly associated with woodland as defined according to the “atmospheric exchange representation” in Figure 2-7 and by the terms A – B – C. If the alternative “sectoral exchange representation” in Figure 2-8 and Equation 2.3 is considered, it is apparent that, sooner or later, this net carbon sink into the woodland (A – B – C) will be balanced by losses from harvesting (D and E).

If the woodland management is consistent with the principle of sustainable yield (in terms of harvesting and wood production), the overall result is a finite carbon stock sequestered in the trees forming the woodland, which neither increases nor decreases in a fully established woodland (see Appendix A1, in particular Sections A1.4 to A1.6). It follows that the accumulation of carbon stocks in woodlands eventually “saturates”, as has been discussed in Section 2.7. This is further illustrated in Figure 2-9, which shows the dependence of the long-term equilibrium carbon stocks in trees on the rotation applied and the thinning treatment, for three example woodland types:

1. Fast-growing Sitka spruce (yield class 24)
2. Moderately-growing Sitka spruce (yield class 12)
3. Slow-growing oak (yield class 4)

Two results are shown for each woodland type, based on assuming the woodlands are regularly thinned or left unthinned. The estimates of long-term carbon stocks in Figure 2-9 are taken from the UK Woodland Carbon Code Carbon Calculation Spreadsheet (UK Woodland Carbon Code 2020).

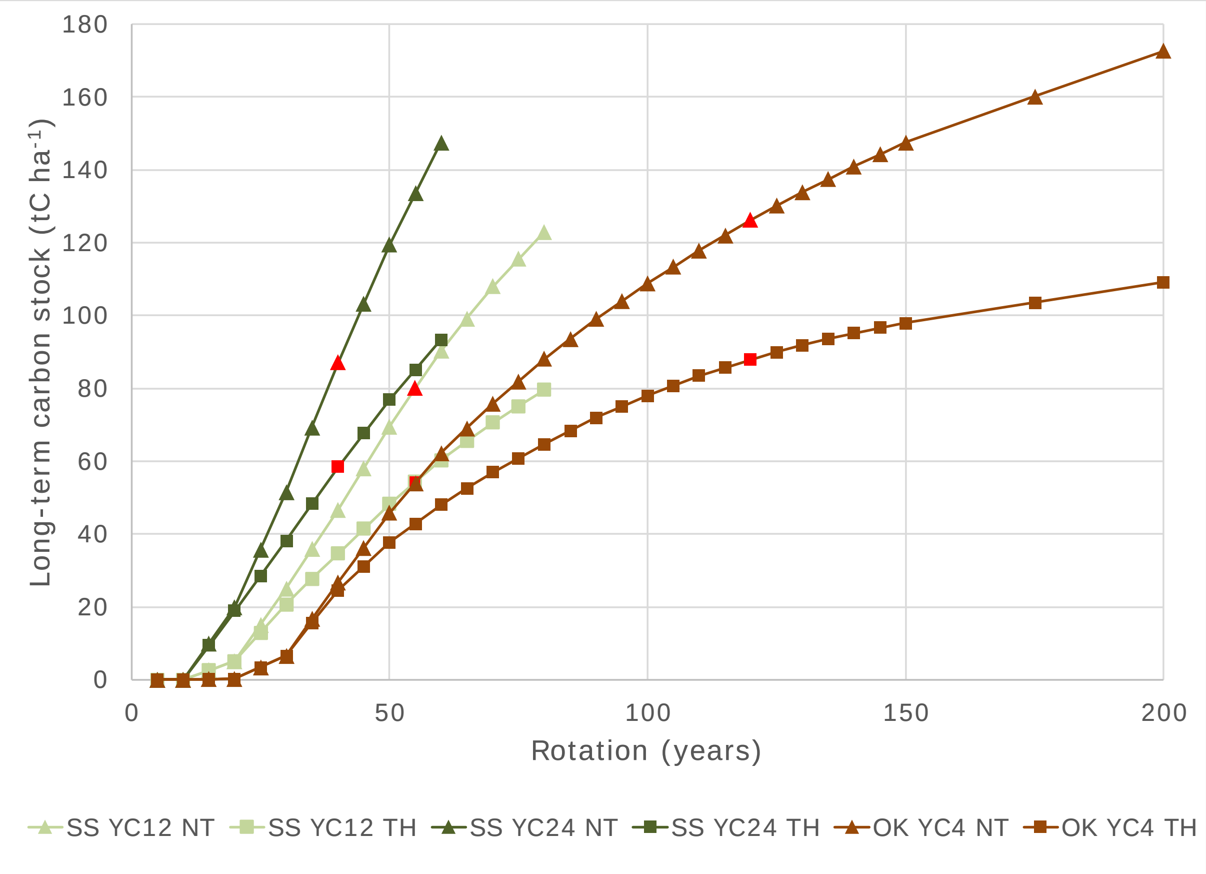

Figure 2-9 Examples of the dependence of long-term equilibrium carbon stocks in trees forming a woodland. Three woodland types are considered: moderately-growing Sitka spruce (SS YC12), fast-growing Sitka spruce (SS YC24) and slow-growing oak (OK YC 4). Results are shown for stands managed with regular thinning (TH) and left unthinned (NT). The bright red symbols in each trajectory highlight results for typical rotations for each woodland type. Source: results from "Clearfell_Max_Seq_Values" worksheet in Woodland Carbon Code Carbon Calculation Spreadsheet Version 2.2, 9th January 2020 (UK Woodland Carbon Code 2020).

The positive correlation between the long-term equilibrium carbon stock in woodlands and the applied rotation age is apparent in Figure 2-9.

The results for the Sitka spruce stands in Figure 2-9 are truncated to 60 years (yield class 24) and 80 years (yield class 12) because longer rotations are likely to be unrealistic in even-aged stands of this type (for example, very old even-aged stands of spruce are likely to become subject to high risk of storm damage). Typical rotations in stands of fast-growing Sitka spruce are around 35 to 45 years, with rotations around 50 to 65 years typical for moderately-growing Sitka spruce. Rotations in managed even-aged stands of oak (if they are managed in this way at all) are likely to be much longer, running from at least 80 years, potentially up to 200 years and beyond. A typical rotation might be 120 years.

In Table 2.3, results for long-term equilibrium tree carbon stocks from Figure 2-9 are repeated for a range of rotation ages relevant for the three woodland types. Some important differences are apparent, notably that equilibrium carbon stocks are lower in thinned woodland compared with unthinned woodlands, as would be expected (see Appendix A1, Section A1.6). However, it is also apparent that if the results for thinned stands or unthinned stands for the three different woodland types are compared, the ranges in estimates of long-term carbon stocks for all three woodland types overlap, suggesting that the magnitudes of the carbon stocks sequestered in the three types of woodland are comparable.

Table 2.3 Estimates of long-term equilibrium carbon stocks in living tree biomass in three example woodland types, for typical rotation ages

Woodland type	*Management*	*Rotation range (years)*	*Long-term carbon stock range (tC ha^{-1})*
Sitka spruce YC24	Without thinning	35-45	69-103
	With thinning	35-45	48-68
Sitka spruce YC12	Without thinning	50-60	80-99
	With thinning	50-60	54-65
Oak YC4	Without thinning	80-150	88-148
	With thinning	80-150	65-98

The implications of the results in Table 2.3 are that:

- The relatively fast rates of carbon sequestration in fast-growing woodlands are counterbalanced by their management on shorter rotations
- The relatively slow rates of carbon sequestration in slow-growing woodlands are compensated for by their management on longer rotations (if such stands are managed on rotations at all)
- As a consequence, carbon stocks in woodlands composed of different tree species with different growth rates may be quite similar, because of the ways in which woodland management is adapted to reflect the tree species and growth rates involved
- It may be noted that, when creating new woodlands, the long-term carbon stock is achieved most rapidly in faster-growing stands.

It is also apparent from these results that the details of woodland management (decisions about thinning and rotation ages) can have a pivotal influence on levels of carbon sequestration and ultimate carbon stocks in woodlands. The potential for measures in support of climate change mitigation based on choices amongst a range of woodland management options is assessed in Sections 3 and 4.

The analysis of the carbon impacts of fast-growing woodlands presented so far raises two further issues in the case of productive fast-growing woodlands:

1. Is there a significant additional contribution to carbon sequestration in the form of carbon retained in wood products supplied from the woodlands?
2. Does the potential role of wood products supplied from the woodlands in avoiding (displacing) more GHG-intensive non-wood products make such woodlands the most effective option for climate change mitigation?

Considering the first of these issues, it is true that wood products can represent an additional reservoir of “off-site” carbon associated with woodlands managed for wood production. However, assessments of the additional carbon sequestered in wood products indicate that this can be significant (see for example Appendix A1, Sections A1.4 and A1.8). However, in general, allowing for these overall carbon stocks (woodland plus products) does not suggest a significantly different conclusion to that reached above when comparing woodland management options. (Note that, in the case of the results in Figure 2-9 and Table 2.3, a contribution from wood-product carbon stocks would need to be added in all of the cases considered, so these contributions will tend to cancel out, for example when comparing carbon stocks for different rotations).

There are several factors that limit the additional contribution made by carbon sequestered in wood products. Two main factors are relevant when considering the relative contributions made by wood products for different woodland types:

1. Generally, wood products do not last forever, even if recycling, re-use and landfilling are taken into account. As a result, a point is eventually reached when the accumulation of carbon stocks in wood products supplied by an area of woodland is balanced by the losses of carbon from wood products that decay, are destroyed or combusted for energy generation. Hence, as with on-site woodland carbon stocks, the wood-product carbon stocks associated with an area of woodland reach a long-term level, after which there are no further increases in the total carbon stocks. There is some potential to maximise carbon stocks in wood products by favouring the manufacture of long-lived products, but there are practical limits to this potential (see Section 2.11).
2. Potential differences in the magnitudes of woodland and wood-product carbon stocks associated with different woodland types tend to be evened out by certain factors. As already discussed, the tendency for faster-growing tree species to be managed on shorter rotations, and for slower-growing tree species to be managed on longer rotations, is one such factor. Another factor reflects a tendency for the wood of faster growing tree species to be of lower density, when compared with the density of slower-growing tree species (although the correlation is not perfect). Another factor involves relationships between branchwood and root biomass with stemwood, which vary with tree species. A further factor is the suitability of wood of different tree species for utilisation for long-lived structural timber products. All these factors tend to even out the differences between results for woodland and wood-product carbo stocks observed for different woodland types.

The second issue raised earlier (the “GHG emissions displacement” or “substitution” role of wood products supplied by productive woodlands) is important and should be taken into account when assessing the contributions of different types of woodlands to climate change mitigation. However, this potential emissions-displacement role of products supplied by managed woodlands should not be confused with the carbon sequestration potential of woodlands and wood products. Furthermore, it is important to recall the cautionary comments in Section 2.12 about the uncertainties in estimates of the contribution made by substitution in the longer term.

Nothing in the above assessment of the role of fast-growing productive woodlands serves to deny that such woodlands have a contribution to make towards climate change mitigation, or that this contribution is small or limited. On the contrary, the analysis demonstrates that such woodlands can play an effective part in any programme of woodland creation and management, where one of the aims is climate change mitigation. However, the analysis does not support the notion that these types of woodlands are intrinsically significantly more effective than other types of woodland. A key theme that emerges from a systematic assessment such as presented in Sections 3 and 4 is that different types of woodlands and woodland management can contribute to climate change mitigation in different ways and over different timescales, and that choices amongst available options depend on a number of factors and local circumstances.

2.16.2 "Avoiding tree harvesting will maximise woodland carbon sequestration"

This idea also comes from a consideration of the characteristic pattern of growth and carbon sequestration in a stand of trees, as described in Section 2.5 and illustrated in Figure 2-4, and further informed by results such as those in Appendix A1 and illustrated in Figure 2-9 in Section 2.16.1. It is evident from these results that:

- Managing woodlands on rotations that maximise the *rate* of carbon sequestration generally involves a trade-off with the levels of carbon *stocks* in woodlands
- Woodlands managed on longer rotations, with limited thinning and potentially no clearfelling, or no harvesting at all, can accumulate large carbon stocks.

It is true that the form of woodland management (or perhaps non-management) suggested in the second point above should allow woodlands to accumulate more carbon stocks than would be the case if the woodlands were managed on relatively shorter rotations to produce significant quantities of timber and biomass products.

When considered in terms of the "sectoral exchange representation" system diagram in Figure 2-8, in effect, managing woodlands with limited or no harvesting reduces or eliminates the outflow of carbon from the woodland system box (E) and has a similar effect on losses of carbon from decaying residual wood left on site after harvesting (D). This should shift the woodland carbon balance in favour of carbon inputs over outputs. However, such an approach has limitations. As already discussed, as woodland stands grow older, the processes of tree photosynthesis (A in Figure 2-8) and respiration and mortality (B and C) will come into balance, such that the woodland will attain an equilibrium carbon stock, neither increasing nor decreasing. In other words, carbon sequestration in the woodland will "saturate" (see for example Section A1.2 in Appendix A1). As noted previously (Section 2.7), some analysts have suggested an alternative possibility of "indefinite" carbon sequestration by woodlands, but the evidence in support of this notion is limited and partial.

It is also unclear to what extent the very large carbon stocks estimated for old, undisturbed stands of trees are achievable in all situations. In some situations, high levels of carbon stocks will be a theoretical possibility only, because of the impacts of disturbance events on woodlands (see Section 2.6), which may increase in likelihood and severity in older woodlands with high carbon stocks. Hence, there could be issues of impermanence attached to activities aimed at enhancing woodland carbon sequestration and conserving woodland carbon stocks (see Section 2.8). As also explained in Section 2.8, the impermanence issue can also “lock in” future generations to maintain the carbon sequestered by such measures taken historically, potentially limiting options for future woodland management and use.

A further issue arises from the focus of the suggested approach to woodland management on maximising carbon sequestered in the “woodland system box”, i.e. the left-hand box in Figure 2-8. Specifically, the contributions to the overall carbon balance potentially made by the “wood-products system box” (the right-hand box in Figure 2-8) are ignored. As discussed earlier, carbon stocks retained in wood products can compensate for to some extent for the lower carbon stocks in woodlands managed for production (although they are unlikely to compensate fully). In the absence of other factors, a decision to reduce or stop harvesting in woodland reduces or stops the flow of carbon into the wood-products system box (F and G in Figure 2-8). However, losses of carbon from material wood products (J) harvested previously would continue for some time, as these products decay, are destroyed or combusted for energy, either after their primary use or following a period of re-use or recycling. The implication is that the net emissions from the wood-product system box would increase, at least for some time.

It is likely there would be market-mediated responses to the reduced supply of products from the affected area of woodland, that is:

- Either the requirement for the wood products would be met through harvesting in other forests
- Or non-wood resources would be used to manufacture the products (see further discussion of these points in Sections 2.12 and 2.13).

Such responses would involve impacts in GHG emissions, either in other woodland areas or in other industrial sectors. These impacts are potentially important and should be taken into account when assessing the contributions of different types of woodlands to climate change mitigation. However, as in the previous discussion, this potential emissions-displacement role of products supplied by managed woodlands should not be confused with the carbon sequestration potential of woodlands and wood products. It is also important to recall the cautionary comments in Section 2.12 about the uncertainties in estimates of the contribution made by substitution in the longer term.

Again, mirroring the discussion in Section 2.16.1, nothing in the above assessment serves to deny the existence of a potential role for conserving and enhancing carbon stocks in woodlands through measures aimed at reducing harvesting and/or retaining older trees. On the contrary, the analysis demonstrates that such measures can play an effective part in any programme of woodland creation and management, where one of the aims is climate change mitigation. However, the analysis does not support the notion that these types of woodlands are intrinsically significantly more effective than other types of woodland. It is stressed again that a key theme that emerges from a systematic assessment such as presented in Sections 3 and 4 is that different types of woodlands and woodland management can contribute to climate change mitigation in different ways and over different timescales, and that choices amongst available options depend on a number of factors and local circumstances.

"Proforestation"

Recently, a concept that has been termed "proforestation" has been receiving attention in debates about how to manage woodlands to mitigate climate change. This term is defined quite vaguely by its proposers (Moomaw et al. 2019) but appears to involve some of the more extreme woodland carbon conservation activities covered in the preceding discussion, specifically activities consistent with converting managed woodlands to "wilderness" woodlands. Advocates of "proforestation" appear to suggest (although this is not absolutely clear) that the suspension of all management (including forest protection) could allow the development of more resilient woodlands. (For example, attention is drawn to evidence that forest fires in some regions have worsened, compared to earlier times when there was not fire protection.) There appears to be an implicit assumption that this type of approach could be adopted in "suitable" woodland areas, but it is unclear what types of woodland might be regarded as "suitable". Proponents also appear to discount the potential consequences of suspending harvesting in woodland areas on wood supply, including any implications for shifting wood production elsewhere or for changes in GHG emissions associated with product displacement.

From the perspective of the discussion in this paper, whilst the emergence of this new strand in the debate over the management of forests for climate change mitigation may be noted, essentially the idea of "proforestation" is covered in the discussion presented above.

2.16.3 "Allowing land to regenerate to a wilderness-woodland by natural colonisation is the best option for woodland creation to mitigate climate change"

This is an extreme extension of the idea covered in the previous discussion. Again, the focus is on maximising carbon sequestered in the "woodland system box" of the "sectoral exchange representation" system diagram in Figure 2-8. Essentially, the assessment in Section 2.16.4 also applies in this case.

The additional point here is the idea that the most effective way to sequester carbon in vegetation is to abandon the existing use of land (e.g. arable, pasture or conceivably production forestry) and allow the land to naturally recolonise with trees, apparently (although not always stated) with an assumption that these trees will be native broadleaf trees. The term "rewilding" is sometimes used to refer to this kind of approach to climate change mitigation through passive woodland creation or management. Such rewilding is expected by its proponents to provide several ecosystem services, notably enhanced biodiversity, alongside carbon sequestration. Discussion of these other possible beneficial impacts of rewilding is beyond the scope of this annex, as is consideration of the practical approaches and challenges involved in implementing such projects.

In terms of potential carbon sequestration, relatively little is known about carbon dynamics of land reverting to natural woodland by natural succession from some other type of vegetation. One important example of relevant evidence comes from the "Rothamsted classical experiments", as described in Appendix A1 (Section A1.3). As discussed there, it is difficult to interpret the limited results from the Rothamsted experiments. Confounding factors frustrate attempts to draw any conclusions from comparisons between the measured carbon stocks from the experiments and model projections of carbon stocks for even-aged stands. Relevant factors include uncertainty over the speed of natural succession processes following abandonment, uncertainty over the growth rates of equivalent even-aged stands and the inclusion of understorey vegetation in biomass estimates reported for the Rothamsted experiments.

One possible but very tentative interpretation of the results is that woodlands established by natural succession accumulate carbon stocks very slowly initially (compared with planted woodlands, or those in which regeneration is assisted), but can exhibit relatively fast rates of accumulation later on (e.g. between perhaps 50 and 150 years). Outcomes also appear to vary considerably from site to site, depending on how long the expected broadleaved trees take to start regenerating (assuming this occurs) and the types of trees involved. It should also be noted that the sites at Rothamsted were previously arable fields with quite high management inputs prior to abandonment, where vegetation might be expected to regenerate relatively quickly. It is not possible to comment on whether such stands of trees would accumulate more carbon stocks at the point of saturation than an equivalent stand of planted trees.

This assessment does not rule out the possibility of a role for “rewilding” as part of any programme of woodland creation and management, where one of the aims is climate change mitigation. However, the analysis does not suggest any particular advantage from adopting such measures, compared with the options of production forestry and the conservation of carbon in “woodland carbon reserves”, including the creation of woodlands by assisted regeneration rather than passive recolonisation. Furthermore, some uncertainty over the achievement of desired outcomes (e.g. carbon sequestration in climate change-relevant timescales) must be noted when relying on a passive approach to land management.

2.16.4 “Bioenergy produced from woodlands (wood fuel) is carbon-neutral”

This idea comes from a consideration of the cycle formed by growing vegetation, thereby sequestering carbon from the atmosphere, then harvesting the vegetation biomass and burning it as a source of energy. In principle, the carbon dioxide released by burning the biomass should be equivalent to the carbon sequestered when the biomass was grown, with the result that the system forms a closed cycle and, overall, carbon dioxide is neither removed nor added to the atmosphere whilst generating useful energy. It is true that such a situation can occur, in specific circumstances, but certainly not all.

When considered in terms of the “atmospheric exchange representation” system diagram in Figure 2-7, the assumption is made that the woodland-wood products system is in balance, i.e. in a steady state. That is, the inflow of carbon to the system (A in Figure 2-7) matches the outflows (B, C, D and just g and G in the case of a simple wood fuel production system). This assumption may be viewed as being reinforced by the “sectoral exchange representation” system diagram (Figure 2-8), in which the inflow of carbon into the wood-products system box (F) should be equal the outflow (H), such that the two terms should cancel out.

Some commentators have attributed the view of bioenergy as being carbon-neutral to this last point, and the fact that this "sectoral exchange representation" is the way that relevant carbon exchanges are represented when calculating and reporting GHG emissions of bioenergy in National GHG Inventories under the UNFCCC. Actually, the assumption pre-dates such reporting. There was a time (early 1990s) when bioenergy researchers genuinely took the view that bioenergy was carbon-neutral, at that time, having not fully considered all possible situations in which bioenergy might get produced.

The problem with the carbon-neutrality claim for bioenergy arises when the inflows and outflows of carbon for the system in Figure 2-7 (and for the left-hand "woodland system box" in Figure 2-8) are *not* in balance but rather are being perturbed by human interventions. Unfortunately, such a situation may often be the case. Where woodlands have been managed to produce a certain level of wood production for many decades (or where the woodlands were created for this purpose in the first place), it may be reasonable to assume that the carbon balance of the woodland-wood products system is at least in a steady state (see for example Appendix A1, Section A1.5). However, where there is a *change* to woodland management, to produce more bioenergy than was the case previously, a pre-existing steady-state carbon balance will be disturbed. *Initially*:

- The outflow of carbon from the woodland will increase relative to the inflow
- Carbon stocks in the woodland will decrease, compared with previous levels.

If the higher level of harvesting and bioenergy production are maintained (and assuming harvesting does not exceed the growth potential of the woodlands), *eventually*:

- The outflow and inflow of carbon in the woodland system will come back into balance
- Carbon stocks in the woodland will stabilise, but generally at a lower level than was the case under the previous management regime which involved less harvesting.

The consequences of the increased bioenergy production for the carbon balance are thus:

- A period in which there are net CO_2 emission from the woodland-wood products system
- A finite but maintained reduction in woodland carbon stocks.

This possibility of a period of net CO_2 emissions before woodlands can come back into a steady state, and the possibility of a net reduction in carbon stocks, associated with increased wood fuel production are sometimes referred to (individually or together) as the "carbon debt" of wood fuel or forest bioenergy (see Section 2.12). In some cases, the period during which net CO_2 emissions occur can be short (a few years) but in others this period may last for decades or centuries.

Matthews et al. (2014b, 2015, 2018) have suggested that the variability in possible outcomes arising from bioenergy production (which may involve anything from significant CO_2 emissions to enhanced carbon sinks) can be understood and managed. This remains a subject for further debate and analysis before a consensus can be achieved about the benefits for climate change mitigation (or otherwise) of bioenergy produced from woodlands.

Further discussion and clarification of relevant issues can be found in Matthews et al. (2018), in particular in Sections 3.3.1 to 3.3.5 and Section 6.1.

2.16.5 "Bioenergy produced from woodlands (wood fuel) releases more CO_2 emissions than burning coal"

This idea comes from the observation that, at the point of combustion, wood fuel releases more CO_2 than burning the equivalent quantity of coal to produce the same amount of energy. Generally, this point is true (see for example, Matthews et al. 2014b, Section 1.2 including Table 1.1). When considered in terms of the "atmospheric exchange representation" system diagram in Figure 2-7, this conclusion comes from focussing principally on the outflow of carbon from burning wood fuel (H in Figure 2-7), and the outflow that would otherwise occur if coal were to be burnt instead (not considered and not shown in Figure 2-7). However, this ignores all the other flows of carbon in the woodland-wood products system, including the inflow (A).

As explained in the previous discussion, it cannot be generally assumed that inflows of carbon to the woodland-wood products system always perfectly balance the outflows, which would allow that burning wood fuel results in zero net emissions (i.e. is carbon neutral). Equally, it is an oversimplification to assume that the net CO_2 emissions from burning wood fuel can be represented just by the CO_2 released at the point of combustion. A related comment about CO_2 emissions from harvesting wood for use as fuel states:

"It takes seconds to cut down a tree but it takes decades or centuries to replace the carbon by growing another tree"

This is a simplified way of referring to the rather more complicated issue of potential "carbon debt" associated with increased wood fuel production, as discussed in Sections 2.12 and 2.16.4. As also explained there, situations also exist in which wood harvesting (for fuel or material products) can take place with no net change in overall woodland carbon stocks and with no net CO_2 emissions from burning the wood, either in the short term or long term, when the woodland-wood products system is considered as a whole (see for example Appendix A1, Section A1.5).

This issue has been the subject of many studies and reports (see for example, Marelli et al. 2013; Matthews et al. 2014b). Whilst suggestions have been offered about how variability in the CO_2 emissions of wood fuel sources could be managed, this remains a subject for further debate and analysis before a consensus can be achieved about the benefits for climate change mitigation (or otherwise) of bioenergy produced from woodlands.

Further discussion and clarification of relevant issues can be found in Matthews et al. (2018), in particular in Sections 3.3.1 to 3.3.5 and Section 6.1.

2.16.6 "Wood products (including wood fuel) are carbon-neutral as long as the carbon harvested from woodlands in harvesting does not exceed the woodland carbon sink"

This idea comes from the observation that, as part of the sustainable management of woodlands, forestry practitioners usually aim to ensure that the level of wood harvesting in woodland areas they are managing does not exceed the growth or "increment" of those woodland areas. Demonstrating that woodland growth/increment is at least equal to the rate of harvesting is generally regarded as one important indicator of sustainable forest management. This can lead to the reasoning that, if the rate of woodland growth (carbon sequestration) is at least equal to and possibly greater than the rate of (carbon loss from) harvesting, then surely the wood products and fuel produced in this way must be at least carbon-neutral.

When considered in terms of the "sectoral exchange representation" system diagram in Figure 2-8, such a conclusion is based on a situation in which the net inflow of carbon into the woodland system box (A – B – C in Figure 2-8) is greater than or at least equal to the outflow of carbon resulting from harvesting (D and E). This must mean that carbon stocks in the woodland system must be at least stable and potentially are increasing.

The equivalent interpretation of the "atmospheric exchange representation" system diagram in Figure 2-7 involves cases (ignoring harvesting for material products to aid clarity) in which CO_2 emissions from producing and burning wood fuel (D, h and H) are equalled or exceeded by the net inflow into the woodlands (A – B – C).

In such cases, how can the utilisation of the wood products, including burning harvested wood fuel, involve (increased) net CO_2 emissions?

As already noted in an earlier discussion, there can indeed be situations in which bioenergy sources such as wood fuel can be carbon-neutral or better. However, issues arise when woodland management is changed (generally when harvesting is increased) to supply more wood for products including fuel than was the case previously. Consider the following example, based on the exchanges of carbon shown in the "atmospheric exchange representation" system diagram in Figure 2-7. (Again, to aid clarity, the production of wood is assumed to consist of just wood fuel, but a similar example could be developed including material wood products.)

A quite large area of woodland is sequestering carbon at a rate of about 100 thousand tonnes of carbon per year, that is:

$$A - B - C = 100{,}000 \text{ tC yr}^{-1}.$$

Some harvesting is going on in the woodlands, to produce wood fuel. The rate of harvesting has been around the same level for many years and the processing and burning of the wood fuel results in the loss of 1 thousand tonnes of carbon from the system every year, that is:

$$D + g + G = 1{,}000 \text{ tC yr}^{-1}.$$

The net carbon balance of the system (Figure 2-7) is thus:

$$100{,}000 - 1{,}000 = 99{,}000 \text{ tC yr}^{-1} \text{ (a net carbon sink).}$$

The opportunity is recognised to produce a lot more wood fuel, whilst continuing to maintain a net carbon sink for the overall system. Measures are taken to increase harvesting and wood fuel production. Consequently, the processing and burning of wood fuel now results in the loss of 50,000 tonnes of carbon from the system every year, that is:

$$D + g + G = 50{,}000 \text{ tC yr}^{-1}.$$

If the *admittedly simplistic* assumption is made that the woodland continues to sequester carbon at the same rate of 100,000 tC yr^{-1}, the net carbon balance of the system becomes:

$$100{,}000 - 50{,}000 = 50{,}000 \text{ tC yr}^{-1} \text{ (still a net carbon sink).}$$

The problem here is that, although the system is still a net sink, the magnitude of this sink has been significantly reduced by the measures to increase harvesting and production of wood fuel from the woodlands. It should be apparent that, “from the point of view of the atmosphere”, a *reduced net carbon sink* from the atmosphere is *exactly equivalent to* an *increased net carbon emission* (as CO_2) to the atmosphere.

Moreover, as noted in Section 2.1, the Paris Agreement sets the goal of balancing sources (emissions) and sinks of GHGs in the second half of this century. If the existing net sink in woodlands is “eaten up” by efforts to produce more wood-based materials and energy, such a goal will be much more challenging to meet, needing to rely on the development of technological solutions to sequester carbon from the atmosphere.

Earlier, it was highlighted that the assumption in the above example of an unchanged woodland carbon sink (100 1000 tC yr^{-1}), regardless of the woodland management and level of harvesting), was simplistic. In discussions of this subject, it is frequently pointed out that:

‘Active (and sustainable) forest management can “strengthen” i.e. increase the rate of carbon sequestration by woodlands’.

This is true, but it is very unlikely that the increased carbon sink will compensate fully for the increased emissions resulting from burning greater quantities of wood fuel. Moreover, “intensifying” the management of woodlands, even if this enhances the woodland carbon sink, can often involve reductions in woodland carbon stocks and problems with “carbon debt”, as already covered in Sections 2.12 and 2.16.4. Matthews et al. (2018, Section 3.3.3) give a specific example illustrating the overall effect of intensified woodland management on the woodland carbon sink, carbon stocks and carbon losses from harvesting.

As already noted in Section 2.16.5, these types of issue have been the subject of many studies and reports. Whilst suggestions have been offered about how variability in the CO_2 emissions associated with wood production systems could be managed, this remains a subject for further debate and analysis before a consensus can be achieved about the benefits for climate change mitigation (or otherwise) of materials and bioenergy produced from woodlands.

Further discussion and clarification of relevant issues related to wood fuel can be found in Matthews et al. (2018), in particular in Sections 3.3.1 to 3.3.5 and Section 6.1.

3. Woodland Climate Change Mitigation Measures

Following the discussions of Schlamadinger et al. (2007) and Nabuurs et al. (2007) and the detailed consideration of specific options presented by Mason et al. (2009), Matthews and Broadmeadow (2009) and Matthews et al. (2017), it is possible to identify a number of specific forest management activities relevant to developing a bioeconomy and/or contributing to climate change mitigation:

- Creation of new woodland areas (afforestation)
- Prevention of woodland loss (avoidance of deforestation)
- Conservation or enhancement of carbon in existing woodlands, including protection against disturbances and extreme events such as fire
- Enhancement of production, e.g. through increased harvesting in existing woodlands, to achieve substitution/displacement impacts in other sectors.

The list defined above constitutes a simplified version of the range of woodland measures considered and evaluated in Schelhaas et al. (2006). The range of measures is also broadly similar to those considered in a report to the EU Standing Forestry Committee (Standing Forestry Committee 2010). These measures are considered in detail in Sections 3.1 to 3.3. Indicative estimates of per-hectare mitigation potentials are given in Section 4.6. The basis of these estimates is explained in Section 4.1.

The carbon dynamics of woodland systems are innately time dependent and responses to management interventions can be complex. One common feature for all measures, however, is that any carbon sequestration will eventually saturate (biologically or technically, see Section 2.7) in the long term.

3.1 Woodland creation (afforestation)

The conversion of non-woodland to woodland, through tree planting or the encouragement of natural regeneration, generally involves a net increase in vegetation and soil carbon stocks (certainly when considered together). A quite extreme example would involve afforestation on former pasture to create a “wilderness woodland”, which could sequester a significant reservoir of carbon, assuming major disturbance events do not occur (see for example Appendix A1, Section A1.2).

If newly created woodlands are managed for production of timber and fuel, there should also be significant positive impacts on GHG emissions in other sectors, compared with the option of simply allowing carbon stocks in the new woodlands to accumulate (see for example Appendix A1, Sections A1.4 to A1.6). However, uncertainties surrounding these contributions in the longer term have been highlighted in the main report. The balance between CO_2 removals from the atmosphere in the growing trees and cross-sectoral impacts from utilisation of harvested wood will depend on the type of woodland system considered.

Based on the consideration of results such as those in Appendix A1 (Sections A1.2 to A1.6), it is suggested that woodland creation with the objective of climate change mitigation can include options involving widely varying degrees of management, from no harvesting to intensive wood production. The main options involve:

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

Caution is still necessary when pursuing afforestation activities. If carbon stocks on land are already high before the forest is created (e.g. the site being considered is a peatland or a soil with very high levels of organic matter, which includes many types of grasslands), the net change in carbon stocks resulting from the creation of the forest may be small and will probably involve an initial reduction. In situations where a net reduction in carbon stocks takes place, it may take decades to restore a carbon stock of similar magnitude. There is an ongoing debate about the response of soil carbon in the years immediately following tree planting, generally with regard to the initial loss of carbon stocks and time needed to replenish them.

Cases involving the drainage of soils with high organic matter content in preparation for afforestation are likely to be unsuitable in terms of GHG emissions mitigation. Drainage would increase aerobic conditions in the soil, which would be likely to result in oxidation of organic matter and increased emissions (see Section 2.9).

In all cases, carbon sequestration will eventually saturate, at one extreme when the “biological” limit of a wilderness is reached, or on the other hand up to the time of final harvest in woodlands managed according to a regime involving clearfelling (see Section 2.7).

3.2 Prevention of woodland loss (avoidance of deforestation)

The conversion of woodland to other types of land generally involves a net reduction in vegetation and soil carbon stocks. The magnitude of the carbon stock reductions would be the reverse of the carbon stock increases estimated for the creation the relevant forest (see previous discussion and Appendix A1). The emission of GHGs to the atmosphere as a result of the vegetation loss (i.e. loss of trees) might be quite rapid (say, over 1 to 5 years, but this depends strongly on what is done with the biomass in the felled trees. The loss of carbon in soil might take place over many decades. Prevention of deforestation would thus be expected to mitigate these GHG emissions, suggesting mitigation potentials of equal magnitude the estimates given for afforestation but over shorter timescales.

Whilst it may be generally the case that prevention of deforestation represents a GHG emissions mitigation measure, there may be certain specific exceptions. For example, the restoration of afforested peatlands by removing trees, particularly in cases where the trees have a low growth rate, may have the potential to reverse losses of carbon and other GHG emissions from peatland soils caused by their previous drainage and afforestation.

3.3 Conservation or enhancement of carbon in existing woodlands

When an area of woodland is being managed for wood production (through thinning of trees or periodic felling on a rotation), there is an impact on carbon stocks. Specifically, carbon stocks in woodlands managed for production are typically lower compared to similar woodlands left to develop into a wilderness (Broadmeadow and Matthews 2003; Matthews and Robertson 2006; Mason et al. 2009; see also Section 2.16.1 and Appendix A1). By implication, carbon stocks could be increased in woodland areas (with consequent net removal of CO_2 from the atmosphere) if appropriate changes were introduced in the way woodlands are managed for production (Mason et al. 2009). In effect, certain changes in woodland management can change the "technical saturation" level of carbon stocks in woodlands from an initial value (associated with the previous management of the woodlands) to an enhanced value. Relevant woodland management measures generally involve leaving trees to grow for longer before harvesting, or not harvesting them at all. The main options include:

- Longer rotations in even-aged managed stands (Section 3.3.1)
- Avoidance of clearfelling in managed stands ("continuous-cover" management, Section 3.3.2)
- Restricting production (Section 3.3.3)
- Conversion managed forests to wilderness woodland (Section 3.3.4)
- Conservation of long-established woodlands with existing high carbon stocks (by avoiding harvesting, Section 3.3.5).

These options are discussed below, according to the section numbers given above, whilst a summary assessment of the options is given in Section 3.3.6.

3.3.1 Introducing longer rotations in even aged stands

Based on the discussion earlier in this annex and in Appendix A1, it is apparent that:

- Typically, a woodland can sequester a finite (long-term mean) stock of carbon
- The magnitude of this carbon stock depends on management, with the rotation applied being a big influence
- Generally, the level of harvesting (thinning and clearfelling) in forests will affect carbon stocks.

If the period between clearfelling events in managed even-aged stands forming a woodland is extended, then the overall carbon stock in the forest should increase (this is the converse of the discussion in Section 2.16.1).

Based on a consideration of the carbon stock estimates Figure 2-9 in Section 2.16.1, if typical rotation ages were to be extended by 20 years, then additional carbon stocks would be sequestered in forest areas with a magnitude of around 10 to 20 tC ha^{-1}. This is a relatively small quantity of additional sequestered carbon but this could still be significant if it involved large areas of forest. If such a measure were to be introduced in all of the woodland stands close to clearfelling age, this would lead to a significant drop in wood production in the short term, so it seems likely that the longer rotation would be applied gradually across different forest areas as part of a programme of woodland restructuring. However, the details would depend on the existing age distribution of the woodlands. The carbon stock change would occur over the period taken for the stands to adjust to the longer rotations, which would depend on age distribution but might take anything between 80 to 100 years. These magnitudes, periods and consequent rates depend on the details of how the woodlands were being managed originally and the extent of the change in rotation. The changes in carbon sequestration over time will be complex. It should also be noted that changing the management of woodland areas in ways that do not always meet market requirements for production is likely to lead to market-mediated effects such as increased imports and possibly associated GHG emissions arising from leakage (e.g. intensification of forest harvesting elsewhere), in addition to having negative economic implications.

3.3.2 Avoidance of clearfelling in managed stands

If a woodland is being managed as an ensemble of even aged stands with periodic clearfelling, then the practice of clearfelling could be changed to a system based on selective felling of individual trees or small groups of trees (otherwise known as “continuous-cover” silviculture or management). Such a system is also likely to involve retaining some trees for longer than was the case under the previous clearfelling system. However, other changes to the silvicultural system may involve increased harvesting amongst trees of smaller sizes. There is some debate over the net impacts on stand carbon stocks resulting from the introduction of such “continuous-cover” methods of management in woodland areas previously managed on a clearfelling regime. However, there is also some evidence to suggest that long-term average carbon stocks in “continuous cover” stands may be somewhat larger than for “clearfelled” stands (Seidl et al. 2007; Stokes and Kerr 2009).

In general, continuous cover management also reduces the extent of disturbance of the soil compared with clearfelling events. Avoidance of clearfelling (and adoption of continuous-cover management) thus represents a possible measure for mitigation of GHG emissions, particularly in woodland areas with high soil organic matter content. The carbon stock change involved is likely to be similar to or somewhat greater than estimated for the option of extending rotations in even-aged forests (see Section 3.3.1). The carbon stock changes might occur over the period taken to transform the stands to continuous-cover management, which would depend on the age distribution of the forests but might take anything up to 100 years. These details would depend on the specifics of how the woodlands were being managed for production originally and the extent of the transformation. The changes in carbon sequestration over time will be complex.

Woodland management options such as conversion from even-aged stands managed with clearfelling to continuous-cover management could also be combined with encouraging the development of stands composed of more diverse mixtures of tree species. Whilst this can make management more complicated and costly, it could also increase the resilience of woodlands to disturbance (e.g. pests and diseases) and future climate change. Depending on the tree species involved, there may also be opportunities to enhance the overall growth rates of the mixed-species forests. Conversely, greater representation of mixed tree species in stands without consideration of wood production objectives could lead to a reduction of forest productivity.

3.3.3 Restricting production in managed stands

Where existing woodlands are being managed for production, the extent of this production could be greatly reduced, for example through limiting the felling of trees to very occasional small groups. It should be noted that this is effectively the same as managing the woodlands as an ensemble of very small clearfell stands on very long rotations. The impact of introducing such management is thus similar to very significantly extending rotations (see Section 3.3.1; Figure 2-9 in Section 2.16.1 may also be referred to for estimates of the impacts of significant extension of rotations).

As previously, the details would depend on the specifics of how the woodlands were being managed for production originally and the extent of the change in rotation (i.e. the change in extent of wood harvesting). The changes in carbon sequestration over time will be complex. Restricting production would have significant economic impacts on the forestry sector and risk shifting demand for wood in Wales to wood supplied from sources outside Wales.

3.3.4 Conversion to wilderness woodland

The logical final extension of the conservation options considered so far is to withdraw managed woodlands completely from management for production. The impact of stopping harvesting for production completely is greater than when production is merely restricted as discussed above, with potentially very large overall change in carbon stocks in trees and soil (see for example results in Sections A1.2 and A1.4 of Appendix A1). As previously, the details would depend on the specifics of how the woodlands were being managed for production originally. In some cases, the tree species composition of the original managed woodlands may need to be adjusted, for example shifting from fast-growing productive but sometimes short-lived tree species to more enduring tree species. The changes in carbon sequestration over time will be complex. Restricting production would have significant economic impacts on the forestry sector and risk shifting demand for wood in Wales to wood supplied from sources outside Wales.

3.3.5 Conservation of long-established woodlands with high carbon stocks

As a complement to activities involving the enhancement of carbon stocks in managed woodlands, measures may be taken to conserve existing high carbon stocks in log-established natural and semi-natural woodlands. This would involve avoiding harvesting in these areas and, where practical, protecting these woodlands from natural disturbances such as fires.

In situations where there may be the possibility of harvesting happening in such woodland areas, the merits of conservation and protection appear to be compelling. However, there may be limits to such activities. It may not be feasible to protect woodlands entirely from fires, storms and outbreaks of pests and diseases. Whilst this should not deter efforts to conserve natural and semi-natural woodlands with high carbon stocks, it should be recognised that such ecosystems are still developing dynamically and there may be periods in which carbon stocks are lost (and there are net CO_2 emissions) as a result of natural processes of tree mortality and disturbance, as well as periods of net carbon sequestration when woodlands recover from environmental perturbations.

3.3.6 Consideration of woodland carbon conservation options

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

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

Climate change is likely to increase the likelihood of natural disturbances, such as storms, fires and pests and diseases, which could compromise woodland carbon stocks and potentially reverse carbon sequestration, including in woodland areas subject to carbon conservation measures. Managing the risks associated with these uncertainties may limit the potential for enhancing or maintaining large carbon stocks. As noted in preceding discussion, some forest carbon conservation activities may involve changes to existing tree species or the diversification of the species composition of forests, as part of ensuring forest resilience.

3.4 Enhanced production in existing woodlands

As noted in preceding discussion, some forest carbon conservation activities may involve changes to existing tree species or the diversification of the species composition of forests, as part of ensuring forest resilience. If production of biomass and/or timber from woodlands can be increased then the supply of renewable timber and wood fuel can be enhanced and there should be more opportunities to reduce GHG emissions through the retention of sequestered carbon in wood products and their utilisation in place of more GHG-intensive materials and fossil-based energy. The main relevant options are:

- Adjusting rotations applied to even-aged forest stands closer to the productive maximum (Section 3.4.1)
- Mobilising production from previously undermanaged/unmanaged forests (Section 3.4.2)
- Increasing the harvest of timber offcuts and branchwood (harvesting residues, Section 3.4.3)
- Changing/enriching the tree species composition and growth rates of managed forests (Section 3.4.4).

These options are discussed below, according to the section numbers given above, whilst a summary assessment of the options is given in Section 3.4.5.

3.4.1 Adjusting rotations closer to the productive maximum

Trees (and stands of even-aged trees) have a characteristic rotation (i.e. the time between planting and felling with restocking) for which timber and biomass production are maximal (see Appendix A1, Section A1.7). The period of this rotation and the magnitude of maximum productivity vary depending on tree species and growth rate and the types of material specified for production (e.g. raw biomass and/or structural timber). Typically, such “optimum” rotations in Wales are between 30 and 120 years for conifers and between 30 and 150 years for broadleaves, depending on tree species, growth rate etc. If trees or stands are felled on a rotation significantly shorter or longer than the optimum, then productivity (timber volume or biomass per hectare per year) will be less than the potential maximum. Consequently, adjusting rotations closer to the optimum period should increase wood/biomass production.

Assuming a typical mix of end uses for the extra harvested material, this should result in potential long-term reductions in GHG emissions achieved through utilisation of bioenergy and timber. It should be noted that this conclusion relates specifically to the substitution benefit of the increased use of the timber and bioenergy; this needs to be considered in combination with any effects on woodland carbon stocks resulting from changes to rotations. Such a contribution may be relatively modest in some cases but it could still be significant if it were possible to implement this sort of measure over very large areas of woodland. However, because rotations are generally long, any positive effects of adjusting rotations may take time to implement and consequently for the impacts to become apparent.

The potential impacts on woodland carbon stocks are very important to consider when deciding whether to adjust rotations in forest areas in order to increase the supply of wood products and wood fuel (see Appendix A1, Section A1.7). For example, woodland areas in Wales and elsewhere are managed on variable (and frequently longer) rotations to achieve a range of economic, environmental and landscape objectives. If a decision were to be taken to shorten rotations to increase total biomass or sawlog production, this would most likely lead to a reduction in the overall level of carbon stocks in these forest areas. On the other hand, there are also examples of forest areas which are managed on relatively short rotations, largely driven by market demands or reflecting a degraded tree growing stock in the forest. If a decision were taken to extend rotations to increase total biomass or sawlog production, this would most likely lead to an increase in the overall level of carbon stocks in these forest areas (with implied sequestration of biogenic carbon). It follows that actions to 'intensify' management of forest areas to increase supply of forest bioenergy, through adjustments to rotations, can have antagonistic or synergistic effects on forest carbon stocks, i.e. carbon stock losses or carbon sequestration.

Sometimes, forestry practitioners claim that shortening the rotations of older forest stands closer to the productive maximum can strengthen the rate of forest carbon sequestration (see e.g. Hektor et al. 2016). However, evidence presented in support of these claims is based on a particular interpretation of the forest carbon sink (see Section 2.16.1) and appears to overlook the negative impacts on forest carbon stocks (see Matthews et al. 2018, Section 3.3.3). Nevertheless, it remains the case that adjusting rotations in stands of trees to increase overall productivity can have negative, positive or neutral impacts on forest carbon stocks, depending on local circumstances (i.e., whether adjustments to rotations involve shortening, lengthening or a combination of both).

3.4.2 Mobilising production in previously undermanaged/unmanaged woodlands

Where woodlands are not being managed for production, or management for production is very limited, the possibility exists to significantly increase harvesting of timber and biomass for the manufacture of materials and use as renewable energy. The potential GHG emissions reductions could be significant and long-term, provided that these products substitute for more GHG-intensive alternative products. However, the increased production and potential for product substitution is generally at the expense of reductions in woodland carbon stocks, which can be significant. For example, this is apparent from a comparison of the long-term mean carbon stocks in the mixed broadleaf stand and the managed spruce stand, discussed in Sections A1.2 and A1.4 of Appendix A1. The carbon stock change resulting from the introduction of management should be "one off", while the emissions reductions from product substitution should continue. However, a number of research studies have suggested that the "break-even point" when GHG emissions reductions from product substitution exceed carbon stock reductions may take many decades to achieve (see e.g. Matthews et al. 2014b, Section 5.3.2).

3.4.3 Increasing the harvest of offcuts and branchwood (harvesting residues)

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

The amount of biomass available to harvest from offcuts and branchwood is very site-specific. The GHG emissions reductions that might be achieved from the utilisation of this biomass as energy would depend on the energy conversion process and the type of energy source replaced. There is an ongoing debate about the effect of harvesting non-stem material on long-term site sustainability (e.g. in terms of soil fertility, acidity and structure). The need to protect site and soil quality is likely to place significant constraints on the harvesting of non-stem material, notably in cases where the quantities of residual wood left on site by conventional harvesting are small.

As illustrated in Section A1.11 in Appendix A1, whilst the extraction of harvesting residues may provide an additional source of biomass, there are also impacts on carbon stocks in deadwood and litter in woodlands which can initially offset the GHG emissions reductions achieved by using the biomass (e.g. as an energy source).

The removal of stumps and roots as part of biomass harvesting can add to the total biomass output and to substitution benefits, but the increased disturbance of soil and litter, with associated GHG emissions, and the risk of a number of other potential impacts (on nutrient cycling, productivity, biodiversity) suggest that this option only be relevant as a GHG emissions mitigation measure in very specific circumstances (e.g. where required as part of disease control or where negative impacts on soil quality and carbon stocks are limited).

3.4.4 Changing/enriching the tree species composition & growth rates of managed forests

When trees are thinned or felled the possibility exists to replace them with trees of different species which have higher growth rates. This could increase the per-hectare productivity of stands while maintaining carbon stocks. The potential for increasing stand productivity in this way is likely to be very specific to local circumstances. However, a specific example with relevance to Wales is the restocking of productive stands of Sitka spruce with genetically improved stock (see Sections A1.4 and A1.6 in Appendix A1). The potential reductions in GHG emissions achieved through utilisation of bioenergy and timber should continue into the long term, provided that these products substitute for more GHG-intensive alternative products. It should be noted that Sitka spruce areas in Wales are already being restocked with “improved” trees.

Although the option of changing and enriching tree species appears to offer some potential, there are limitations and risks to its implementation. For example, it may be difficult to predict the productivity increase actually realised on individual sites by changing species. In addition, in some situations, the replacement species may grow faster but the wood produced may not have the qualities necessary to be used for the same end uses as the original species, which may lead to marketing difficulties and a lower potential for GHG abatement through substitution. There are risks related to pests and diseases which would become significant if one or a restricted number of species were to be selected. Because of the long period over which woodland trees are likely to grow, the effect of climate change will influence species selection which, again, may be difficult to predict. On the other hand, the possibility may exist to diversify the composition of forest stands by encouraging or creating tree species mixtures, which could support forest resilience to environmental change and disturbance events, whilst maintaining long-term forest productivity.

Matthews et al. (2014b) identify a woodland management activity referred to as “enrichment” of woodland growing stock. Such an activity might involve, for example, replanting diseased stands or improving the growing stock in failed or degraded woodland stands, or in areas of scrub. Potentially, these types of activity could enhance the capacity of woodlands to produce timber and fuel, whilst also enhancing woodland carbon stocks. However, the extent of the potential for woodland enrichment activities is unclear. The potential of activities involving tree species change or stand enrichment (and the implications for forestry practices) constitute a specific but important knowledge gap.

3.4.5 Consideration of enhanced production options

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

There are also potentially significant limitations, drawbacks and risks associated with such measures. For some options, the impacts in terms of GHG emissions abatement are relatively small. In many situations there will be practical limits to the enhancement of production in existing woodlands. For example, stands may be managed on non-optimum rotations or not managed for high production to ensure evenness of timber supply, or to avoid negative impacts on the landscape or to protect important habitats.

Generally, interactions between woodland management and impacts on landscape and habitat are highly location-specific and changes in management could have either positive or negative effects. Fundamentally, the case for increasing timber and biomass supply assumes that there is sufficient demand (and capacity) for its utilisation. This implies a need for concomitant measures to enhance the efficient use of timber and biomass to substitute for materials and fuels with higher life-cycle GHG emissions.

Most (but not all) options based on the enhancement of production in existing forests involve negative impacts on tree carbon stocks. The CO_2 emissions resulting from reductions in woodland carbon stocks can be significant but eventually the long-term benefits of the enhanced production (through cross-sectoral impacts) should outweigh these losses, provided that the measures are sustained and product substitution continues to deliver GHG emissions reductions in the long term. However, as already noted in the discussion of some options, the “payback period” before net GHG emissions reductions are attained can be very long.

4. Quantification of Potential Climate Impacts of Measures

The purpose of this assessment is to present a summary of indicative per-hectare mitigation potentials for the various measures described in Section 3.

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

4.1 Basis of estimates referred to in assessments

The potential for woodlands in Wales to contribute to climate change mitigation can be assessed quantitatively in a number of ways. Examples include:

1. Synthesising evidence and reported estimates from published studies relevant to Wales
2. Estimating the impact of a specified management intervention involving woodlands, for a notional one-hectare area of land.
3. Carrying out a large-scale scenario modelling exercise based on available information on the composition and management of woodlands in Wales, and evaluating the impacts of specified interventions in woodlands over time. Interactions with other land uses (e.g. as a result of woodland creation) would need to be allowed for. Such methods are already employed in estimating and reporting GHG sinks and sources associated with woodlands in Wales, as part of National GHG Inventories for the UK under the UNFCCC. Related projections of future woodland GHG sinks and sources under different policy scenarios are also produced in support of national carbon budgeting exercises.
4. Applying an integrated land use modelling platform to explore scenarios for land-use change and management interventions within existing land uses in Wales, with a particular focus on options involving woodlands.

The assessment in this annex is expected to be based on evidence from existing published studies. Hence, the first approach described above is strictly appropriate as the basis for the assessment. Published projections of woodland GHG balances can be used to establish the contributions of existing woodlands in Wales to carbon sequestration, under a limited range of scenarios. Evidence of this type, based on the best projections currently available for Wales, is considered in Section 4.7. Contributions made by wood products and displacing other more GHG-intensive products are not included in those projections.

There are very few other relevant published evidence sources (e.g. Bateman 1996; Bateman and Lovett 2000; Binner et al. 2018). These sources have limitations (e.g. wood products substitution is not considered and the impacts of detailed options for interventions involving existing woodlands are not covered).

New modelling using approaches such as described in (3) and (4) above could be carried out but such options are out of scope for this current assessment. This leaves an approach such as suggested in (2) above, provided that published estimates are available to permit such an assessment. This is the approach adopted in this annex, as described below.

4.1.1 Data sources

Estimates relevant for an assessment based on the approach identified have been published in a report produced for Natural Resources Wales by Matthews et al. (2017). These were based on a relatively limited set of results produced by the CARBINE model, and it was suggested that the estimated mitigation potentials could be referred to as a rough guide.

The existing results from Matthews et al. (2017) were used in this assessment for evaluating a scenario of increasing biomass production from woodlands by extracting harvesting residues, i.e. a proportion of branchwood and offcuts of stem wood otherwise left to rot on site. However, for other scenarios considered in this assessment, the main data source referred to consists of a more substantial and consistent set of results produced as part of the ERAMMP project. As part of the modelling for this project, the Forest Research CARBINE model was applied to produce a very large table of estimates of the impacts on woodland carbon sequestration and wider GHG emissions resulting from different options for woodland creation. These estimates could also be adapted to assess the impacts of a number of examples of management interventions in existing woodlands. The raw ERAMMP results have not been published but the relevant results referred to in this study are reported here in full in Appendix A2.

The ERAMMP results were supplemented with estimates of long-term carbon stocks in woodlands, published as part of the UK Woodland Carbon Code Carbon Calculation Spreadsheet (UK Woodland Carbon Code 2020). The main application of these additional results was in assessing the impacts of woodland management options involving changes to forest management, e.g. adjustments to rotations (see discussion in Section 2.16.1, especially Figure 2-9).

The ERAMMP results cover a range of tree species and growth rates (yield classes) and four indicative woodland management regimes:

1. “Reserve”, woodland establishment with no further management (and no wood harvesting), to create a woodland “reserve” with relatively high carbon stocks. This option is assumed to involve exclusively broadleaf tree species.
2. “Continuous cover”, woodland establishment with management for wood production involving regular thinning for wood production, but with avoidance of clearfelling. Management is intended to support the woodland evolving into an uneven-aged structure.
3. “Thin & fell”, woodland establishment with management for wood production involving regular thinning and clearfelling on a specified rotation
4. “Short Rotation Forestry (SRF)”, establishment of woodland with management more like that of a perennial agricultural crop, on a relatively short rotation, to produce biomass as a source of wood fuel (bioenergy) or possibly for fibre or

as a feedstock for materials or chemicals (these latter options are not considered here).

4.1.2 Tree species

The tree species modelled as part of ERAMMP so far are listed in Table 4.1, along with the abbreviations used in presenting some of the results later in this section.

Table 4.1 Tree species modelled as part of ERAMMP (as at April 2020)

Tree species	***Abbreviation***
Beech	*BE*
Oak	*OK*
Silver birch and birch	*BI*
Aspen and black poplar	*PO*
Scots pine	*SP*
Sitka spruce	*SS*
Douglas fir	*DF*

This relatively small number of potential tree species was selected to represent the range of possible growth characteristics and productive potentials of different types of woodland in Wales, constrained to a degree by what was available in the ERAMMP results.

4.1.3 Yield class

Results (ERAMMP and Woodland Carbon Code) have been produced for a wide range of growth rates (yield classes). However, to simplify the assessment presented here, a selection was made amongst results for each different yield classes, for each of the tree species, as shown in Table 4.2.

This selection was based on estimates of potential mean yield class for each tree species in Wales obtained from the FR Ecological Site Classification system, ESC (Pyatt et al. 2001), assuming a baseline scenario for climate to 2100 and alternatively a scenario based on a UKCP09 11-RCM (medium emissions) scenario (Met Office 2009). Between two and four yield classes were selected for each tree species, based on the ESC estimates. It should be noted that estimates of potential yield class cover both existing woodland and non-woodland land types and will therefore differ from estimates reported for existing woodlands (e.g. as reported in the GB National Forest Inventory).

To simplify some assessments, results for a single yield class were referred to when considering different tree species. These yield classes were selected to be broadly representative of the mid-range of the selected estimates in Table 4.2 (second column), tending to be conservative if a choice needed to be made between two possible values. The yield classes assumed for these single-estimate assessments are shown in the third column of Table 4.2. These single-estimate results are referred to in subsequent discussions as the “candidate” results.

Table 4.2 Estimates of potential yield class selected to represent growth rates of tree species

Tree species	*Selected yield classes*	*Single-estimate yield class*
BE	*2, 4, 6*	*4*
OK	*2, 4, 6*	*4*
BI	*4, 6, 8, 10*	*6*
PO	*2, 4, 6, 8*	*4*
SP	*8, 10*	*8*
SS	*12, 20*	*12*
DF	*8, 10, 12*	*10*

4.1.4 Climate

CARBINE simulations were also produced for a range of climatic conditions in Wales (based on a classification referred to in ESC):

- Sub-alpine
- Cool wet
- Warm wet
- Warm moist
- Warm dry.

When using "candidate" results in assessments, results for the climate class of "warm moist" were used, as this class is most representative of conditions across Wales.

Assumptions about climatic conditions affect the yield class used as input to CARBINE (indirectly through ESC) and directly influence simulations by CARBINE of carbon dynamics in deadwood, litter and soil.

4.1.5 Soil

CARBINE simulations for ERAMMP were run for five classes of soil, capturing the main variations in soil carbon dynamics:

1. Sand
2. Loam
3. Gley
4. Organo-mineral (gley)
5. Organic (peat).

Results for the classes of "loam", "gley" and "organo-mineral" were selected for this assessment, as being most relevant to woodland creation activities in Wales and also reasonably representative of existing woodland (with the exception of those areas on organic soils). The assumption was made that woodland creation on organic soils would be avoided.

When using "candidate" results in assessments, results for the soil class of "loam" were used, as these represented mid-range estimates for soil carbon stock changes, out of the three selected types of estimate.

4.1.6 Previous land use

A further factor allowed for in the CARBINE results produced for ERAMMP was previous land use; two options of arable land and pasture/grassland were considered. Only the results for pasture/grassland were referred to for the purposes of this assessment. These results are likely to represent conditions on marginal sites where woodland creation might be considered, which give results for soil carbon sequestration (in the long term) that are conservative in comparison with those for a previous land use of arable land.

Following the description above, the ERAMMP estimates referred to for making this assessment consisted of results for the following combinations of factors:

- The tree species listed in Table 4.1
- The yield classes listed in Table 4.2 (with "candidate" results for single yield class used for some assessments)
- A climatic class of "warm moist"
- Soil classes of "loam", "gley" and "organo-mineral" (with mid-range "candidate" results based on "loam" used for some assessments)
- Previous land use of pasture/grassland
- Woodland management regimes of "Reserve", "Continuous cover", "Thin & fell" and "SRF".

An exception was made in the case of the coniferous tree species (Scots pine, Sitka spruce and Douglas fir), for which results for the management type of "Reserve" were not included in assessments, as this type of management was regarded as more relevant for broadleaf tree species.

4.1.7 Rotations

The CARBINE simulations for the "Thin & fell" management regime included in the ERAMMP scenarios involved assuming a rotation (i.e. a stand age at clearfelling). The rotations assumed for each tree species are listed in Table 4.3.

Table 4.3 Rotations assumed in "Thin & fell" management regime

Tree species	***Assumed rotation (years)***
BE	*100*
OK	*120*
BI	*70*
PO	*50*
SP	*70*
SS	*50*
DF	*70*

The assumption of a single, generic rotation for each tree species is a simplification. In reality, rotations will vary with respect to a number of biological and technoeconomic factors. In the case of commercial coniferous woodlands in particular, the rotation period will tend to show an inverse relationship with increasing yield class (although this is modulated by other practical factors and constraints). Of the rotations applied, notably, an assumption of 50 years is rather long for Sitka spruce with a yield class of 20. However, this assumption should not drastically influence the overall pattern of results, and the substance of comparisons between estimates for different tree species and management regimes should be unaffected.

4.1.8 ERAMMP results

The ERAMMP results based on CARBINE simulations relevant for this assessment consist of the following six estimates of potential GHG emissions impacts for a notional 1 hectare of woodland, established in the year 2020:

1. Carbon stock changes in living tree biomass, deadwood and litter
2. Carbon stock changes in soil under the woodland
3. Carbon stock changes in the biomass of wood products harvested from the woodland
4. GHG emissions from operations carried out as part of woodland establishment and management (e.g. machinery, materials and energy used in site preparation, weed control and tree harvesting)
5. Changes in GHG emissions associated with the use of harvested wood as fuel (bioenergy)
6. Changes in GHG emissions associated with the use of harvested wood in material products (e.g. paper, wood-based panels, pallets, fencing and structural timber).

Note that the CARBINE model reports separate estimates of carbon stock changes for living tree biomass, deadwood and litter but these have been combined in the ERAMMP results. It would be possible to produce disaggregated estimates but this is out of scope for this current assessment.

The last three categories of GHG emissions impacts listed above are not always included in assessments of the climate change mitigation potential of woodlands (e.g. Binner et al. 2018). Such an approach may be defendable when assessments are being made of the contributions of existing woodlands to climate change mitigation under existing policies and management practices. However, as explained in Section 2.2, according to the principles of consequential LCA, it is necessary to adopt a wide system boundary when assessing possible changes to forest policy, to land use involving woodlands or to the management of existing woodlands. In this context, the inclusion of these “off-site” GHG emissions impacts is necessary, to capture the full consequences of the actions being assessed. It should be noted that such an approach is not always accepted by some stakeholders, despite this being an essential requirement of the consequential LCA methodology.

The ERAMMP results are reported as annualised estimates of carbon stock changes or GHG emissions, with respect to three policy-relevant time horizons and a fourth time horizon representing the very long term:

1. 2020-2025
2. 2020-2050
3. 2020-2100
4. 200 years (2020-2220).

For example, taking the time horizon of 2020-2050, a result for soil carbon stock change is calculated as

$$\frac{\text{Cumulative change in soil carbon stocks per hectare from 2020 to 2050}}{2050 - 2020}.$$

Typically, the estimates for mitigation potentials and other impacts of woodland management options on carbon sinks and GHG emissions are expressed in units of tCO_2-eq. ha^{-1} yr^{-1} (carbon dioxide equivalent per hectare per year).

Negative results for carbon stock changes or GHG emissions indicate net carbon sequestration or net GHG emissions reductions (sometimes referred to as "GHG emissions savings"); positive results indicate net GHG emissions/increases.

For the purposes of generating the ERAMMP results, simple GHG emissions displacement factors were used to produce estimates of changes in GHG emissions associated with changes in the supply of wood fuel and material wood products (see Section 2.12):

- For wood fuel, an emissions displacement factor of 0.72 tC per tC of carbon in wood fuel was assumed
- For material products, an emissions displacement factor of 1 tC per tC of carbon in product woody biomass was assumed.

Note that, by convention, carbon sequestered in the woody biomass of products is included as part of wood-product stock-change results, hence these contributions are not included in estimates of GHG emissions reductions in other sectors through product substitution. This includes emissions of CO_2 and other GHGs from wood products that are disposed of at end of life. The approach to modelling does not explicitly allow for the possible re-use or recycling of wood products. It should be noted that the retention of carbon in woody biomass through the re-use and recycling of wood products is frequently allowed for when calculating estimates of GHG emissions displacement factors (e.g. the use of waste wood as a feedstock in the manufacture of particleboard). However, this is not done consistently in LCA studies and the representation of wood supply and utilisation chains explicitly including re-use and recycling is an area where modelling could be improved.

Results for woodland creation (afforestation)

The ERAMMP results were designed for the purpose of evaluating options for woodland creation. Hence, these estimates could be applied directly for this purpose in this assessment.

Results for avoidance of woodland loss (avoided deforestation)

Estimates of GHG emissions impacts associated with avoided woodland loss were calculated for all of the woodland types included in the assessment, with the exception of those representing Short Rotation Forestry (SRF), for which results were not considered relevant at present, given that currently no areas of SRF exist in Wales. The analysis was limited to the “candidate” results discussed earlier.

Losses of tree carbon stocks (and implied CO_2 emissions) avoided by preventing woodland loss were estimated by referring to results for long-term average carbon stocks in different woodland types as reported in the UK Woodland Carbon Code Carbon Calculation Spreadsheet. The woodland loss event that *would have* occurred was assumed to be prevented in 2020, avoiding the immediate loss of all tree carbon stocks in that year. Estimates of emissions avoided over different time horizons were calculated by dividing the long-term average carbon stock estimates (expressed in $tCO_2\ ha^{-1}$) by the period covered by the relevant time horizon (e.g. 5 years for the period 2020 to 2025).

Estimates for other impacts on GHG balances were more approximate:

- It was not possible to estimate avoided impacts on litter carbon stocks but these make a relatively small contribution to overall woodland carbon stocks.
- Continuing carbon sequestration in soil under the conserved woodland was estimated using the ERAMMP results for a 200-year time horizon.
- For woodland types involving wood production (“Avoided clearfell” and “Thin & fell” whilst “SRF” not included), continuing carbon sequestration in products and GHG emission displacement (by fuel and material products) were also estimated using the ERAMMP results for a 200-year time horizon. This also applied to continuing GHG emissions from woodland management operations.

The use of the 200-year estimates in calculations gives conservative estimates of continuing carbon sequestration and avoided GHG emissions.

Results for changes to management in existing woodlands

The ERAMMP and Woodland Carbon Code (WCC) results are not well suited for estimating the impacts on woodland carbon stocks and GHG emission that may occur as a result of changes to the management of existing woodlands. (Essentially, the results currently available are intended for assessing such impacts in relation to woodland creation.) The analysis was limited to the “candidate” results discussed earlier.

The best possible use was made of the ERAMMP and WCC results to estimate the impacts of different types of management interventions in existing woodlands. The resultant estimates should be regarded as uncertain and provisional, but offering an improvement on estimates reported previously (Matthews et al. 2017), having been generated using a more systematic and consistent set of data sources and calculation methods.

For any case considered, the general approach to calculations involved:

1. Identifying a pair of ERAMMP and WCC results, the first to represent woodland management before the specified intervention was made (the “Initial condition”) and the second to represent the situation after management has been changed (the “Final condition”)
2. Estimating the impacts on tree carbon stocks (i.e. the total change in tree carbon stocks) from the difference between the estimates for long-term

average carbon stocks (WCC results) for the Initial condition and the Final condition.
3. Estimating how long (in years) the total change in tree carbon stocks would be expected to take from the start of changing management.
4. Annualising the total tree carbon stock change by dividing by the relevant time horizon, or by the period over which the change would take place, whichever is the longer.
5. Estimating impacts on soil carbon sequestration or emissions from the difference between the relevant ERAMMP estimate for a 200-year time horizon, for the Initial condition and the Final condition. A similar approach was adopted for wood-product carbon stock changes and GHG emissions displaced through use of wood fuel and wood-based materials in place of other non-wood products.

Steps (2) to (4) above can be expressed mathematically as

$$\frac{\text{WCC carbon stock for Final condition} - \text{WCC carbon stock for Initial condition}}{\max(\text{Estimated Duration of change, Time horizon})}.$$

The use of the 200-year estimates in calculation step (5) above gives conservative estimates of impacts on continuing carbon sequestration and avoided GHG emissions.

Table 4.4 gives details of the results referred to in estimating the GHG impacts of different types of management interventions in existing woodlands. Additional assumptions were needed when considering interventions involving conversion to species mixtures or to tree species and growth rates. Details are given in Table 4.5.

Table 4.4 WCC and ERAMMP results and assumptions referred to in estimating GHG impacts of management interventions in existing woodlands

<table>
<tr><th rowspan="2">Intervention</th><th colspan="3">Tree carbon stock change (based on long-term average carbon stock estimates from Woodland Carbon Code Carbon Calculation Spreadsheet)</th><th rowspan="2">Litter carbon stock change</th><th colspan="2">Wood products carbon stock change/displaced GHG emissions (ERAMMP results, 200-year time horizon)</th></tr>
<tr><th>Initial condition</th><th>Final condition</th><th>Duration</th><th>Initial condition</th><th>Final condition</th></tr>
<tr><td>Longer rotation</td><td>WCC estimate for thinned stand

Rotation in Table 4.3</td><td>WCC estimate for thinned stand

Rotation in Table 4.3 + 10 years</td><td>10 years</td><td rowspan="3">Not included (could not be estimated from available results)

Relatively small contribution to overall result</td><td colspan="2">Assumed to be 10% of results for “Avoid clearfelling” (see below)</td></tr>
<tr><td>Avoid clearfelling</td><td>WCC estimate for thinned stand

Rotation in Table 4.3</td><td>WCC estimate for thinned stand

Rotation in Table 4.3 + 25 years</td><td>25 years</td><td>“Thin & fell” results</td><td>“Continuous cover” results</td></tr>
<tr><td>Restrict production/convert to wilderness</td><td>WCC estimate for thinned stand

Rotation in Table 4.3</td><td>WCC estimate for unthinned stand

Rotation 200 years

For initial coniferous stands, use mean of results for BE, OK, BI and PO</td><td>200 years minus rotation in Table 4.3</td><td>“Thin & fell” results</td><td>“Reserve” results

For initial coniferous stands, use mean of results for BE, OK, BI and PO</td></tr>
<tr><td>Adjust rotation closer to optimum production</td><td colspan="6">Inverse of “Longer rotations”</td></tr>
<tr><td>Mobilise unmanaged woodlands</td><td colspan="6">Inverse of “Restrict production/Convert to wilderness”</td></tr>
<tr><td>Change species</td><td colspan="6">See Table 4.5</td></tr>
<tr><td>Harvest offcuts and branchwood</td><td colspan="6">Estimates based on Matthews et al. (2017), Section 8.4.5, Table 8.1</td></tr>
</table>

Table 4.5 Details of WCC and ERAMMP results and assumptions referred to in estimating GHG impacts of management interventions in existing woodlands involving transformation to mixtures or restocking with genetically improved trees

Change	Tree carbon stock change (based on long-term average carbon stock estimates from (Woodland Carbon Code Carbon Calculation Spreadsheet)			Wood products carbon stock change/displaced GHG emissions (ERAMMP results, 200-year time horizon)	
	Initial condition	Final condition	Duration	Initial condition	Final condition
SP to broadleaf mixture	SP, WCC estimate for thinned stand Rotation in Table 4.3	Mean of OK and BI WCC estimates for thinned stands Rotation in Table 4.3 + 25 years	145 years (OK rotation in Table 4.3 + 25 years)	SP, “Thin & fell”	Unchanged for time horizon to 2025. Mean of “Continuous cover” for OK and BI
SS to broadleaf mixture	SS, WCC estimate for thinned stand Rotation in Table 4.4	Mean of OK and BI WCC estimates for thinned stands Rotation in Table 4.3 + 25 years	145 years (OK rotation in Table 4.3 + 25 years)	SS, “Thin & fell”	Unchanged for time horizon to 2025. Mean of “Continuous cover” for OK and BI
SS to coniferous mixture	SS, WCC estimate for thinned stand Rotation in Table 4.3	Mean of SS and DF WCC estimates for thinned stands Rotation in Table 4.3 + 25 years	95 years (DF rotation in Table 4.3 + 25 years)	SS, “Thin & fell”	Unchanged for time horizon to 2025. Mean of “Continuous cover” for SS and DF
SS to improved SS (same rotation)	SS, WCC estimate for thinned stand Rotation in Table 4.3	SS, WCC estimate for thinned stand, yield class changed to 20 Rotation in Table 4.3	50 years (Rotation in Table 4.3)	SS, “Thin & fell”	SS, “Thin & fell”, yield class changed to 20
SS to improved SS (shortened rotation)	Long-term stock change assumed to be negligible (see Sections A1.4 and A1.8 in Appendix A1)			SS, “Thin & fell”	SS, “Thin & fell”, yield class changed to 20

The estimates of Duration in Tables 4.4 and 4.5 are essentially assumptions, based on the details (also assumed) of the management interventions. For example, the impacts on woodland carbon stocks arising from extending a rotation by 10 years (see Table 4.3) are assumed to occur over 10 years (i.e. until the stand of trees is felled 10 years later). Such an approach is simplistic but should give robust results particularly over longer time horizons.

The estimates derived for different types of management interventions in existing woodlands using the above do not include an allowance for impacts on carbon stocks in litter and deadwood because these could not be inferred from the available WCC and ERAMMP results. The carbon stock changes involved are likely to be small compared with those in other components of woodland carbon, notably living tree biomass.

4.2 Introduction to assessment results

Figure 4-1 is an illustration of a set of assessment results for the scenario of woodland creation for a woodland type of:

- Scots pine
- Yield class 8
- Warm, moist climate regime (assumed in all of the results referred to in this assessment)
- Loam soil
- Previous land use of pasture/grassland (assumed in all of the results referred to in this assessment)
- “Thin & fell” management regime.

This is the “candidate” result (see earlier) for Scots pine under a management regime of Thin and fell.

The woodland is assumed to be created in 2020.

For each of the four specified time horizons (2020-2025, 2020-2050, 2020-2100 and 200 years), the figure shows the contributions made to the overall impacts of woodland creation on GHG emissions by:

- Carbon stock changes in soil (“Soil”)
- Carbon stock changes in trees, deadwood and litter (“Trees & litter”)
- Carbon stock changes in wood products produced from the woodland (“Products”)
- GHG emissions from operations carried out in the woodlands such as from machinery used in site preparation and harvesting (“Operations”)
- Changes in GHG emissions as a result of using wood fuel supplied from the woodland in place of fossil fuels (“Energy”)
- Changes in GHG emissions as a result of using wood-based products supplied from the woodland in place of non-wood products (“Materials”).

The estimates are expressed in units of tCO_2-eq. ha^{-1} yr^{-1} (carbon dioxide equivalent per hectare per year). Negative results for carbon stock changes or GHG emissions indicate net carbon sequestration or net reductions in GHG emissions; positive results indicate net losses of carbon stocks or net GHG emissions.

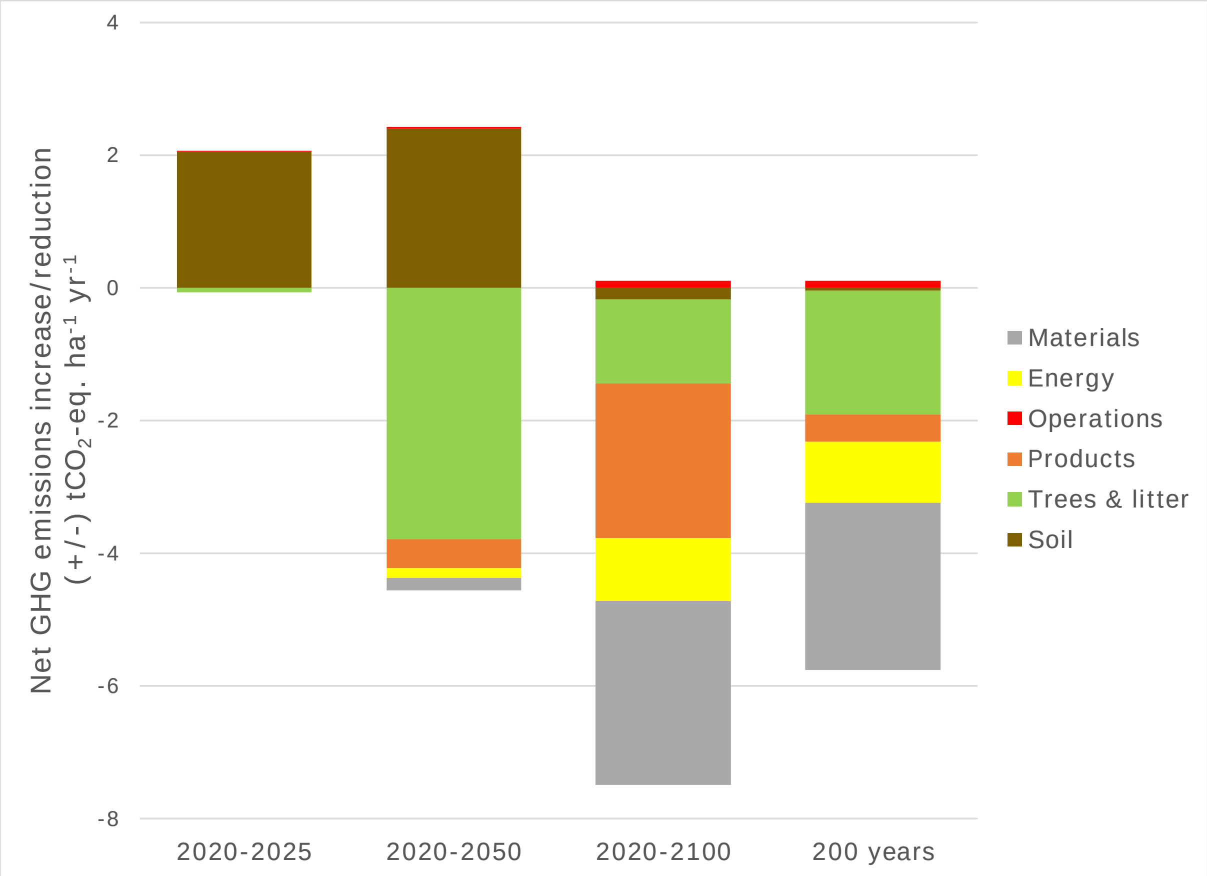

Figure 4-1 An example of the ERAMMP results referred to in this assessment. The example illustrates the impacts on GHG emissions of creating a new Scots pine woodland managed for wood production.

A number of features are evident in the results in Figure 4-1, as discussed below.

Time horizon 2020-2025

Initially, the GHG balance is dominated by net CO_2 emissions from loss of soil carbon stocks (2.0 $tCO_2\ ha^{-1}\ yr^{-1}$), which occur as a result of site preparation and the time involved in the transition occurring between the loss of pre-existing vegetation on the site and the full establishment of the trees.

Time horizon 2020-2050

Over this somewhat longer time horizon, CO_2 emissions from loss of soil carbon stocks remain significant (2.4 $tCO_2\ ha^{-1}\ yr^{-1}$) but these emissions are more than balanced by carbon sequestration in the living biomass of trees and in deadwood and litter (-3.8 $tCO_2\ ha^{-1}\ yr^{-1}$), as the trees grow through their full-vigour phase (see Section 2.5, Figure 2-4). There is also a modest contribution to carbon sequestration in the form of carbon stock increases in wood products (-0.4 $tCO_2\ ha^{-1}\ yr^{-1}$). This relatively small contribution represents production from smaller trees harvested in thinnings. At this point GHG emissions impacts arising from fuel and product substitution effects (see Section 2.12) are almost negligible, reflecting the relatively recent start of wood production from the woodland (as thinnings) over this time horizon.

Time horizon 2020-2100

Over the time horizon to the end of this century, the contribution from soil carbon stock changes has switched from a significant net loss (CO_2 emissions) to a small net sink (net carbon sequestration). This occurs as a result of the woodland having become fully established and grown to maturity, so that inputs of organic matter to the soil from living trees (notably via fine roots) and decaying deadwood and litter more than compensate for the initial losses of organic matter from soil.

The net carbon sink (rate of carbon sequestration) in trees, deadwood and litter over this time horizon has declined (-1.3 tCO_2 ha^{-1} yr^{-1}), compared with the 30-year period represented by the time horizon of 2020-2050. This is because by 2100 the trees have grown beyond the phase of full-vigour growth and have reached maturity, with slower associated growth and carbon sequestration. In fact, by 2100 the woodland has been clearfelled and restocked (70-year rotation, see Section 4.1.7, Table 4.3). Essentially, the rate of carbon sequestration is exhibiting “saturation” (see Section 2.7).

In contrast, carbon sequestration in wood products is significant over this time horizon, and greater in magnitude compared with that of trees, deadwood and litter, at -2.3 tCO_2 ha^{-1} yr^{-1}. This also reflects the fact that the time horizon encompasses the first clearfelling of the woodland, i.e. the most significant production event over the rotation of the woodland. For similar reasons, by this period, there are significant contributions to GHG emissions reductions from wood fuel substituting for other fuels and wood products substituting for other more GHG-intensive non-wood products (-0.9 tCO_2 ha^{-1} yr^{-1} and −2.8 tCO_2 ha^{-1} yr^{-1} respectively). GHG emissions from forest operations are almost negligible.

It is appropriate to repeat a note of caution must be sounded with regard to the results for wood fuel and wood product substitution, as discussed in Section 2.12. It may be possible and defendable to make reasonable assumptions about the kinds of commodity that wood fuel and wood products substitute for under current conditions (e.g. fossil fuels, grid electricity and products made from steel, plastic or concrete using current manufacturing processes). However, this becomes more challenging the further projections are made into the future. Assuming that efforts are made to decarbonise across all economic sectors, it may be expected that the GHG emissions associated with the manufacture of non-wood products will decrease in the future. Furthermore, the consumption of fossil fuels is likely to decline significantly in the future, assuming that fossil fuel reserves will become depleted, if for no other reason. This highlights the very high uncertainty that should be attached to estimates of GHG emissions displaced by wood fuel and wood products in the longer term. Amongst the implications of this point, this emphasises a requirement for the forestry and wood processing sectors to minimise GHG emissions from woodland management and wood product supply chains (including those contributed by carbon stock changes in woodlands).

200-year time horizon

Over 200 years, carbon sequestration in trees, deadwood, litter, soil and wood products is diminishing. (The slight increase in the estimate for the category, “Trees & litter” in Figure 4-1 compared with the time horizon 2020-2100 is an artefact of the combination of the periods covered by these two time horizons and the rotations selected for the example woodland in Figure 4-1 of 70 years. In reality, the carbon sink in the woodlands has completely saturated beyond 2100.)

Only contributions to GHG reductions from wood fuel and product substitution are sustained in the longer term. However, cautionary remarks above about such estimates should be recalled here.

Overall impacts on GHG emissions

As the time horizon is expanded from 5 years (2020-2025) to 30 years, 80 years and finally 200 years, the combined contributions from carbon stock changes in trees, deadwood, litter, soil and wood products initially result in annualised net CO_2 emissions of 2.0 tCO_2 ha^{-1} yr^{-1}, switching to annualised net carbon sequestration of -1.8 tCO_2 ha^{-1} yr^{-1}, which increases in magnitude to -3.8 tCO_2 ha^{-1} yr^{-1} and then declines to -2.3 tCO_2 ha^{-1} yr^{-1}. The decline reflects the saturation of the woodland carbon sink in later decades.

The contributions to net GHG emissions reductions from product substitution only become significant over longer time horizons, reflecting the time lag between establishment of the woodland in 2020 and the development of the woodland to the stage where significant wood production becomes possible. However, once wood production comes on stream, product substitution (including wood fuel) makes a sustained contribution to GHG emissions reductions of about -3.5 tCO_2 ha^{-1} yr^{-1}. Earlier cautionary remarks about these types of contributions should be recalled.

4.2.1 Alternative presentation of results

When interpreting results used in this assessment, such as depicted in Figure 4-1, it is very important to understand how results for different time horizons have been calculated and reported. As described in Section 4.1.8, the results for the period 2020-2100 (for example) have been calculated by

- Adding up all of the relevant carbon stock changes and GHG emissions changes over the full period from 2020 to 2100
- Dividing the result by the duration of the period, i.e. 80 years (annualising).

This means that the results for the four time horizons considered are not independent of one another. For example, when the results for the time horizon 2020-2100 are compared with those for a shorter time horizon, such as 2020-2050, the estimates for 2020-2100 include the carbon stock changes and GHG emissions changes for the shorter period. An important implication is that the results for the 2020-2100 time horizon do not represent annualised results for a period that is separate and sequential to the period 2020-2050, as would be the case if a time horizon of 2051-2100 was adopted instead. The question may arise as to what the results would look like if calculated for successive sequential periods (rather than the overlapping periods considered in Figure 4-1), i.e. 2020-2025, 2026-2050, 2051-2100 and 2101-2220. It is possible to derive such estimates from the ERAMMP results and an example of such a set of estimates is shown in Figure 4-2. This figure is based on results for the same example woodland creation scenario as considered in Figure 4-1. Essentially, the results in Figure 4-2 are the same as in Figure 4-1 but presented in a different way, as explained above.

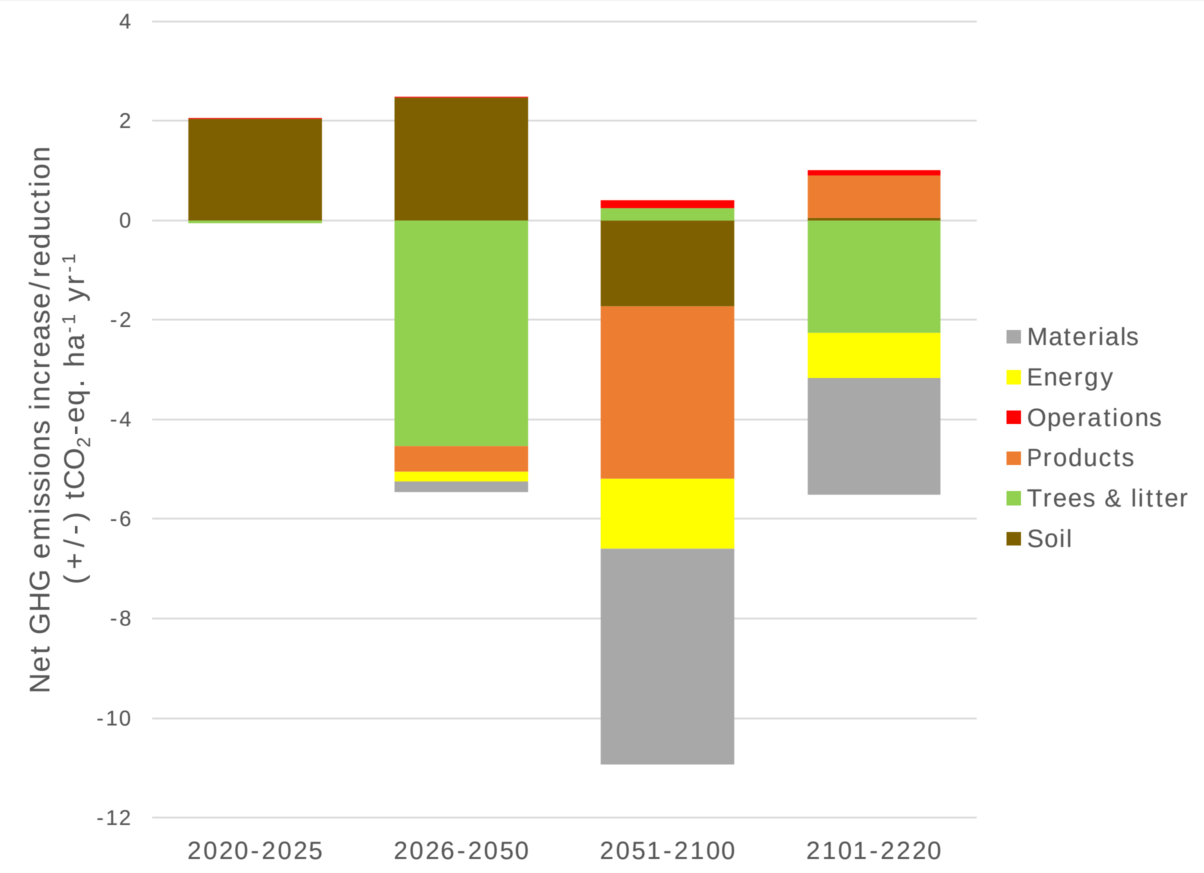

Figure 4-2 An example of the ERAMMP results referred to in this assessment. These results are the same as those in Figure 4-1 but the periods to which the results apply are different (compare x-axes).

Figure 4-2 highlights the variation in the different contributions for the successive and sequential periods, notably:

- Net loss of soil carbon stocks in the periods 2020-2025 and 2020-2050, counterbalanced by net soil carbon sequestration in the period 2051-2100.
- The concentration of carbon sequestration in trees, deadwood and litter in the period 2025-2050, a period that encompasses the full-vigour phase of growth of the woodland created in 2020.
- Effectively no carbon sequestration in the trees, deadwood and litter in the period 2051-2100 (in fact a small net loss), reflecting the clearfelling of the woodland towards the end of the period (in the year 2090).
- Recovery of carbon sequestration in trees, deadwood and litter in the period 2101-2220. In fact by this time the woodland is “cycling” between net loss of carbon stocks and net carbon sequestration (see for example Appendix A1, Section A1.4). This result is a snapshot for an arbitrary 120-year period in the life cycle of the woodland (covering the end of the second rotation and the start of the third rotation), for which the result happens to indicate net carbon sequestration.
- A particularly large contribution from carbon sequestration in wood products in the period 2051-2100, reflecting the first clearfelling of the woodland (i.e. the most significant production event in the first rotation) towards the end of the period.

- A decline in the rate of carbon sequestration in wood products in the period 2101-2220, reflecting saturation, as some wood products manufactured in earlier periods start to be disposed of, leading to the onset of losses of carbon from wood products, which begin to balance out the additions from new wood products.
- A particularly large contribution to GHG emissions reductions from product substitution (wood fuel and particularly materials) in the period 2051-2101, reflecting the clearfelling of the woodland towards the end of the period (in the year 2090).
- A lower contribution to GHG emissions reductions from product substitution in the period 2101-2220, reflecting levels of wood production closer to the average annual levels over a full rotation in this period, compared with the period 2051-2100.

Earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here.

Assessments based on the analysis and interpretation of estimates calculated and reported according to the conventions adopted in Figure 4-1 and Figure 4.2 both have their merits and limitations. The former approach has been taken for the assessment presented in this annex but the ERAMMP results could be re-analysed using the alternative conventions illustrated in Figure 4-2.

Figure 4-3 is another illustration of a set of assessment results, this time for a scenario of woodland creation for a woodland type of:

- Oak
- Yield class 8
- Warm, moist climate regime
- Loam soil
- Previous land use of pasture/grassland
- “Reserve” management regime (i.e. effectively management based on minimum intervention and in particular no harvesting).

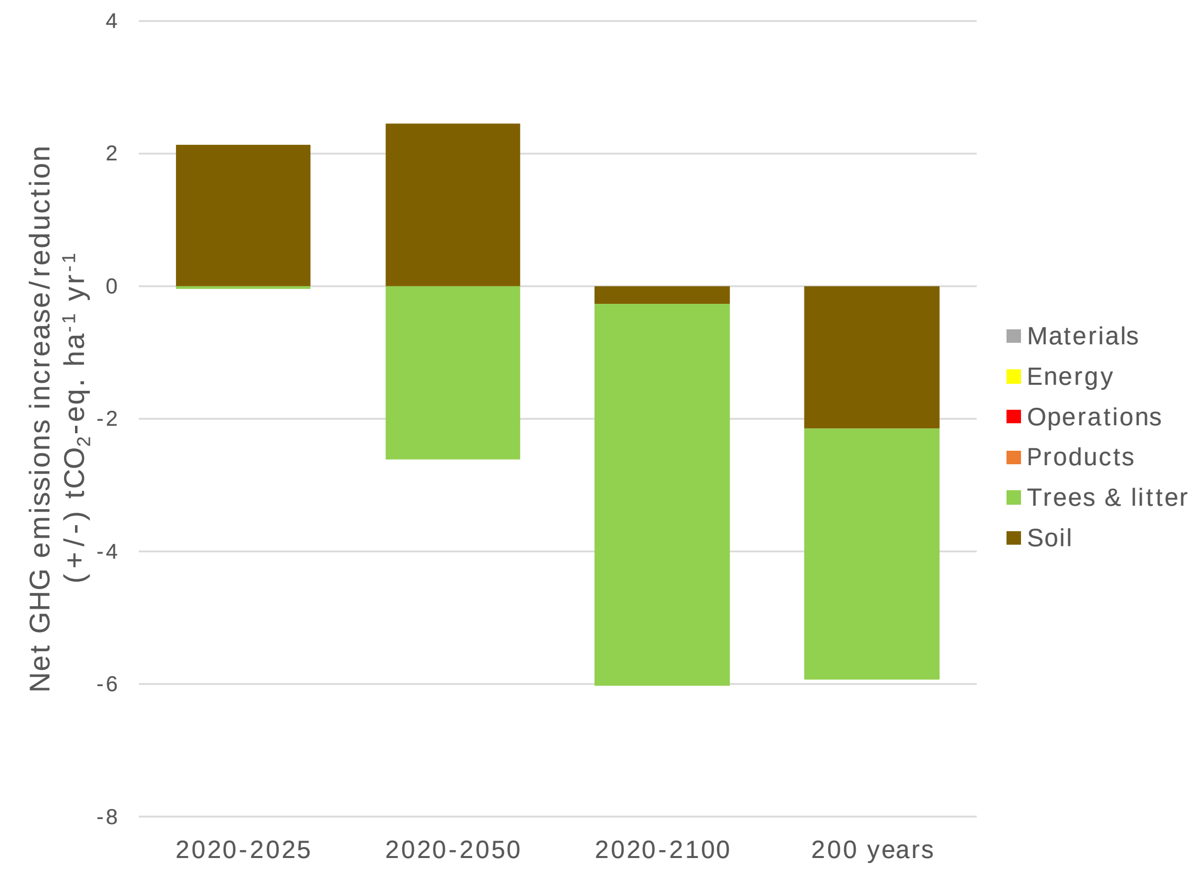

Figure 4-3 An example of the ERAMMP results referred to in this assessment. The example illustrates the impacts on GHG emissions of creating a new oak woodland managed as a woodland carbon reserve

Comparing the results for the four time horizons, the overall pattern is broadly similar to that exhibited in Figure 4-1. However, all of the impacts are contributed by carbon stock changes in trees, deadwood, litter and soil, since no harvesting for wood production is practiced under this scenario. Some other important differences can be identified in Figure 4-3, compared with Figure 4-1:

- In the period 2020-2050 in Figure 4-3, CO_2 emissions arising from losses of carbon stocks in soil continue to almost completely offset carbon sequestration in trees, deadwood and litter. Losses of soil carbon stocks are similar in the two scenarios in Figures 4-1 and 4-3 but carbon sequestration in the broadleaf trees in considered Figure 4-3 takes longer to reach the full-vigour phase, because of the time involved for a relatively slow-growing stand of oak to become established.
- Whilst annualised total net carbon sequestration in the oak woodland is almost negligible for the period 2020-2050, net carbon sequestration over longer time horizons is greater than that estimated for the example in Figure 4-1, and is sustained for longer. Carbon stock changes in trees, deadwood, litter and soil all contribute to carbon sequestration over longer time horizons. This reflects the capacity for ongoing growth in a woodland comprising slow-growing by enduring tree species such as oak (under UK conditions), when managed with minimum intervention including no harvesting.

- It is apparent that carbon sequestration in trees, deadwood and litter is declining in the 200-year time horizon, compared with the period 2020-2100, as saturation sets in. This is almost compensated for by increased carbon sequestration in soil, reflecting the high inputs of carbon to the soil in the mature, undisturbed woodland. Ultimately, this soil carbon sink will also saturate, although net carbon sequestration is nevertheless sustained over a period of a century or more.

4.3 Woodland creation (afforestation)

Figures 4-4, 4-5, 4-6 and 4-7 show the “candidate” results for GHG impacts, for creating woodlands with different tree species and management regimes represented in the ERAMMP results, respectively, for time horizons of 2020-2025, 2020-2050, 2020-2100 and 200 years. The different contributions to overall impacts are shown, similarly to the example Figures 4-1 and 4-3 considered previously.

Note that results are not given for the “Reserve” management regime in the case of the coniferous tree species (Scots pine, Sitka spruce and Douglas fir), as this type of management was regarded as more relevant for broadleaf tree species.

A number of features are apparent in these figures, as discussed below.

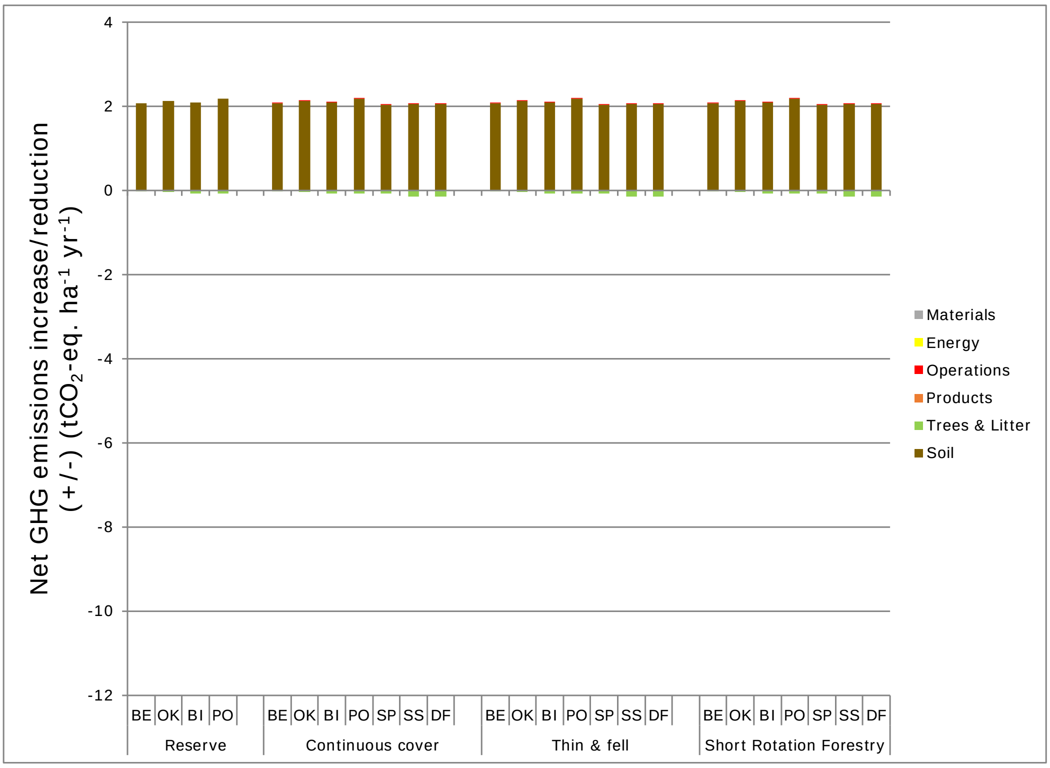

Figure 4-4 Estimated impacts on GHG emissions for different woodland creation options, showing contributions from different elements of carbon sequestration and product substitution: time horizon 2020-2025.

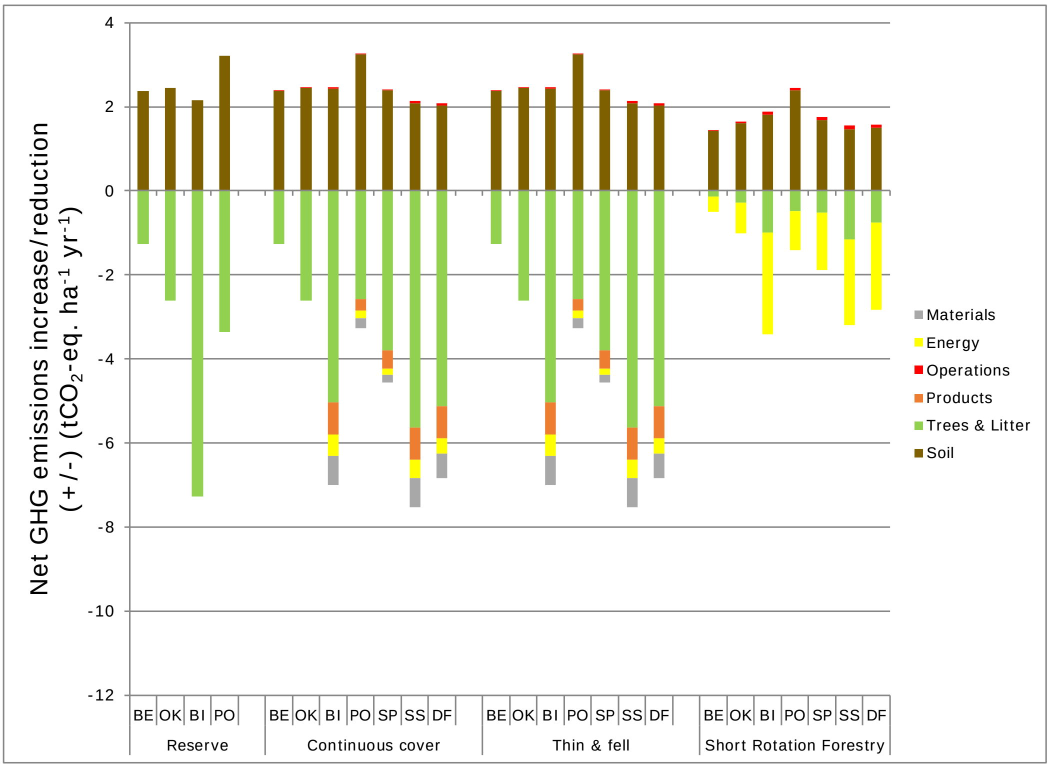

Figure 4-5 Estimated impacts on GHG emissions for different woodland creation options, showing contributions from different elements of carbon sequestration and product substitution: time horizon 2020-2050.

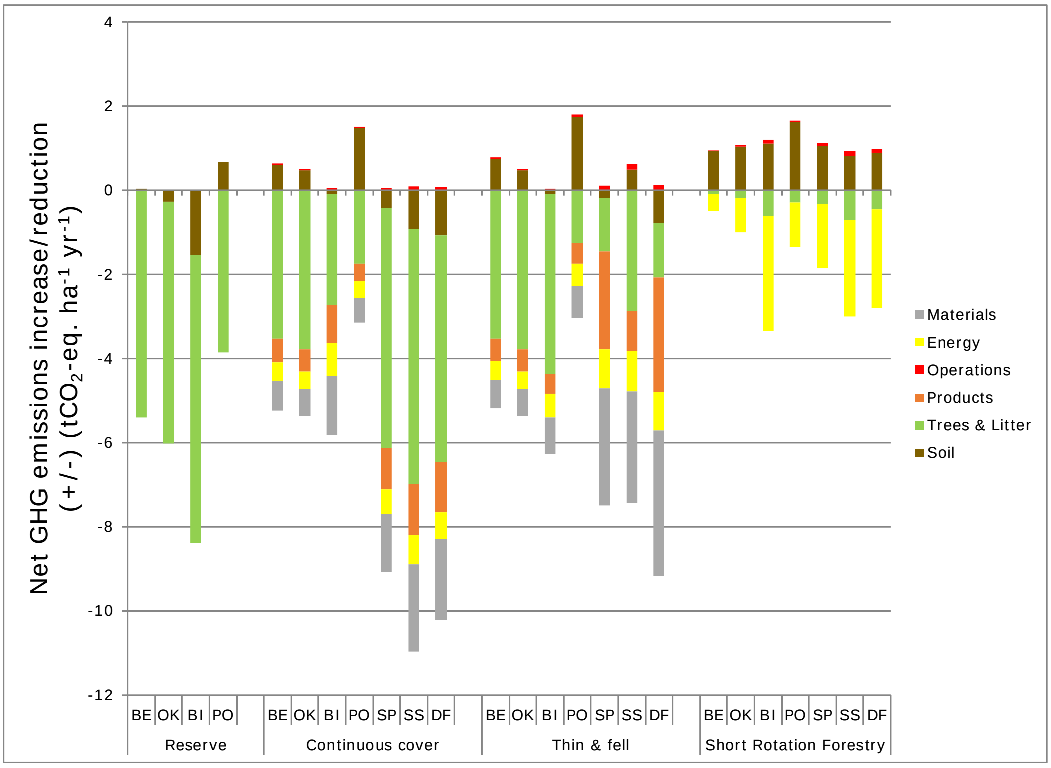

Figure 4-6 Estimated impacts on GHG emissions for different woodland creation options, showing contributions from different elements of carbon sequestration and product substitution: time horizon 2020-2100.

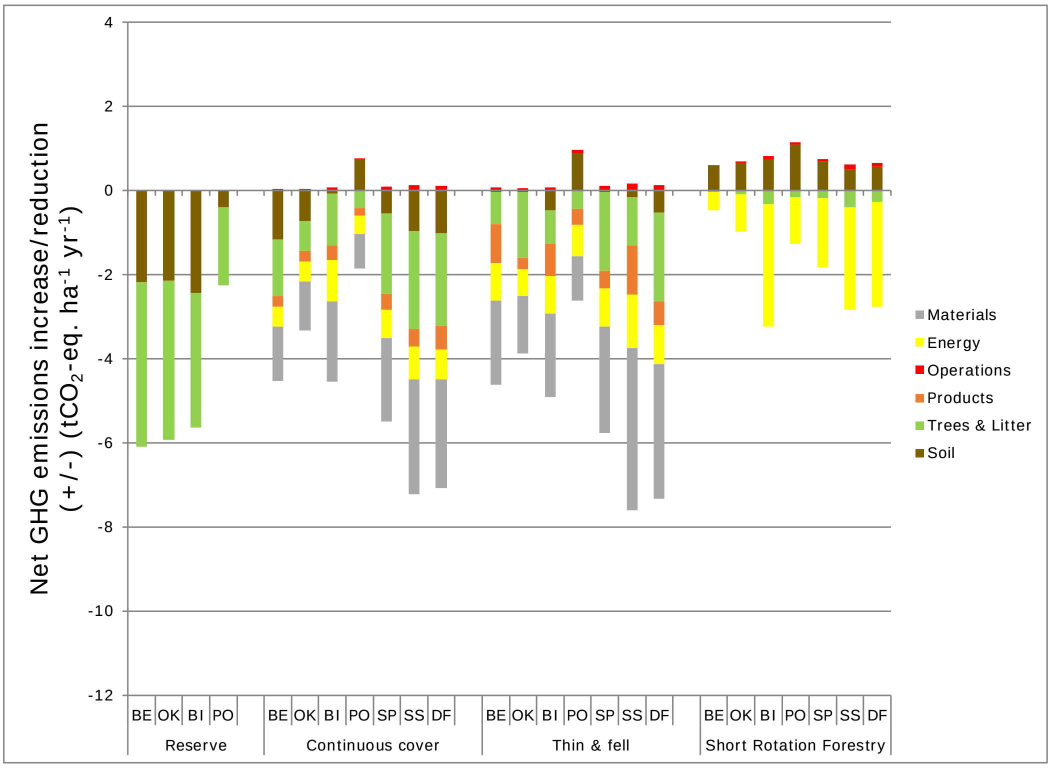

Figure 4-7 Estimated impacts on GHG emissions for different woodland creation options, showing contributions from different elements of carbon sequestration and product substitution: time horizon 200 years.

Figure 4-4 (time horizon 2020-2025)

In all cases, initially, the GHG balance is dominated by net CO_2 emissions from loss of soil carbon stocks, which occur as a result of site preparation and the time involve in the transition occurring between the loss of pre-existing vegetation on the site and the full establishment of the trees.

Figure 4-5 (time horizon 2020-2050)

Across all relevant management regimes, coniferous tree species (SP, SS, DF) are consistently exhibiting significant net CO_2 sequestration and GHG emissions reductions. Results for broadleaf tree species are more variable, with net GHG emissions estimated for beech, net carbon sequestration for birches, and modest net carbon sequestration for oak and aspen/black poplar. These results for broadleaf tree species reflect the relatively low growth rates compared with coniferous tree species and the time taken for the woodlands to become fully established. The better result for birches reflects a higher assumed yield class, revealing the importance of tree growth rate in determining outcomes (e.g. net loss or gain of carbon stocks) over this time horizon.

For the majority of the scenarios, the main contributions determining net GHG emissions increases or reductions over this time horizon are the carbon stock changes in trees, deadwood, litter and soil. Generally, carbon sequestration in wood products and potential product substitution effects make minor contributions over this time horizon.

The scenarios for the SRF management regime are an exception with respect to the previous point: carbon sequestration in woodlands is quite limited (as a result of the management of SRF on a relatively short rotation of 25 years) but contributions estimated for wood fuel displacing fossil energy sources are significant. Generally, the results for the SRF management regime are variable and estimates of GHG emissions reductions (where these are observed) are generally lower than for the other management regimes considered.

For the non-SRF management regimes, it is pertinent to note that all three management scenarios considered include example results with significant net CO_2 sequestration over this time horizon. This indicates that no particular option (broadleaf or conifer, manage for production or leave as a reserve) stands out as “better” than the others. Some qualification of this point: the results for the “Continuous cover” management regime are almost the same as for the “Thin & fell” regime over this time horizon. This is because the management of the newly created woodlands only deviates for these two regimes over longer timescales. (Beyond this time horizon, for “Thin & fell”, there is clearfelling on the assigned rotation followed by restocking with another even-aged stand of trees; for “Continuous cover”, transformation to an uneven-aged woodland is managed by continuous thinning and encouraging regeneration.)

Figure 4-6 (time horizon 2020-2100)

Over this time horizon, the different estimates of net carbon sequestration for the management regimes of “Reserve”, “Continuous cover” and “Thin & fell” overlap and all these options can result in significant net carbon sequestration. For the

“Continuous cover” and “Thin and fell” management scenarios, this is “topped up” by carbon sequestration in wood products and by GHG emissions reductions through potential product substitution. Earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here.

Results for SRF scenarios are still variable (still giving net GHG emissions in some cases) and generally net GHG emissions reductions (where realised) are lower than for the other management regimes considered. Nevertheless, net GHG emissions reductions can still be significant for some SRF cases (generally those involving higher tree growth rates).

Figure 4-7 (200-year time horizon)

Over this time horizon (particularly in comparison to 2020-2050 and 2020-2100), reduced rates of carbon sequestration are apparent, as a result of the onset of saturation. This is the case for all management regimes but carbon sequestration is most sustained for the “Reserve” scenarios, in which interventions such as harvesting are avoided.

Scenarios for the “Continuous cover” and “Thin & fell” management regimes exhibit a balance between reduced carbon sequestration but sustained GHG emissions reductions through product substitution. Earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here.

Scenarios involving SRF are still variable but with some cases (where tree growth rates are relatively high) giving moderate net GHG emissions reductions, compared with results for the other management regimes. Nearly all of these emissions reductions in SRF cases are achieved through wood fuel substituting for fossil fuels.

4.3.1 Woodland creation: all scenarios

In Figures 4-8 to 4-11, results are shown for total annualised GHG emissions decreases or increases, for the full set of ERAMMP results representing all the woodland creation scenarios considered in this assessment (see Section 4.1 for description). Figures 4-8, 4-9, 4-10 and 4-11 show, respectively, results for the time horizons of 2020-2025, 2020-2050, 2020-2100 and 200 years.

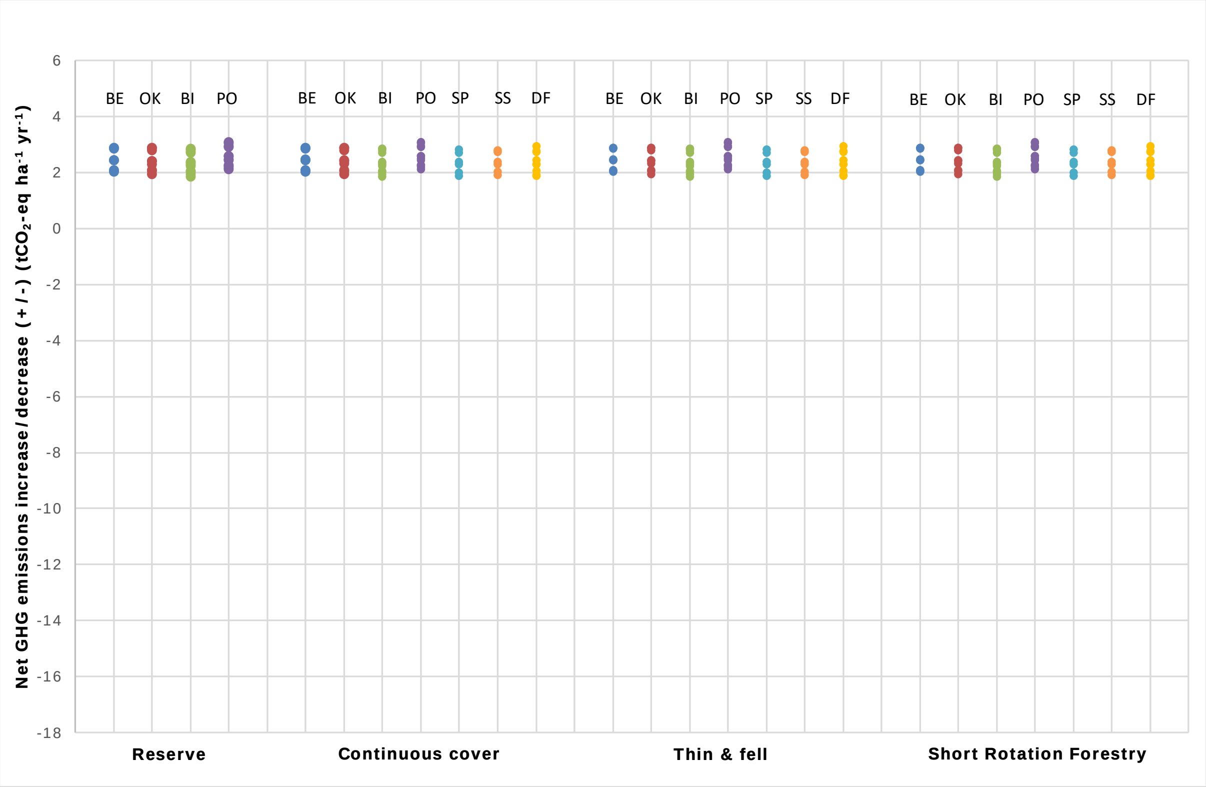

Figure 4-8 Estimated net impacts on GHG emissions for different woodland creation options time horizon 2020-2025.

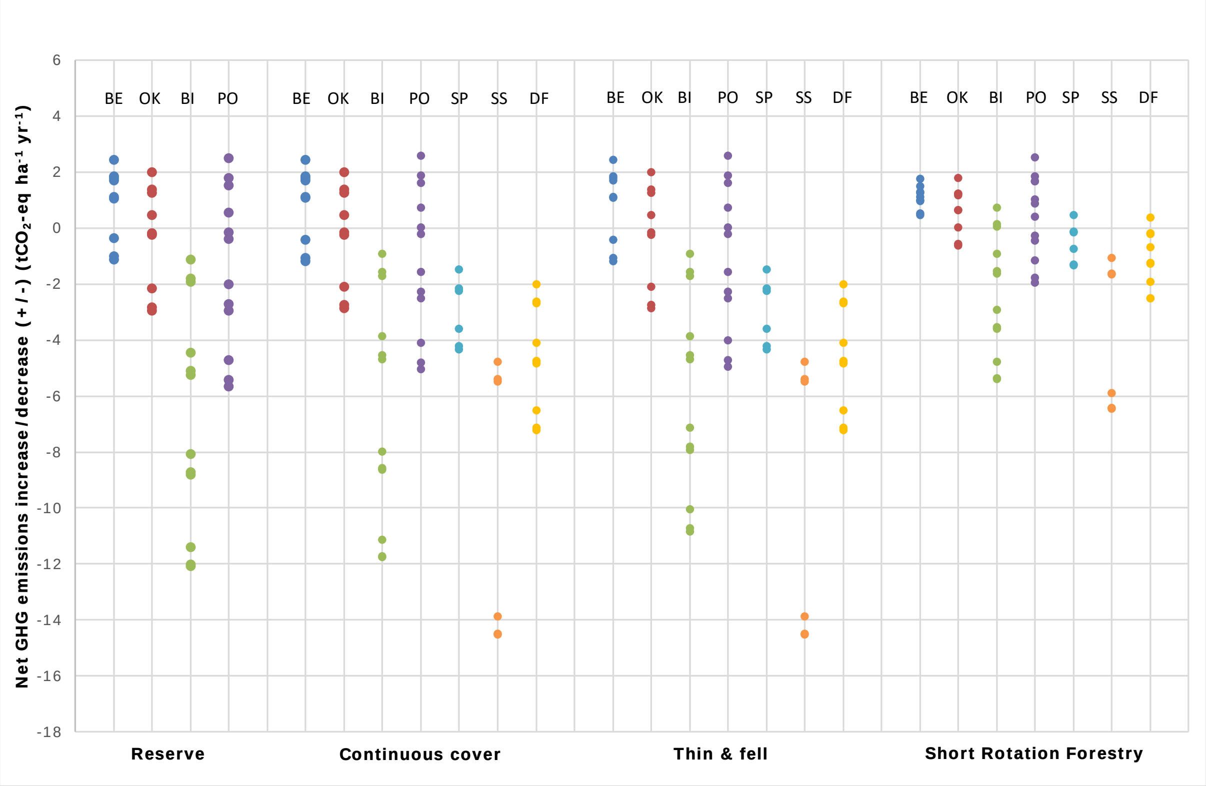

Figure 4-9 Estimated net impacts on GHG emissions for different woodland creation options time horizon 2020-2050.

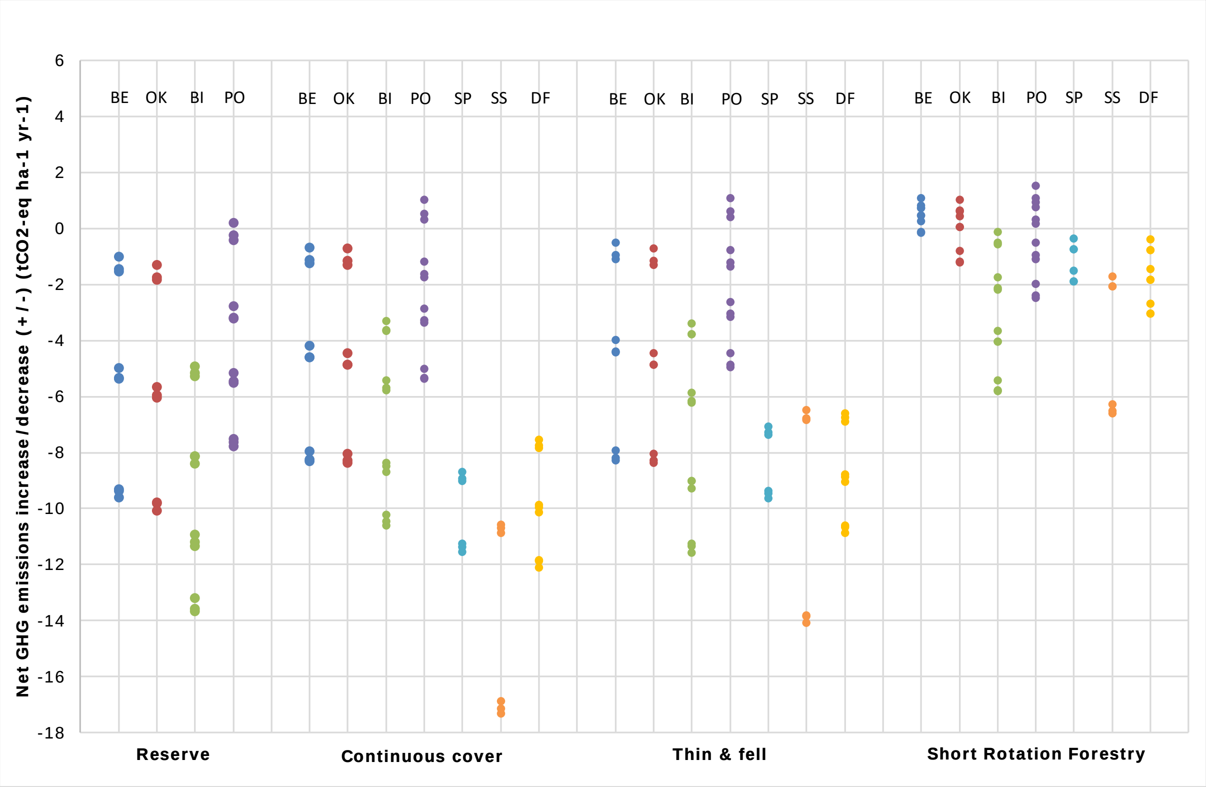

Figure 4-10 Estimated net impacts on GHG emissions for different woodland creation options time horizon 2020-2100.

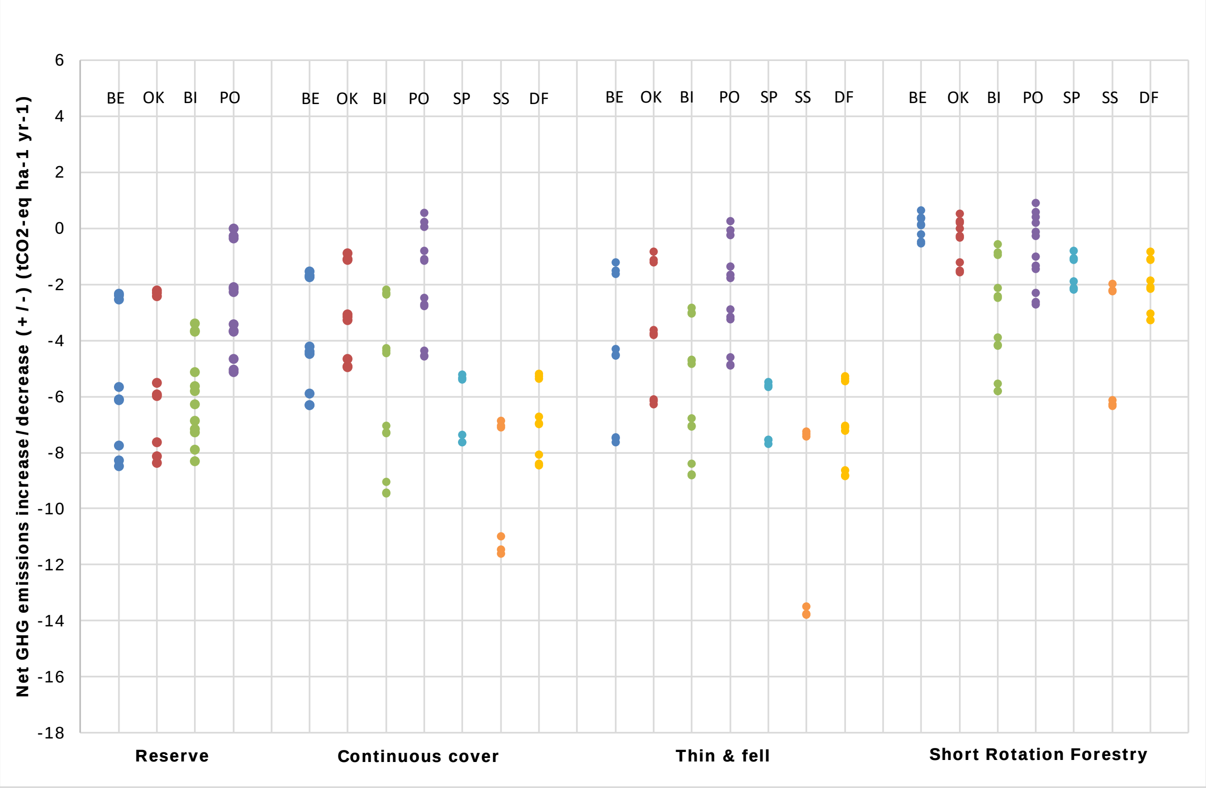

Figure 4-11 Estimated net impacts on GHG emissions for different woodland creation options time horizon 200 years.

The estimates for different time horizons and scenarios in Figures 4-8 to 4-11 exhibit the same general patterns as already described for the set of "candidate" results in Figures 4-4 to 4-7. However, the ranges in the results are wider, with net GHG emissions increases up to 3 tCO_2 ha^{-1} yr^{-1} and net GHG emissions reductions of nearly -18 tCO_2 ha^{-1} yr^{-1} in some cases. The worse cases are associated with scenarios involving low tree growth rates (yield class 2 or 4), particularly in combination with woodland creation on an organo-mineral soil.

These results confirm that all the scenarios considered (in terms of tree species and management regimes) have the potential to contribute to climate change mitigation. However, GHG emissions reductions contributed by SRF scenarios appear to be more modest, compared with the other management regimes considered. For management regimes involving wood production, a component of the GHG emissions reductions is contributed by product substitution (wood fuel and materials). It is important to recall earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution.

4.4 Prevention of woodland loss (avoidance of deforestation)

Figure 4-12 shows the GHG emissions reductions estimated for activities involving the avoidance of woodland loss, for the time horizon of 2020-2025. The different contributions to overall impacts are shown, similarly to the examples for woodland creation considered in Figures 4-1 and 4-3. The estimates have been derived from calculations based on the "candidate" results for the range of tree species and management regimes covered in this assessment (see Section 4.1). Only the time horizon of 2020-2025 is included as a figure for this type of activity. This is because the impacts on GHG emissions are dominated by contributions from the tree carbon stocks conserved by avoiding the loss of the woodland, which occur over a short period (i.e. the period in which the woodland would have otherwise been felled and a change of land use would have occurred). This is apparent in Figure 4.21. There are other smaller but important and longer-term contributions to GHG emissions reductions, which are also discussed briefly below.

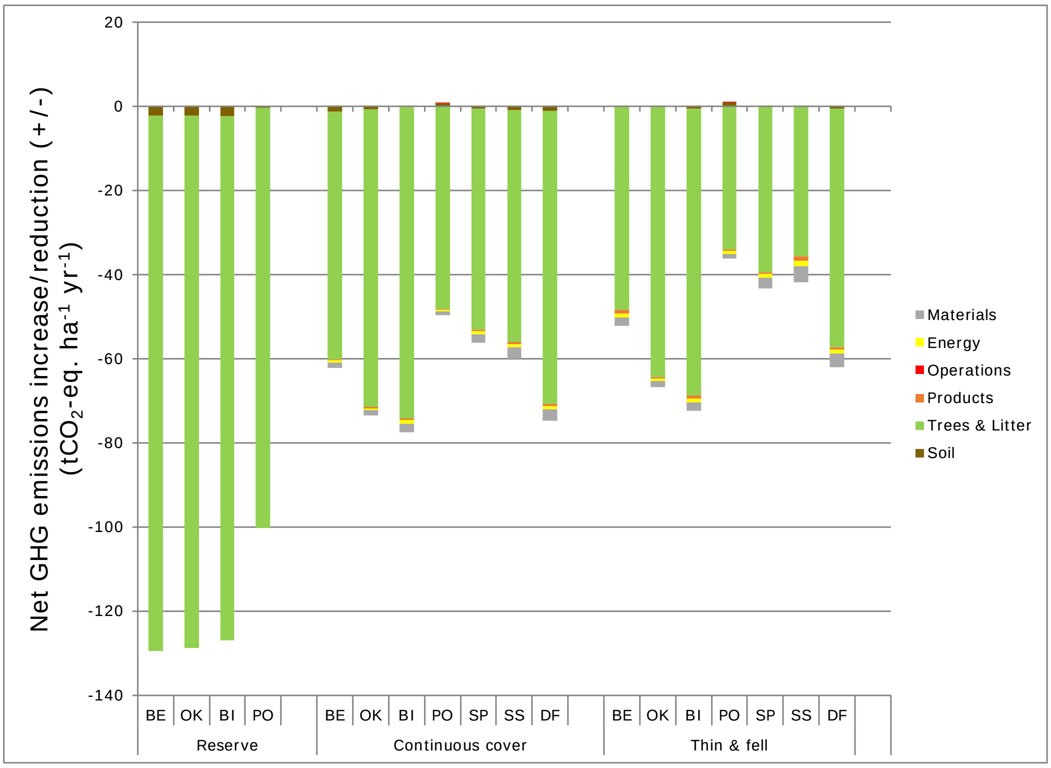

Figure 4-12 Estimated net impacts on GHG emissions for different options involving avoiding woodland loss, showing contributions from different elements of carbon sequestration and product substitution: time horizon 2020-2025.

According to the results in Figure 4-12, the GHG emissions avoided by conserving woodland that would otherwise have been lost are around -120 tCO_2 ha^{-1} yr^{-1}, for woodlands that have been left as “reserves” (i.e. little or no harvesting) and somewhat lower for woodlands managed for wood production, at around -55 tCO_2 ha^{-1} yr^{-1}. Note that these estimates involve the assumptions that, if the woodlands had not been conserved, the woodlands would have been completely removed as part of land-use change and that all of the tree biomass would have been destroyed in some way (releasing CO_2 to the atmosphere) within a 5-year period.

In the longer term, there can be contributions to ongoing carbon sequestration particularly in the soils of “reserve” woodlands that are not deforested, with a range estimated at between -2.4 tCO_2 ha^{-1} yr^{-1} and -0.4 tCO_2 ha^{-1} yr^{-1}. For woodlands managed for wood production, long-term emissions reductions are contributed through product substitution (that would otherwise have been lost), with estimates ranging from -4.9 tCO_2 ha^{-1} yr^{-1} and -1.2 tCO_2 ha^{-1} yr^{-1}. Earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here.

4.5 Changes to management of existing woodlands

Figures 4.-13 to 4-16 show results for some of the scenarios in this assessment for changes to the management of existing woodlands.

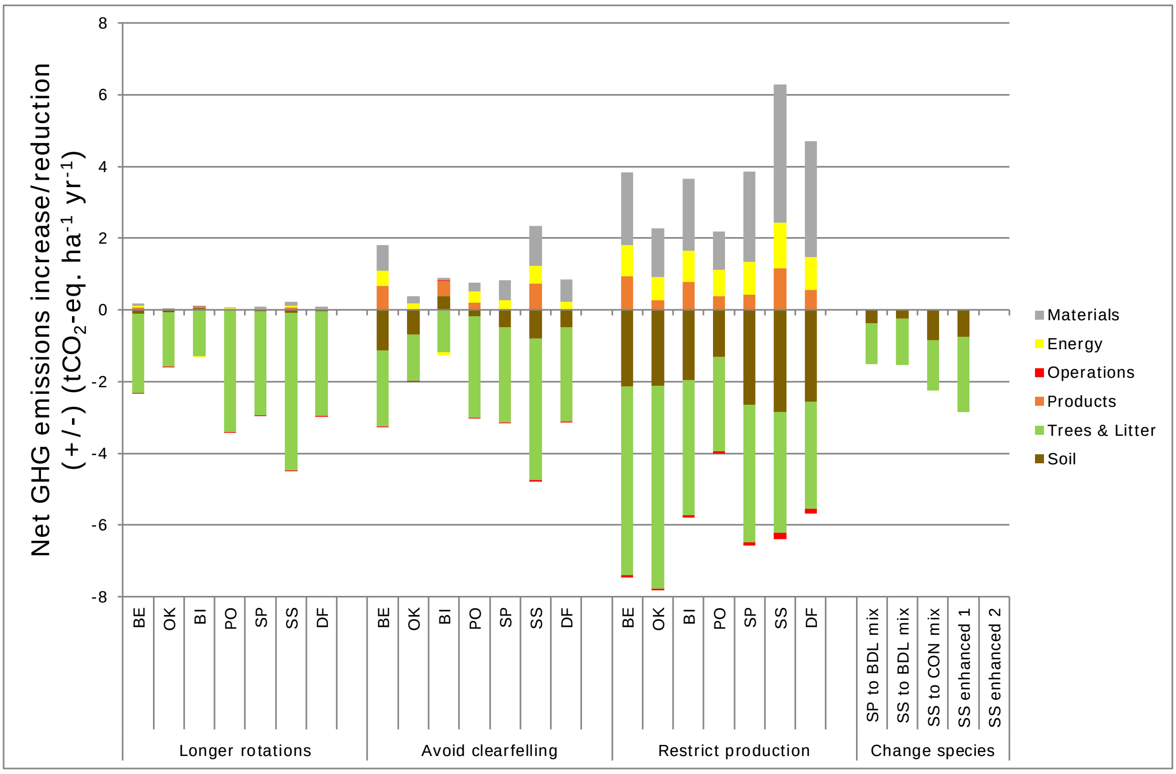

Figure 4-13 Estimated net impacts on GHG emissions for different options involving changes to woodland management, showing contributions from different elements of carbon sequestration and product substitution: time horizon 2020-2025.

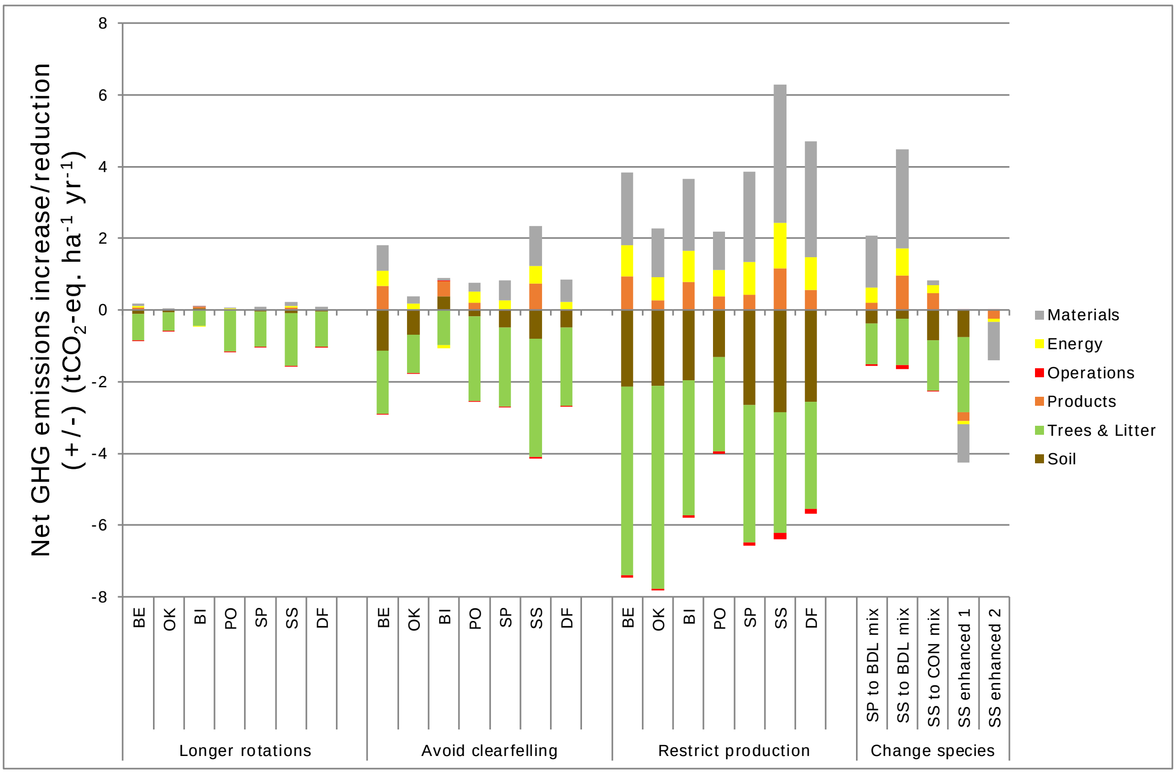

Figure 4-14 Estimated net impacts on GHG emissions for different options involving changes to woodland management, showing contributions from different elements of carbon sequestration and product substitution: time horizon 2020-2050.

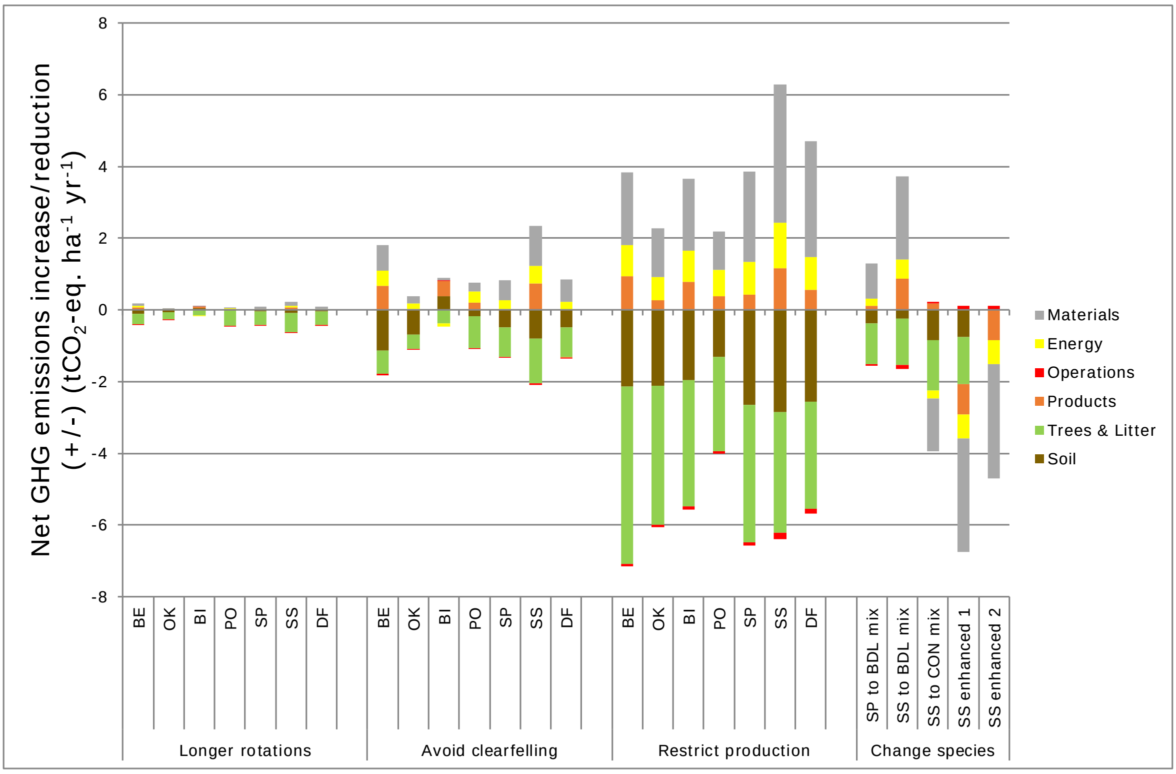

Figure 4-15 Estimated net impacts on GHG emissions for different options involving changes to woodland management, showing contributions from different elements of carbon sequestration and product substitution: time horizon 2020-2100.

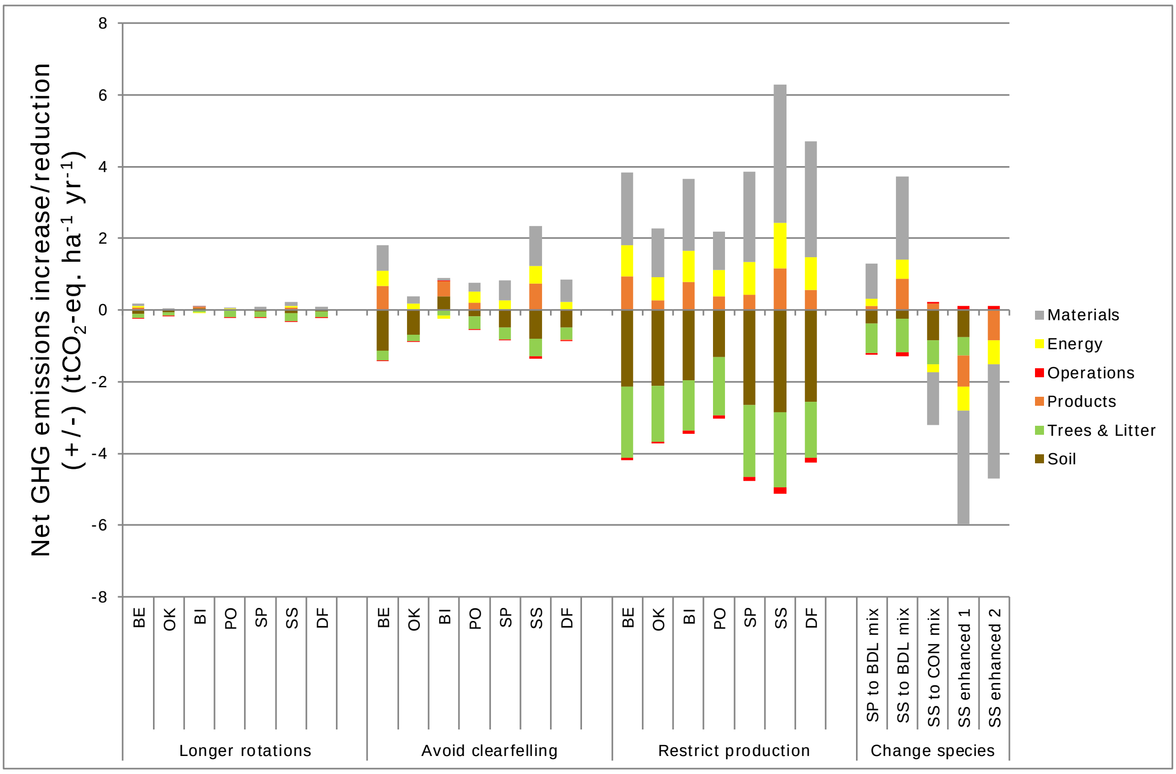

Figure 4-16 Estimated net impacts on GHG emissions for different options involving changes to woodland management, showing contributions from different elements of carbon sequestration and product substitution: time horizon 200 years.

These estimates have been derived from calculations based on the “candidate” results for the range of tree species and management regimes considered in this assessment (see description in Section 4.1). Figures 4-13, 4-14, 4-15 and 4-16 show, respectively, results for the time horizons of 2020-2025, 2020-2050, 2020-2100 and 200 years. The different contributions to overall impacts are shown in the figures, similarly to the examples for woodland creation considered in Figures 4-1 and 4-3. The changes in the management of woodlands are assumed to start in 2020.

The results for most woodland management scenarios involving increased wood production from woodlands are not shown in Figures 4-13 to 4-16. Essentially, the results for these scenarios are the inverse of certain scenarios involving conservation of woodland carbon stocks. Results for the overall impacts of the full range of management scenarios are presented subsequently in Figures 4-17 to 4-20. Estimates for scenarios involving changes to the species composition and growth rates of woodlands are included in Figures 4-13 to 4-16, as these have no equivalent scenarios involving conservation of woodland carbon stocks. (Arguably, these types of management intervention cut across the binary classification of management scenarios as either “woodland carbon stock conservation” or “increased wood production”). Separate results are shown for five individual cases of such scenarios:

1. “SP to BDL mix”
2. “SS to BDL mix”
3. “SS to CON mix”
4. “SS enhanced 1”
5. “SS enhanced 2”.

Further details of these scenarios are given in Table 4.5.

Note that scenarios in which coniferous woodlands originally managed for production are transformed into reserves (“Restrict production” scenarios) also involve an assumption of species change to more enduring broadleaf tree species (see discussion of methods in Section 4.1).

A number of features are evident in Figures 4-13 to 4-16, as discussed below.

Longer rotations

Extending rotations in even-aged stands managed for production results in increased net carbon sequestration in trees, deadwood and litter over a relatively short time horizon (Figure 4-13). The magnitude of the carbon sequestration is significant at between -4 tCO_2 ha^{-1} yr^{-1} and -1 tCO_2 ha^{-1} yr^{-1}. However, this effect saturates quickly over longer time horizons, when the modified woodland management will involve still clearfelling the stand but on a longer rotation (Figures 4-14 to 4-16). Impacts on carbon sequestration in wood products and GHG emissions through product substitution are estimated to be negligible. Note that all of the preceding observations for this scenario are partly the result of assuming a quite modest extension to the existing rotation (by 10 years).

Avoid clearfelling

For time horizons up to 2050 (Figures 4-13 and 4-14), the transformation of even-aged stands managed for production to a “continuous cover” silvicultural regime results in increased carbon sequestration in trees, litter and soil of between -5 tCO_2 ha^{-1} yr^{-1} and -1 tCO_2 ha^{-1} yr^{-1}. For longer time horizons (which encompass the completion of the transition from the old management regime to the new one), these contributions to enhanced carbon sequestration decline because of saturation. Over all time horizons, there are small to moderate but sustained increases in GHG emissions (up to 2 tCO_2 ha^{-1} yr^{-1}) resulting from some reductions in levels of wood production. This involves net losses of carbon sequestered in wood products and net increases in GHG emissions through reduced production substitution. Earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here.

Restrict production

Restricting production (i.e. harvesting) in woodlands (also involving species change to broadleaves in formerly coniferous woodlands) results in significant carbon sequestration in trees, deadwood, litter and soil over time horizons up to 2100 (in the range -8 tCO_2 ha^{-1} yr^{-1} and -4 tCO_2 ha^{-1} yr^{-1}). A decline in woodland carbon sequestration is apparent for a 200-year time horizon, reflecting the onset of saturation. Over all time horizons there are significant and sustained increases in GHG emissions (up to 6 tCO_2 ha^{-1} yr^{-1}) resulting from the cessation of wood production. This involves net losses of carbon sequestered in wood products and net increases in GHG emissions through reduced production substitution. Earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here.

Change species

These scenarios have variable impacts on net GHG emissions:

- The two scenarios involving transformation of even-aged coniferous woodlands to mixed broadleaf woodlands (managed according to continuous-cover silviculture) result in additional net carbon sequestration in woodlands of around -1.5 tCO_2 ha^{-1} yr^{-1}, although saturation causes this to decline over longer time horizons (200 years). However, the additional woodland carbon sequestration is more than counterbalanced by sustained increases in GHG emissions associated with reduced carbon sequestration in wood products and reduced product substitution (between 1 tCO_2 ha^{-1} yr^{-1} and 4tCO_2 ha^{-1} yr^{-1}), reflecting lower levels of wood production.
- A scenario involving transformation of even-aged coniferous woodlands to mixed coniferous woodlands (managed according to continuous-cover silviculture) results in additional net carbon sequestration in woodlands of around -2.3 tCO_2 ha^{-1} yr^{-1}, although saturation causes this to decline over longer time horizons (200 years). There are some initial net GHG emissions increases associated with carbon stock changes in wood products and impacts on product substitution between 2020 and 2050, because of changes in patterns of production associated with transformation from thinning and clearfelling to continuous-cover management avoiding clearfelling. However, over longer time horizons in this scenario, levels of wood production are increased by the combination of continuous cover management and the introduction of faster-growing coniferous tree species into the woodland, resulting in increased carbon sequestration in wood products and deeper

reductions in GHG emissions through product substitution (-1.5 tCO_2 ha^{-1} yr^{-1}).

- Two scenarios involving restocking stands of even-aged Sitka spruce with genetically improved Sitka spruce trees result in a significant and sustained deeper reduction in GHG emissions through increased carbon sequestration in wood products and product substitution. Over a time horizon f 2020-2100 or longer, these GHG emissions reductions are estimated at -4.6 tCO_2 ha^{-1} yr^{-1}. However, earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here. Under a scenario in which the rotations applied to the genetically improved growing stock are shortened compared with those applied previously in the unimproved Sitka spruce woodlands ("SS enhanced 2"), impacts on woodland carbon sequestration are negligible. If the rotations applied previously to the unimproved Sitka spruce are continued for the faster-growing improved stands, there is also increased carbon sequestration of -2.8 tCO_2 ha^{-1} yr^{-1} for time horizons up to 2050. For longer time horizons, carbon sequestration declines and becomes negligible as a consequence of saturation.

4.5.1 Management interventions in existing woodlands: all scenarios

The overall results for the scenarios involving management interventions in existing woodlands are summarised in Figures 4-17 to 4-20. The results are expressed as total annualised GHG emissions decreases or increases, for the set of "candidate" results considered in this assessment (see Section 4.1 for description). Figures 4-17, 4-18, 4-19 and 4-20 show, respectively, results for the time horizons 2020-2025, 2020-2050, 2020-2100 and 200 years. Results for different tree species and growth rates are plotted together in each figure to show the range of possible outcomes for each type of woodland management intervention.

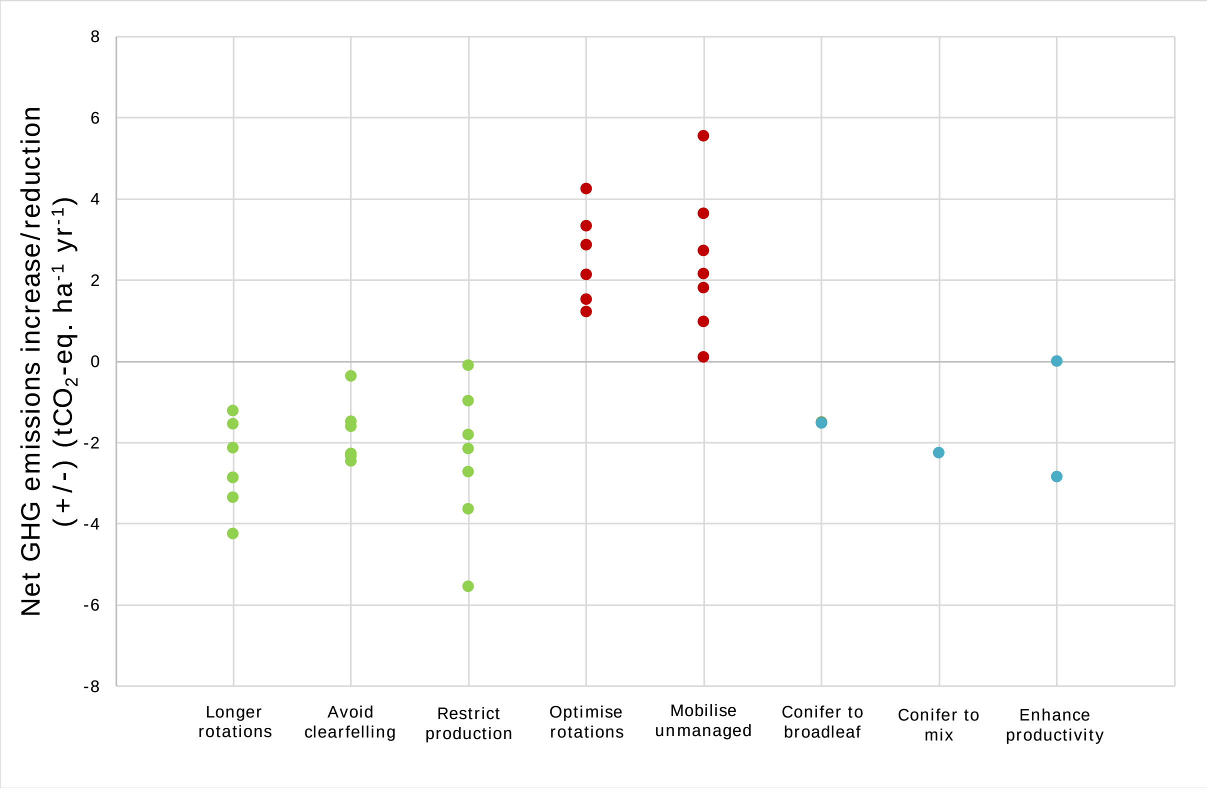

Figure 4-17 Summary of estimated net impacts on GHG emissions for options involving changes to woodland management: time horizon 2020-2025.

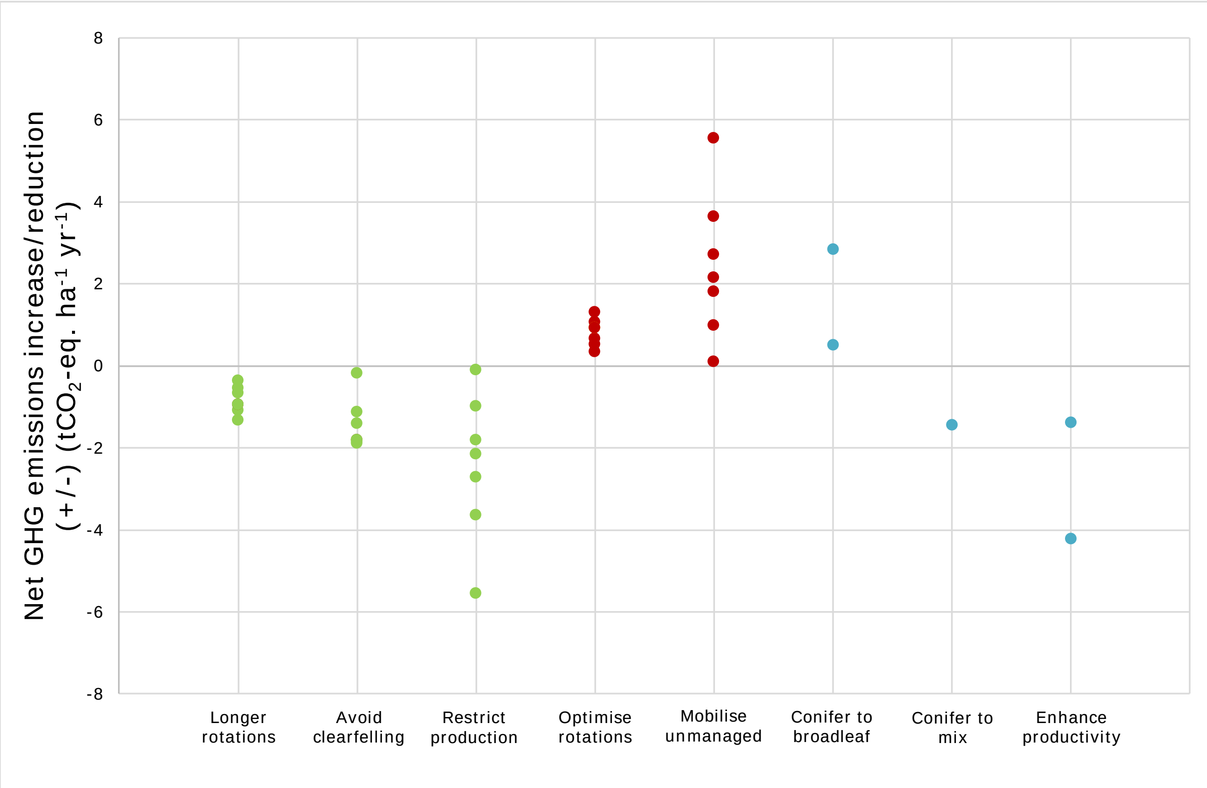

Figure 4-18 Summary of estimated net impacts on GHG emissions for options involving changes to woodland management: time horizon 2020-2050.

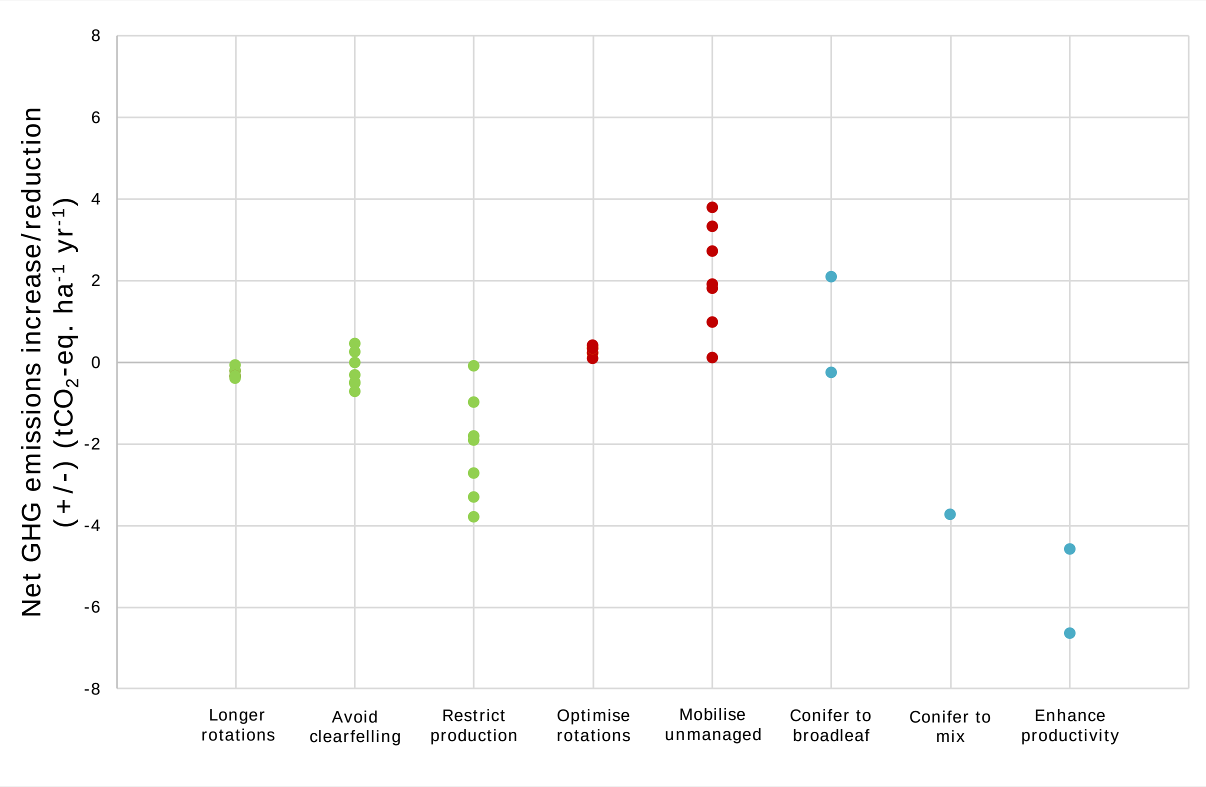

Figure 4-19 Summary of estimated net impacts on GHG emissions for options involving changes to woodland management: time horizon 2020-2100.

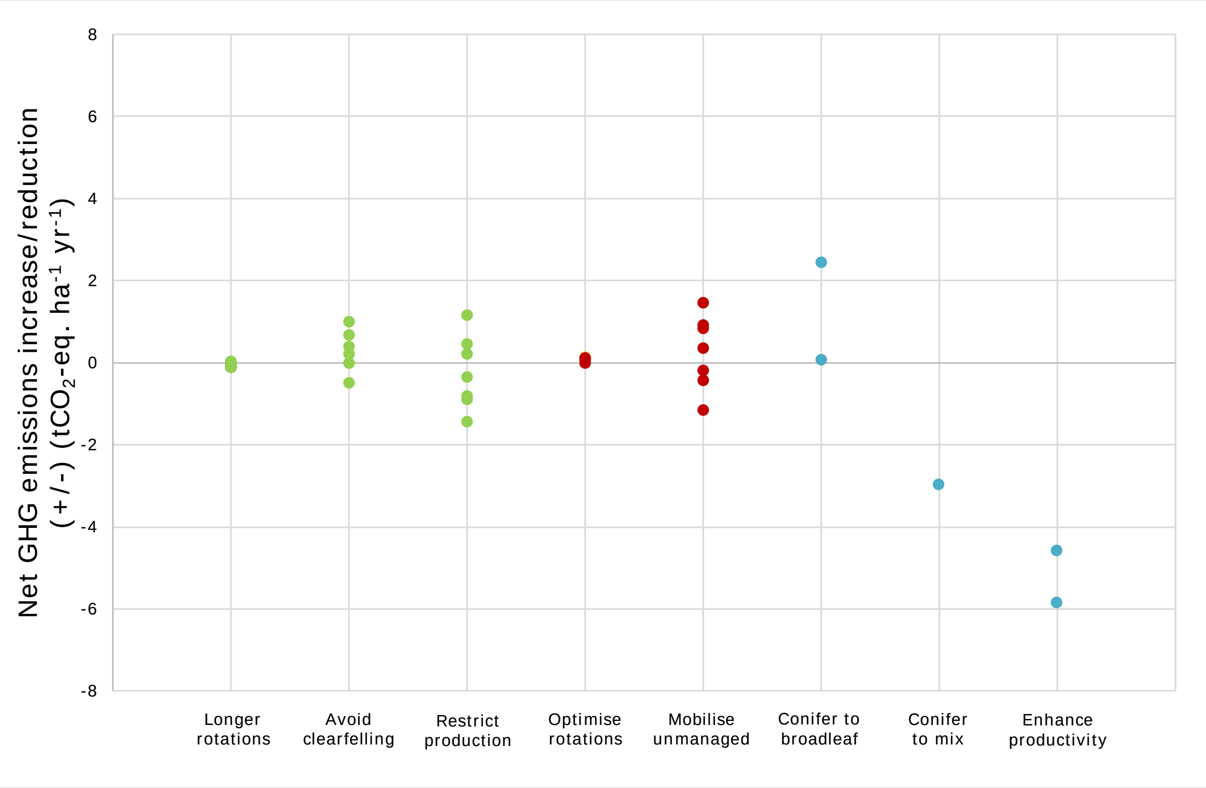

Figure 4-20 Summary of estimated net impacts on GHG emissions for options involving changes to woodland management: time horizon 200 years.

Several broad observations can be made about the results in Figures 4-17 to 4-20:

- In general, results for a particular type of woodland management intervention are very variable. Key factors underlying this variability are tree species, growth rate and (where relevant) changes involving the introduction of new tree species with higher or lower growth rates.
- For types of woodland management intervention involving the enhancement of woodland carbon stocks and carbon sequestration, all interventions result in net decreases in GHG emissions. Broadly, the magnitude of the increased carbon sequestration, and its duration (before saturation), tend to increase as the type of intervention becomes more extreme (i.e. from “Longer rotations” as a “light” intervention to “Restrict production” as “strong” intervention). The time at which the additional carbon sequestration saturates is particularly dependent on the “strength” of the intervention. Over longer time horizons (200 years) results for all of these types of management intervention vary around zero.
- For types of woodland management intervention involving increased wood production, all interventions result in overall net increases in net GHG emissions. This reflects the phenomenon sometimes referred to as “carbon debt”, as discussed in Section 2.12 and Sections 2.16.4 to 2.16.6. Eventually, GHG emissions reductions associated with product substitution compensate for reductions in carbon stocks and carbon sequestration. The time taken for this to happen gets longer as the intensity of the intervention increases, e.g. within 2020-2050 for optimisation of rotations at one extreme, to 200 years for the mobilisation of wood production. Over longer time horizons (200 years) results for all of these types of management intervention vary around zero.
- For two scenarios involving transformation of even-aged coniferous woodlands to mixed broadleaf woodlands (managed according to continuous-cover silviculture), a short period of moderately increased carbon sequestration is reversed over longer time horizons by increased GHG emissions resulting from a drop in product substitution. These results reflect the lower growth rates and reduced level of production in the broadleaf woodlands succeeding the coniferous woodlands.
- For one scenario involving transformation of even-aged coniferous woodlands to mixed coniferous woodlands (managed according to continuous-cover silviculture), there is a sustained reduction in net GHG emissions over all time horizons, initially as a result of enhanced carbon sequestration and subsequently contributed mainly by increased product substitution. Earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here.
- Two scenarios involving restocking stands of even-aged Sitka spruce with genetically improved Sitka spruce trees (labelled “enhanced productivity”) are the only scenarios to exhibit sustained significant reductions in GHG emission over all the longer time horizons (2020-2050, 2020-2100 and 200 years). This is principally contributed by product substitution, reflecting the significantly higher growth rates and levels of production assumed for the genetically improved Sitka spruce trees. Earlier cautionary remarks regarding estimates of GHG emissions reductions arising from product substitution should be recalled here.

4.6 Summary assessment

Table 4.6 presents a synthesis of the results described in Sections 4.3 to 4.5. Results for the two critical time horizons (2020-2050 and 2020-2100) are included in the table. Additional estimates are also included in the table for the management intervention of increasing biomass production from woodlands by extracting a proportion of branchwood and offcuts of stem wood otherwise left to rot on site. These are based on estimates reported in Matthews et al. (2017). Results in the majority of cells in Table 4.6 are given for the minimum, mean and maximum estimates for each category, in the format “minimum/mean/maximum”.

Table 4.6 also includes a qualitative assessment of the “potential” for each activity (scored as “limited”, “moderate” or “significant”), which generally refers to the relative extent of the land area (or woodland area) where the activity might be introduced. Hence, the overall mitigation potential of the activity in Wales is indicated by the combination of the quantitative per-hectare potential for the activity and the qualitative assessment of the extent to which the activity may be relevant as a mitigation activity in Wales.

Some explanatory notes in support of Table 4.6 are given in Box 4.1.

Table 4.6 Synthesis of climate change mitigation potentials for woodland creation and management options

Activity	*Climate change mitigation potential (tCO_2-eq. ha^{-1} yr^{-1})[1]*						*Potential for activity*
	By 2050[2]			*By 2100[2]*			
	Woodland carbon[3]	*Cross-sectoral GHG emissions*	*Total*	*Woodland carbon[3]*	*Cross-sectoral GHG emissions*	*Total*	
Woodland creation							
Reserve	*-12.1/-1.9/2.5*	*0.0*	*-12.1/-1.9/2.5*	*-13.7/-6.2/0.2*	*0.0*	*-13.7/-6.2/0.2*	*Moderate[6]*
Production	*-11.7/-2.6/2.8*	*-2.8/-0.8/0.0*	*-14.5/-3.5/2.6*	*-12.4/-4.6/1.7*	*-6.5/-2.4/-0.5*	*-17.3/-7.0/1.1*	
SRF	*-1.9/1.0/2.9*	*-4.5/-1.8/-0.2*	*-6.5/-0.8/2.5*	*-1.5/0.6/2.0*	*-5.1/-2.0/-0.2*	*-6.6/-1.4/1.5*	
Avoid woodland loss							
Reserve	*-130/-121/-100*	*0.0*	*-130/-121/-100*	*-130/-121/-100*	*0.0*	*-130/-121/-100*	*Limited[7]*
Production	*-75/-56/-33*	*-5/-3/-1*	*-80/-59/-34*	*-75/-56/-33*	*-5/-3/-1*	*-80/-59/-34*	
Conserve/enhance carbon in existing woodlands[4]							
Longer rotations	*-1.5/-0.9/-0.4*	*0.0/0.1/0.2*	*-1.3/-0.8/-0.4*	*-0.6/-0.4/-0.1*	*0.0/0.1/0.2*	*-0.4/-0.3/-0.1*	*Significant[8]*
Avoid clearfelling	*-3.4/-2.2/-0.2*	*0.0/0.7/1.6*	*-1.9/-1.4/-0.2*	*-1.3/-0.9/0.4*	*0.0/0.7/1.6*	*-0.7/-0.2/0.4*	
Restrict production	*-7.5/-5.5/-3.6*	*1.7/3.1/4.9*	*-5.6/-2.4/-0.1*	*-6.1/-5.2/-3.6*	*1.7/3.1/4.9*	*-3.8/-2.1/-0.1*	
Increase production in existing woodlands							
Optimise rotations	*0.4/0.9/1.5*	*-0.2/-0.1/0.0*	*0.4/0.8/1.3*	*0.1/0.4/0.6*	*-0.2/-0.1/0.0*	*0.1/0.3/0.4*	*Limited[9,10]*
Mobilise production	*3.6/5.5/7.5*	*-1.7/-3.1/-4.9*	*0.1/2.4/5.6*	*3.6/5.2/6.1*	*-4.9/-3.1/-1.7*	*0.1/2.1/3.8*	
Mixtures	*-1.8/-1.2/-0.6*	*0.3/1.8/3.4*	*-1.5/0.6/2.8*	*-2.1/-1.4/-0.7*	*-1.6/0.7/2.7*	*-3.7/-0.6/2.1*	*Significant[8]*
Enhance productivity[5]	-3.1/-1.7/-0.2	-1.1	-4.2/-2.8/-1.4	-2.9/-1.9/-0.9	-3.7	-6.6/-5.6/-4.6	*Moderate to significant[11]*
Extract residues	2.0	-0.4	1.6	0.0	-0.4	-0.4	*Moderate[12]*

Box 4.1 Notes to Table 4.6

1. According to the conventions adopted in this assessment, negative values for results expressed in tCO_2-eq. ha^{-1} yr^{-1} indicate net carbon sequestration or net GHG emissions reductions, whilst positive values indicate a net loss of carbon stocks or net GHG emissions increases. Results are usually given as three values in the format minimum/mean/maximum. Ranges are not available or not relevant for some results.
2. Mitigation potentials are annualised over the time horizon indicated starting in the year 2020. The potentials are calculated on the assumption that the specified mitigation activity is carried out in 2020. If activities are carried out later, the time horizons need to be adjusted commensurately.
3. Results for woodland carbon include carbon stock changes in wood products, where relevant.
4. The activity of “conservation of long-established woodlands with high carbon stocks” was not explicitly assessed. However, indicative estimates of potentials can be inferred from the results for the activity of “restrict production”. In this case, it is appropriate to assume that impacts on cross-sectoral GHG emissions are zero. Hence, the results for total mitigation potentials are the same as those of woodland carbon in the case of the activity of conservation of long-established woodlands with high carbon stocks
5. This activity represents the possible improvement of the productivity of woodlands through the introduction of a component of faster-growing trees, including genetically improved Sitka spruce. Note that this latter activity is already taking place in Sitka spruce woodlands in Wales.
6. The potential for this activity is assessed as “moderate”. The potential for “significant” woodland creation activities is likely to be constrained by a number of factors, including other requirements for land, site suitability and avoidance of ecologically sensitive sites. Options involving the creation of woodlands for wood production imply the existence of (or potential to develop) infrastructure for harvesting, processing and using the wood.
7. The potential for this activity assessed as “limited” on the basis that recently reported estimates of annual deforestation rates in Wales are relatively low (around 300 hectares per year), whilst some deforestation may be unavoidable.
8. The potential for these activities is assessed as “significant” on the basis that, in principle, they could be introduced across a significant part of the existing woodland area in Wales.
9. The potential for the activity of “optimise rotation” is assessed as “limited” because of planning and operational constraints on rotations applied to stands managed for production (many of which may already be as close to the productive management as possible).
10. The potential for the activity of “mobilise production” is assessed as “limited” because of the high likelihood of both environmental and operational constraints on introducing management in many areas of managed woodlands in Wales.
11. The potential for this activity is assessed as “moderate to significant” on the basis that, in principle, they could be introduced across a significant part of the existing woodland area in Wales but there may be technical challenges to successfully identifying and introducing more productive tree species. There may also be environmental constraints on introducing some exotic ore genetically improved tree species. Some constraints imply a requirement for the development of workable solutions and capacity for delivery.
12. The potential for this activity is assessed as “moderate” on the basis that, in principle, the activity could be introduced across a significant part of the existing managed woodland area in Wales but that there are very likely to be both environmental and operational constraints on introducing the activity in many areas of managed woodlands in Wales.

4.7 Insights from national-scale projections

The UK reports projections of greenhouse gas emissions and “removals” (sequestration) from Land Use, Land Use Change and Forestry (LULUCF) activities to inform a range of policy needs. These projections are reported for the whole of the UK and also separately for Wales as well as for England, Scotland and Northern

Ireland. The most recent published projections relate to the UK GHG Inventory for the period 1990-2014. Since then, UK GHG Inventories have undergone some important improvements and including one correction to methodology. Approximate projections may be constructed, based on those most published most recently (for the period 1990-2014), combined and reconciled with the most recent published UK GHG Inventory (for the period 1990-2017). The resultant projections are shown in Figure 4-21. It is important to stress that these are approximate projections constructed for the purposes of this assessment and they do not constitute formally published official projections for Wales.

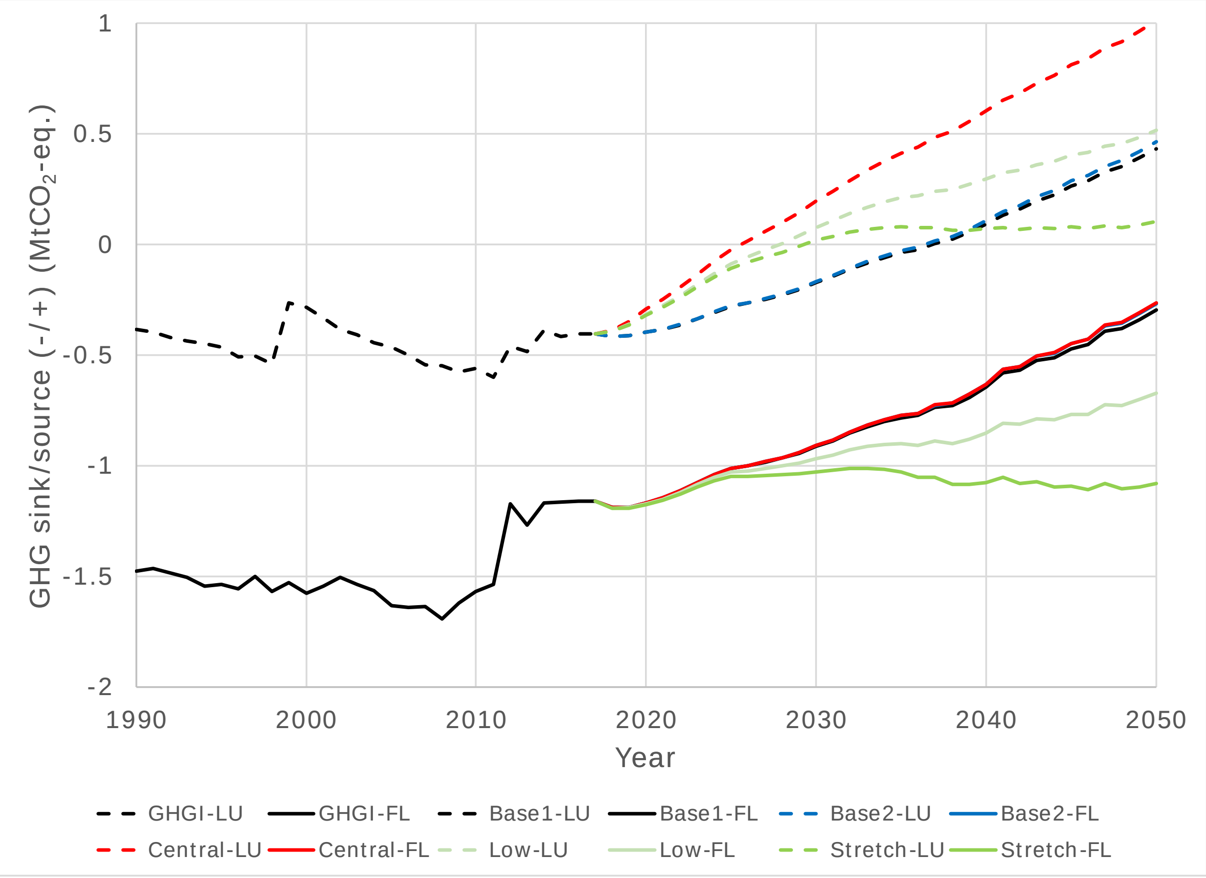

Figure 4-21 Speculative projections of the net GHG sink/source associated with woodlands (FL) in Wales for a range of scenarios. Projections are also shown for all land uses (LU). "GHGI" results from 1990-2017 GHG Inventory for Wales. Results for scenarios (Base1, Base2, Central, Low and Stretch) adapted from projections based on 1990-2014 GHG Inventory. Note that the "LU" projections include impacts as a result of differing interventions in other land-uses. Note also that the projection for the Base2 scenario (FL) is concealed by the projection for the Central scenario.

In terms of options for woodland management, the projections only consider different scenarios for rates of woodland creation, in rough order of magnitude:

- Central: ~20 ha per year new planting from 2020
- Baseline2 ("Base2" in Figure 4-21): 50 ha per year new planting from 2020
- Baseline1 ("Base1" in Figure 4-21): 200 ha per year new planting from 2020

- Low (i.e. “low emissions”): ~2000 ha per year new planting from 2020 until 2040, then ~500 ha per year
- Stretch: 4000 ha per year new planting from 2020 until 2040, then 1000 ha per year.

Under scenarios broadly representing “business as usual” levels of woodland creation in Wales (involving afforestation rates of between 50 and 200 ha per year), the net carbon sink associated with woodlands is projected to decline from the current rate of around 1 $MtCO_2$ yr^{-1} to under 0.3 $MtCO_2$ yr^{-1} by 2050. This decline is related to changes in the age distribution of woodlands and the process of “saturation”. Under these scenarios, LULUCF as a whole (i.e. including cropland, grassland etc.) becomes a net source between 2025 and 2040.

Projections involving enhanced rates of afforestation of about 2,000 and 4,000 ha per year up to the year 2040 (with reduced rates after 2040) suggest that the decline in the carbon sink in the period to 2050 can be moderated (about 0.7 $MtCO_2$ yr^{-1}) or stabilised at about 1 $MtCO_2$ yr^{-1}, respectively.

In terms of the potential impacts of woodland creation on GHG emissions and carbon sequestration, these national-scale estimates, based on an interpretation of published GHG emissions projections for Wales, are consistent with the per-hectare estimates suggested above.

5. Conclusions - the Contribution of Woodlands to Climate Change Mitigation

Activities involving the management of land-based vegetation and soil are prominent amongst only a few options currently available for actively removing greenhouse gases from the atmosphere, as part of efforts to mitigate climate change. The principal process involved is the removal of CO_2 from the atmosphere and sequestration of carbon in vegetation biomass and in soil organic matter. This point is well understood and widely accepted.

It is widely accepted that, internationally, forestry has the potential to make a key contribution to such climate change mitigation efforts. Occasionally, there is conflicting evidence as to what types of activity are most effective.

5.1 Relevant woodland management activities

There is wide acceptance that woodland creation (afforestation) and avoidance of woodland loss (prevention of deforestation) can contribute significantly to land-based carbon sequestration or the retention of land-based carbon stocks, where there are opportunities to undertake such activities.

Certain adjustments to the management of existing woodlands may also contribute towards carbon sequestration. The main examples of relevant management interventions consist of:

- Deferring final harvest (clearfelling) in even-aged commercial woodlands, by extending rotations
- Transformation of woodlands from even-aged management to continuous-cover management, generally by avoiding large-scale clearfelling and maintaining tree cover by developing an uneven-aged structure in woodlands
- Restricting or avoiding tree harvesting in woodlands, with the aim of maximising the accumulation of carbon stocks in trees and soil, possibly requiring transformation of woodlands to be composed of enduring tree species.
- Conservation of long-established woodlands with high carbon stocks.

Whilst all of the above activities can contribute towards maintaining and enhancing carbon stocks and carbon sequestration in woodlands, it is also necessary to recognise the potential contribution that woodlands can make to climate change “beyond the forest gate” (or “off site”). Products manufactured from wood harvested in managed woodlands can retain (i.e. effectively sequester) carbon in the woody biomass from which they are made. Wood products are also recognised as frequently requiring relatively low inputs of energy and other non-renewable resources in their manufacture. Hence, the GHG emissions involved in manufacturing wood products can be relatively low, compared with equivalent products made from other materials. It follows that in many cases, GHG emissions can be reduced if wood products are used to “displace” (or “substitute for”) non-wood products. Whilst this role of wood products in mitigating climate change is well accepted in principle, the question of whether or not this happens in reality is controversial. The implication is that there is a need to be able to verify that such product substitution and its associated effects on GHG emissions actually occur.

The contribution of wood products as a reservoir of carbon suggest the possibility of increasing the size of this reservoir through activities such as:

- Encouraging the use of long-lived wood products, such as structural timber
- Encouraging the re-use and recycling of wood products.

Care is needed to minimise GHG emissions from the decay or combustion of wood when products (primary, re-used or recycled) reach the end of their time in service, through effective disposal methods, such as combustion with energy recovery or possibly disposal to dry landfill.

Harvested wood biomass can also be used as a source of fuel (i.e. a form of "bioenergy"), which can be used to provide heating (and also for power generation if utilised in sufficient quantities). In principle, the use of wood fuel in place of fossil fuels has the potential to reduce GHG emissions. However, there is a large body of conflicting evidence over whether greater use of wood fuel will result in GHG emissions reductions or will lead to GHG emissions increases. Some studies have suggested that both outcomes are possible, and that the causes of variation in GHG emissions from wood fuel can be understood and controlled for.

When considering the role of woodlands in contributing to climate change mitigation off site, such as described above, it should be recalled that wood products and wood fuel are generally traded commodities. This can have the result that climate impacts associated with wood products may be realised in a different country to the one where the wood was harvested, whilst the climate impacts of supplying the wood will always occur in the producing country.

If harvested wood can be utilised effectively in the ways outlined above, this suggests a role for a number of forestry activities to support increased wood supply to enhance carbon stocks in wood products and substitution by wood products for GHG-intensive materials and fuel sources. One such activity is woodland creation with the explicit intention of management for wood production. In addition, adjustments to the management of existing woodlands can contribute towards increased supply. The main examples of relevant management interventions are:

- Optimising rotations in even-aged commercial woodlands for maximum wood production
- Mobilising wood production from previously under-managed or unmanaged woodlands, through the introduction of harvesting (within sustainable-yield levels)
- Enhancing the productivity of woodlands by converting single-species stands to mixed species stands, including a proportion of faster growing tree species
- Enhancing the productivity of even-aged commercial woodlands by restocking them with genetically improved tree species with superior growth rates.

The possibility also exists to increase the quantity of wood extracted when woodland areas are harvested, by extracting a proportion of branchwood and offcuts of stem wood otherwise left to rot on site. These woody biomass sources are mainly suitable for wood fuel (currently).

The above activities can all contribute to increasing the carbon sequestered in wood products or reducing GHG emissions through product substitution or, in some cases, involve both effects. However, a number of the activities involving management interventions in existing woodlands act in antagonism to those activities discussed earlier for conserving and enhancing carbon stocks and carbon sequestration in existing woodlands. Specifically, activities involving more intensive harvesting or more extraction of biomass from woodlands tend to reduce woodland carbon stocks and sequestration. Alternatively, some activities can act in synergy with those to enhance woodland carbon stocks and sequestration. Relevant activities include woodland creation, loss of productive woodland areas, and enhancing the productive potential of existing woodlands by introducing faster growing tree species, either entirely or possibly as a component of mixtures.

5.2 Quantitative assessment of woodland management potentials

A quantitative assessment based principally on results from the ERAMMP project gives the following broad per-hectare estimates for the climate change mitigation potentials of woodland management activities:

- **Woodland creation** can mitigate between 1 and 3.5 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2050 and about 6 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2100. If woodland carbon "reserves" are created, this mitigation comes entirely from woodland carbon sequestration; if woodlands are created for wood production, then a proportion of this potential is contributed by carbon sequestration in products and product substitution.
- The creation of **short rotation forestry plantations** (for raw biomass rather than timber production) can mitigate between 1 and 1.5 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2100.
- The **avoidance of woodland loss** can mitigate between 55 and 120 tCO_2-eq. ha^{-1} yr^{-1}, where opportunities exist to halt or reduce activities that involve deforestation.
- Adjustments to the **management of existing woodlands to conserve or enhance woodland carbon stocks and sequestration** can mitigate between 1 and 2.5 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2050 and between about 0 and 2 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2100.
- Adjustments to the **management of existing woodlands to increase wood production** can mitigate between 0 and 3 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2100 through product substitution. However, generally, this is more than offset by increased emissions (or reduced carbon sequestration) in woodlands of between 0.5 and 5 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2100, because of the impacts of increased harvesting in woodlands.
- **Adjustments to the species composition and growth rates of existing woodlands**, to enhance wood production whilst maintaining carbon stocks, give variable outcomes. The limited evidence available from the ERAMMP results suggests that the overall growth rates of trees in diversified woodlands need to increase for climate change potential mitigation to be realised. Relatively high climate change mitigation potentials are estimated for activities involving the introduction of tree species or varieties with superior growth rates (e.g. genetically improved Sitka spruce), at 3 tCO_2-eq. ha^{-1} yr^{-1} over the

period 2020 to 2050 and 5.5 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2100 (the latter estimate including a significant contribution from product substitution).
- The **extraction of branchwood and offcuts of stemwood** as a biomass feedstock is estimated to result in net GHG emissions of 1.5 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2050, because of the consequent initial reduction in woodland deadwood and litter carbon stocks. This switches to net mitigation of about 0.5 tCO_2-eq. ha^{-1} yr^{-1} over the period 2020 to 2100.

A number of caveats need to be attached to the above estimates:

- The estimates of mitigation potential are based on central/mean values from the ERAMMP results. Individual estimates exhibit significant variability and can range from significant net GHG emissions reductions to net GHG emissions increased. It follows that the actual mitigation achieved by implementing specific measures will exhibit considerable variability as a result of the many factors involved (e.g. woodland composition, growth rates, climate, soil characteristics, patterns of wood use and materials and energy sources substituted etc.).
- The suggested potentials involve an assumption that mitigation activities start in 2020 and are fully implemented within a few decades.
- Rates of carbon sequestration and GHG emissions reductions (through product substitution) vary significantly over time and the rates quoted above are mean annualised estimates for the periods indicated. Rates over shorter periods will vary from these mean estimates. For example, for woodland establishment activities, GHG emissions may increase initially, during the processes of clearing existing vegetation on land and site preparation activities, before trees become established.
- Estimates for some activities involve assumptions that certain practices that could lead to increased GHG emissions will be avoided. A key example is the assumption that woodlands will not be established on highly organic soils.
- The opportunities to carry out the activities list above (in terms of relevant land areas) are variable and, in some cases, this strictly limits the potential mitigation that can be achieved. For example, high per-hectare potentials are indicated above for avoiding woodland loss. However, recently reported rates of deforestation in Wales are relatively low (roughly 300 hectares per year) and an element of deforestation activities may be unavoidable (e.g. for essential infrastructure development).
- It should be noted that some activities considered above are already happening in Wales. In particular, deforestation is already the subject of strong regulation, there have been moves towards more management of woodlands according to continuous-cover silvicultural principles, and commercially managed stands of Sitka spruce are often restocked with genetically improved trees when stands are clearfelled.
- The suitability of land in Wales for the growth of different tree species is very likely to change in the face of changing climatic conditions. This has been allowed for in the assessment based on ERAMMP results, by referring to estimates for potential growth of different tree species for a baseline climate scenario and also for a scenario allowing for climate change (UKCP09 11-RCM medium emissions scenario; Met Office, 2009). However, assumptions about the suitability of climatic conditions for specific tree species and associated growth rates are subject to high uncertainty.

- The assessment of climate change mitigation potentials is based principally on estimates for net carbon sequestration and CO_2 emissions in woodlands, and GHG emissions (savings) potentially associated with wood products. In terms of estimates for on-site climate change mitigation impacts of woodlands, non-CO_2 GHGs are not considered and non-GHG impacts are also now allowed for. Claims that some of these factors, notably impacts on land surface albedo, can negate efforts to mitigate climate change through management of woodland GHG balances, are currently based on conflicting evidence and controversial.

5.3 Evidence from national-scale scenarios

The UK reports projections of greenhouse gas emissions and "removals" (sequestration) from Land Use, Land Use Change and Forestry (LULUCF) activities to inform a range of policy needs. These projections are reported for the whole of the UK and also separately for Wales as well as for England, Scotland and Northern Ireland. The most recent published projections relate to the UK GHG Inventory for the period 1990-2014. Since then, UK GHG Inventories have undergone some important improvements and including one correction to methodology. Approximate projections may be constructed, based on those most published most recently (for the period 1990-2014), combined and reconciled with the most recent published UK GHG Inventory (for the period 1990-2017). In terms of options for woodland management, the projections only consider different scenarios for rates of woodland creation.

Under scenarios representing baseline levels of woodland creation in Wales (involving afforestation rates of between 50 and 200 ha per year), the net carbon sink associated with woodlands is projected to decline from the current rate of around 1 $MtCO_2\ yr^{-1}$ to under 0.3 $MtCO_2\ yr^{-1}$ by 2050. This decline is related to changes in the age distribution of woodlands and the process of "saturation". Under these scenarios, LULUCF as a whole (i.e. including cropland, grassland etc.) becomes a net source between 2025 and 2040.

Projections involving enhanced rates of afforestation of about 2,000 and 4,000 ha per year up to the year 2040 (with reduced rates after 2040) suggest that the decline in the carbon sink in the period to 2050 can be moderated (about 0.7 $MtCO_2\ yr^{-1}$) or stabilised at about 1 $MtCO_2\ yr^{-1}$, respectively.

In terms of the potential impacts of woodland creation on GHG emissions and carbon sequestration, these national-scale estimates, based on an interpretation of published GHG emissions projections for Wales, are consistent with the per-hectare estimates suggested above.

5.4 Implications of assessment for woodland management

The assessment presented in this annex suggests the possibility of a wide range of options for woodland creation and woodland management in Wales to support climate change mitigation. In the right circumstances, and depending on the time horizon, all options can have potential benefits for climate change mitigation. Conversely, no single option appears to offer a "silver bullet" solution above other options. Claims that are occasionally made for or against the case for a particular approach to woodland creation or woodland management are not supported by this assessment. All options are subject to a set of constraints to varying degrees, including:

- Suitability of land in different locations for creation of woodland “reserves” or commercial woodlands, when other factors are considered
- An overriding objective to conserve existing areas of ancient woodland, precluding changes to tree species or management
- Constraints on harvesting or extraction of biomass on sites where soil, nutrient or water regime would be adversely affected
- Potentially long lead times involved in tree breeding research, limiting progress on producing improved stock for different tree species
- Intricate patterns in carbon stock changes in woodlands, partly influenced by management but ultimately the result of biophysical processes which cannot be entirely controlled
- Related to the previous point, the time-dependence (often time lags) of climate impacts associated with woodland management interventions, including woodland creation
- Ultimate saturation of woodland carbon sinks
- Issues related to impermanence and carbon “lock-in” related to conserving woodland carbon stocks and enhancing woodland carbon sequestration.

5.5 Implications for climate change mitigation approaches in woodlands

This assessment has described in some detail a range of activities that may be taken with regard to woodland management, aimed at mitigating GHG emissions. The questions remain of whether and how to put these activities into practice. These questions have been considered in the context of woodlands managed by Natural Resources Wales in the report of Matthews et al. (2017, Section 8.5).

In broad teams, an approach is considered involving a possible strategic approach to woodland GHG management, simplifying woodland GHG management options for strategic purposes based on developing the concepts of Broadmeadow and Matthews (2003), including the three tentative management approaches of

- Woodland carbon reserve management
- Substitution management
- Selective intervention carbon management.

A possible approach to developing a strategy or policy for managing existing woodlands in Wales to support the objective of climate change mitigation could involve supporting specific areas of woodlands to be managed according to one of the three broad options described above. Detailed management of the classified woodland areas could then be determined as part of the woodland management process, referring to appropriate possible measures described in this annex in Sections 4.3 and 4.4.

Matthews et al, (2017) suggest that the strategic planning of the management of woodlands to meet climate change mitigation objectives requires an in-depth assessment of numerous factors including site conditions, potential productivity, vulnerability to natural events, proximity to point of use and the local practicalities of the best and most realistic options for end-use of harvested wood. The planning process could be supported by the development of practical guidance based on consideration of a range of simple relevant criteria.

5.6 Implications for national and international GHG accounting approaches

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

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

The implications of adopting different GHG emissions accounting systems, in particular for forest land, have been discussed in Matthews et al. (2017). Of particular relevance here, Matthews et al. observe that the accounting approaches for forest land adopted by different policy frameworks give different results for the same woodland management activities. In the context of Wales, as part of domestic carbon budgeting, simply maintaining “business as usual” management of woodlands (see Section 4.7) could mean that woodlands would contribute a net GHG sink (depending on the domestic accounting rules applied). In contrast, “business as usual” management of woodlands in Wales would most likely mean that no GHG sink arising from woodlands would be accounted as contributing towards the UK’s current international climate commitments, which are based on a different accounting approach. For any contribution from the management of woodlands in Wales to contribute towards international climate targets (under current accounting rules), it would be necessary for “additional” mitigation activities to be undertaken in woodlands, such as discussed in Sections 3 and 4.

Matthews et al. (2017) also note that the possibility exists that the management of woodlands in Wales could deliver an accounted net carbon sink but register as accounted GHG emissions in the context of international commitments. Such a situation might arise, for example, if the management of Natural Resources Wales (NRW) woodlands was changed from “business as usual”, involving increased biomass extraction from woodlands to support meeting renewable energy targets or greater use of timber in “green building construction”, whilst still maintaining Welsh woodlands as a net carbon sink, but reduced in magnitude compared with the (projected) carbon sink associated with "business as usual" management. At the same time, the contributions of wood products towards GHG emissions reductions through product substitution will not be so obviously attributable to woodland management activities, because the emissions reductions will be accounted for in other sectors.

5.7 Implications for definition of carbon sinks

As discussed in Section 2.15.1, the likelihood that woodland sinks will saturate presents challenges to achieving climate change targets, particularly net zero emissions in the long term. An aspiration to sustain vegetation-based carbon sinks in the longer term would appear to be impossible, given the way in which such sinks are reported under the UNFCCC. Part of the way of addressing this problem may be to view the vegetation carbon sinks (notably woodland carbon sinks) in a different way, i.e. define them in similar terms to forest increment, i.e. by reporting net woodland growth in terms of carbon sequestration, before subtracting losses from woodlands when material is extracted to manufacture products for use as fuel. If the carbon sink is defined in this way, then it may be possible to sustain woodland carbon sinks indefinitely – indeed this is particularly true for managed vegetation. However, this does not alter the need to achieve an overall balance of GHG emissions and GHG sinks. Redefining the carbon sink as suggested would still require emissions from wood fuel and from disposed wood products to be reported, but in other sectors (e.g. energy and waste). This implies that direct GHG emissions from combustion of biomass energy sources or the disposal of biomass products at end of life need to be significantly reduced or mitigated in some way. The overall challenge of balancing emissions and sinks thus remains the same, but the different approach to describing and representing the problem may assist stakeholders of gaining a common understanding of the challenges involved.

5.8 Gaps in knowledge and evidence

There are a number of gaps in knowledge, evidence and methods to inform the realisation of the potential contribution of woodlands towards climate change mitigation. Gaps in data, modelling, underlying scientific evidence and practical tools can be identified. The following discussion offers a non-exhaustive list.

5.8.1 Gaps in data on woodlands and wood products

The estimation, reporting and projection of woodland carbon stocks and stock changes relies on relevant, high quality and sufficiently comprehensive underlying data sets. For example, data are needed on the extent of woodland areas and their composition, how woodlands are being managed and levels of wood production. Data are also needed on long-term growth patterns exhibited by trees and stands of different species and growth rates. Essential information is supplied by forestry statistics compiled for the UK (see for example Forest Research 2019), supported by the GB National Forest Inventory amongst other data sources. However, these data sets are not detailed enough to capture woodland composition, growth and management at the scale of stands or woodland blocks, or even quite large subregions of Wales. This presents challenges to the development of robust spatially-explicit estimates of woodland carbon stocks and stock changes, and to the local modelling of scenarios for woodland management options.

Methods for carrying out rapid stand-by-stand surveys of woodland could be developed but implementing these could face obstacles (e.g. issues related to access, data ownership and privacy). Methods for woodland surveys based on remote sensing products are being actively research but, so far, practical methods that are straightforward to apply in an operational context remain elusive. This applies equally to the registering and tracking of changes to woodland composition ad management that may occur for a range of reasons, including in pursuit of climate change mitigation objectives. This latter point is important when considering the need to verify that mitigation activities have been carried out and that the expected impacts on woodland carbon stocks and stock changes have been realised.

There is also scope for improving data on levels of wood production and particularly how wood is consumed for different end uses, what types of other products the wood-based products are likely to be displacing (if any) and the consequent impacts on GHG emissions. The estimation of GHG impacts suggest a requirement for more extensive LCA studies of domestically produced wood products and of the alternatives when not using wood products.

5.8.2 Gaps in modelling

As covered in this annex, currently, national-scale modelling to assess the potential impacts of woodlands in contributing to future climate change mitigation has only considered a limited range of scenarios involving woodland creation. There would appear to be a case for considering a wider range of scenarios exploring more options for woodland creation (e.g. with respect to tree species selection) and also scenarios involving interventions in the management of existing woodlands. Modelling some of the latter types of scenario may require some methodological developments to existing forest carbon models.

In the context of the previous point, national-scale modelling assessments would benefit from expansion to enable the evaluation of the cross-sectoral impacts of scenarios involving woodland creation and woodland management on other land uses and on GHG emissions in the energy and construction sectors, arising from the utilisation of wood products and wood fuel. These are areas where there is already some progress being made in relevant model development.

The extension of national-scale modelling assessments beyond 2050, e.g. to 2100 or beyond, required to assess the potential longer-term contributions of woodland management to GHG balances and climate change mitigation.

Forest sector carbon accounting models rely on the accuracy of underlying forest growth models. The published standard growth models applied to woodlands in the UK are currently being updated and the development of new models is expected to be completed during 2020. The revised predictions of forest growth and production produced by these new models are likely to have some impacts on estimates of carbon sequestration and product substitution derived from forest carbon accounting models. The new growth models may also offer a step towards modelling a wider range of types of wooded land, e.g. woodlands planted at wider spacings and certain agroforestry systems such as silvi-arable systems. These improvements and developments need to be evaluated once the new growth models are available.

Significant improvements to the modelling of woodland soils have been made in recent years. However, there remain some gaps in these models, notably with regard to the representation of the litter layer and distinct organic and mineral layers within soil. These models also need to be extended to represent non-CO_2 GHG balances associated with soil, involving methane and nitrous oxide. These contributions from woodland soils, whilst generally small, represent the major non-CO_2 contributions to woodland GHG balances.

Models for assessing the climate change mitigation potential of woodlands and woodland management options (working at any scale, e.g. stand scale or larger scale) tend to be limited to the consideration of woodland CO_2 balances and to a limited extent non-CO_2 GHG balances. The extension of these models to enable the integrated assessment of a range of climate change impacts, e.g. potential changes in the land surface albedo, would be highly desirable. However, it is important that such models are extended to include estimates of uncertainty associated with different impacts, preferably quantitative but if necessary qualitative.

The requirements for integrated modelling of the long-term contributions of woodlands to climate change mitigation emphasise the importance of such models having the ability to represent the impacts of climate change on the suitability of site conditions for different tree species and their potential growth rates.

5.8.3 Gaps in tools to support practice

Beyond the modelling of woodland climate change mitigation at different scales, practical tools are needed to support land use and woodland management planning, and decision making at the local and stand scales. There are examples of existing forest models that could be applied for such purposes but they require adaptation to explicitly address the practical questions that arise in woodland planning and management. Examples of such questions are:

- How to plan future woodland creation (e.g. species choices and management objectives)
- How to meet targets for GHG emissions or carbon sequestration across a block or relatively large area of woodland.
- How and when to intervene in the management of an individual woodland stand consistently with climate change mitigation objectives.

5.8.4 Gaps in underpinning scientific evidence

Data, parameters estimates, models and tools can always be improved by more research. However, specific subject areas that appear to be priorities for improving understanding include:

- Estimation of ecophysiological parameters that are relevant for calibrating climate sensitive models of the growth and carbon balance of different tree species.

- Better understanding of the dynamics of soil carbon and soil GHG balances, including for highly organic and organo-mineral soils, particularly during the periods immediately after woodland establishment and after major harvesting events (particularly clearfelling).
- Related to the previous point, better understanding of the dynamics of the growth of trees and other vegetation during the early stages of tree establishment.
- Better estimates of relationships between tree stem biomass and growth and other tree biomass components, such as foliage, branchwood, coarse roots and fine roots, particularly for very large trees and older tree stands.

An area of research that appears to require investigation in support of implementation is how to ensure and manage the feasibility (e.g. in terms of infrastructure) and social acceptability of changes to land use and woodland management aimed at mitigating climate change.

5.8.5 Gaps in evidence for related subjects

Certain agroforestry systems, small woodlands and landscapes with scattered individual trees do not meet the definition for a forest (e.g. as referred to in the GB National Forest Inventory and in conventions adopted in UNFCCC reporting for different land uses). However, it is suggested that the evaluation of these systems is worthy of further evaluation and that this needs to be undertaken consistently with the methods applied to woodlands.

Appendices: Woodland Carbon Dynamics: Detailed technical evidence

A1. Illustrations of the GHG impacts of Woodland Creation & Management

A1.1. Introduction to this appendix

The purpose of this appendix is to provide some illustrations of the potential impacts of decisions regarding woodland creation and management on land-based carbon stocks and wider GHG emissions. Some illustrations are also given of the influence of factors such as tree growth rate and soil characteristics on carbon stocks and GHG emissions.

The illustrations are based on simulation results produced by the Forest Research CARBINE forest sector carbon accounting model (Thompson and Matthews 1989; Matthews 1994, 1996; Matthews and Broadmeadow 2009; Matthews et al. 2020a). Similar results have been presented in previous reports (see for example Morison et al. 2012; Matthews et al. 2014a). The results in Section A1.5 are repeated from Matthews et al. (2014a), whilst those in Section A1.7 are repeated from Matthews et al. (2014b). All other results produced by CARBINE have been updated by applying the latest version, in which improvements have been made to the representation of deadwood, litter and soil carbon dynamics (Matthews et al. 2020a). For the results in this appendix, carbon stock dynamics in wood products have been modelled within CARBINE using methods similar to those described in Matthews et al. (2014a, 2015). The potential impacts of GHG emissions arising from product displacement effects (see Section 2.12 in the main body) have been estimated using GHG emissions displacement factors as discussed in Section 4.1.8 in the main body.

All of the CARBINE simulations of soil carbon dynamics in this appendix are based on an input assumption of a “warm, moist” climate (see Sections 4.1.4 and 4.1.5 of the main annex body) and, unless otherwise stated, a “loam” soil class and a previous land cover of grass. By convention, results for soil carbon stocks and stock changes are reported for a soil depth of 1 m; this is consistent with the convention adopted in UK National GHG inventories.

Unless stated otherwise, results in this annex for woodland carbon stocks and stock changes are expressed, respectively, in units of tonnes carbon equivalent per hectare (tC-eq. ha^{-1}) and tonnes carbon equivalent per hectare per year ((tC-eq. ha^{-1} yr^{-1}). Usually, results for impacts on wider GHG emissions (generally mediated through wood product substitution, see Section 2.12 in the main body) are accumulated over a period from time of woodland creation up to the reporting year, and expressed in units of tonnes carbon equivalent per hectare (tC-eq. ha^{-1}). This approach permits these results to be compared directly with results for woodland carbon stocks (which innately express accumulated carbon sequestration). Where necessary other metrics or units are used for reporting these GHG emissions, as stated in the relevant discussions.

As far as possible, graphs showing the same types of results for different woodland creation/management options are plotted using the same y-axis scale.

A1.2. Broadleaf woodland carbon reserve

Figures A1 to A3 show an example of the impacts on land-based carbon stocks of establishing a new broadleaf woodland (by planting trees or by assisting tree regeneration), and managing the new woodland as a "carbon reserve", i.e. as a protected reservoir of carbon stocks. This example has already been introduced in Section 2.5 of the main body. The tree species involved are assumed to be a mixture of mainly birch (a "pioneer" species in terms of land recolonization by trees) and a smaller proportion of enduring oak trees. The growth rate of the trees is assumed to be 4 m^3 ha^{-1} yr^{-1} over an optimal rotation (i.e. if the stand were to be managed for wood production by clearfelling). This type of measure of tree growth rate is known in British forestry as the "yield class" of the stand of trees, in this case, "yield class 4". A yield class of 4 is reasonably representative of broadleaf woodlands in Wales. (A mean yield class of 4.8 is reported for broadleaf woodlands in Wales in the GB National Forest Inventory, see BEIS, 2020. Note that growth and carbon models currently applied in UK forestry are only defined for even-numbered yield classes.)

The trees are assumed to be planted, or to regenerate, at time zero at a quite high density (at least 4,000 trees per hectare, after which they are allowed to grow whilst protected from disturbance (e.g. fire, disease or tree harvesting). Trees are only lost as a result of competition for space between the trees forming the woodland stand. In maturity, the woodland is formed of large and densely-packed trees with a closed canopy.

A1.2.1 Tree carbon stocks

Figure A1 shows the accumulation of carbon stocks over time in the living trees forming the woodland. This result has already been presented and discussed in Section 2.5 of the main body. In Figure A1, a dashed line is also included, which indicates the long-term carbon stock in living trees that would ultimately develop and be retained by creating this particular type of woodland (i.e. this particular combination of tree species, yield class, planting/regeneration regime and management regime). The ultimate carbon stock in living trees is estimated at 140 tC ha^{-1}.

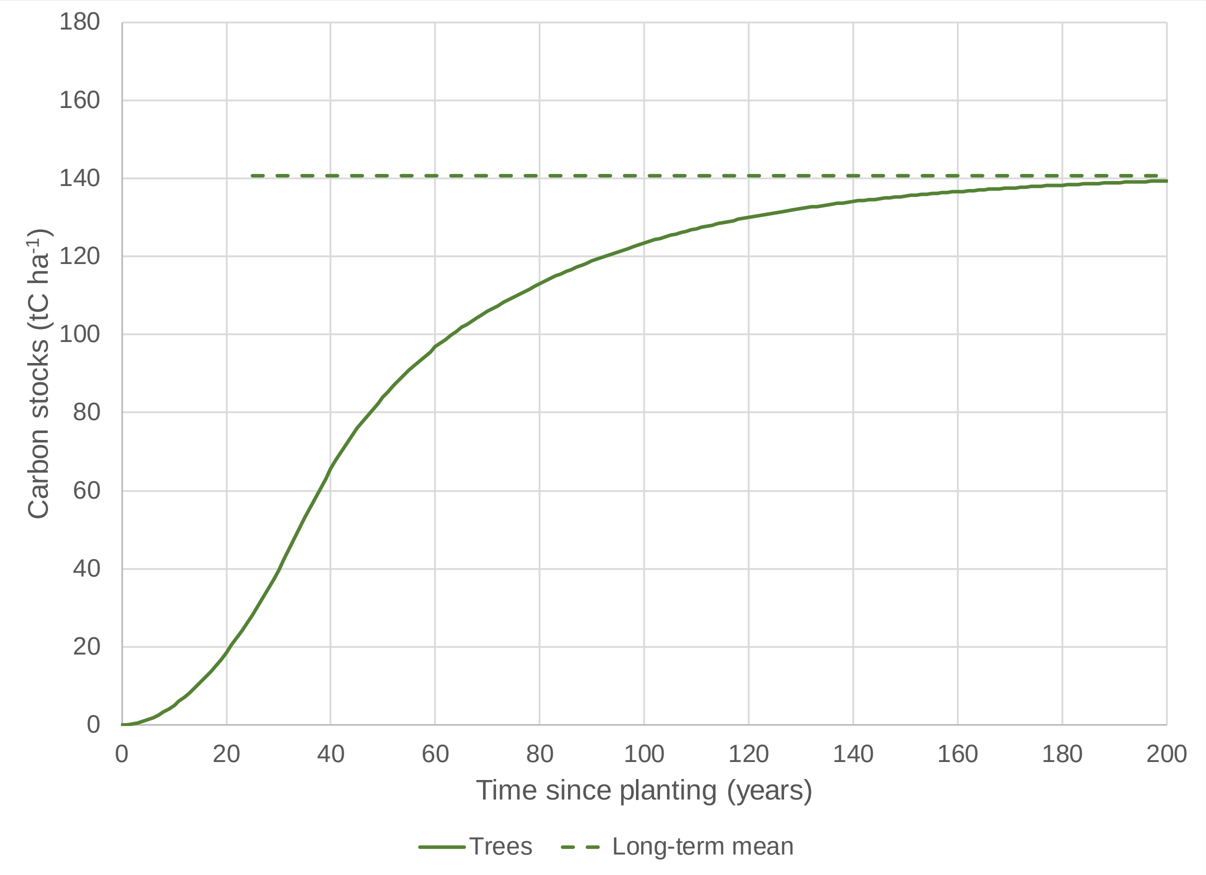

Figure A1 Development of tree carbon stocks in a stand of mixed birch and oak (yield class 4) left undisturbed and protected so as to create a "carbon reserve".

A1.2.2 Total woodland carbon stocks

Figure A2 shows the combined impacts on carbon stocks in living trees, in deadwood and litter, and in soil. The figure shows the total carbon stock in soil before and after the creation (planting or assisted regeneration) of the woodland.

Prior to woodland creation, the carbon stock in soil is 113 tC ha^{-1}. This initial soil carbon stock is sensitive not only to soil characteristics (see Section A1.10) but also climatic conditions. For example, changing the climate input data used to run CARBINE to "warm-dry" (Section 4.1.4) reduces the carbon stock slightly, whilst assuming "cool-wet" conditions increases the carbon stock to over 150 tC ha^{-1}. The creation of the woodland is assumed to involve the removal of any previous vegetation (assumed to be grass in this example). As a consequence, the inputs of carbon to the soil from the grass are lost, and carbon inputs to the soil are only gradually restored after some years, as the new woodland grows and becomes established on the site. This initial reduction in soil carbon inputs results in some losses of soil carbon in early years following woodland creation. The carbon stock in the soil drops to 91 tC ha^{-1} over a period of about 30 years. After this point, the woodland has become well established and inputs of carbon to the soil (from fine roots and litter turnover) are sufficient for soil carbon stocks to increase again. The soil carbon stock is restored to its original level after about 50 years from the time of woodland creation, after which the soil carbon stock increases further. After 200 years, the carbon stock in soil is estimated at 220 tC ha^{-1}.

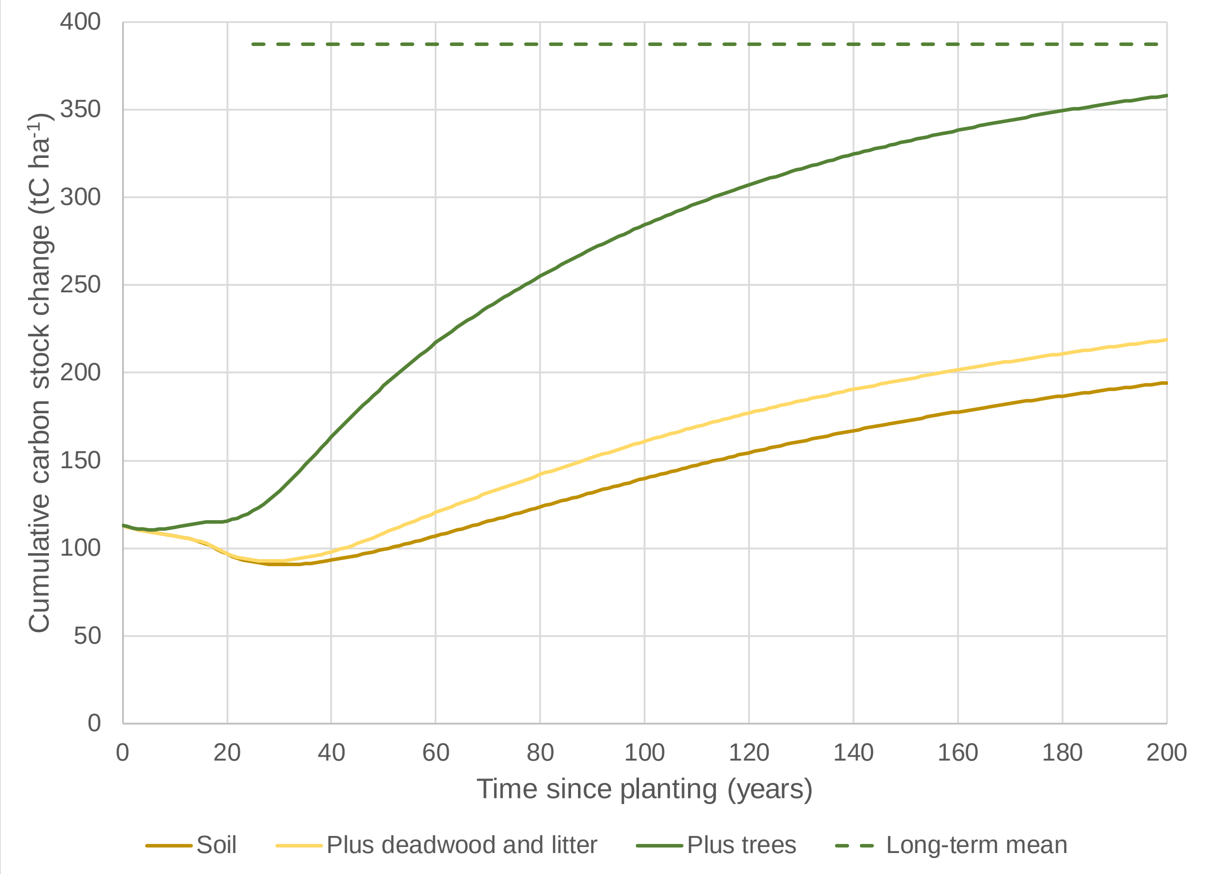

Figure A2 Development of total woodland carbon stocks in a stand of mixed birch and oak (yield class 4) left undisturbed and protected so as to create a "carbon reserve". "Plus deadwood and litter" = soil carbon stocks + deadwood and litter carbon stocks; "Plus trees" = soil carbon stocks + deadwood and litter carbon stocks + tree carbon stocks (i.e. total woodland carbon stocks).

Figure A2 also shows the contributions to total carbon stocks by soil, deadwood and litter combined (the line denoted "Plus deadwood and litter in the figure). The contribution to carbon stocks made specifically by deadwood and litter is thus the difference between this line and the line indicating carbon stocks in soil. Carbon stocks in deadwood and litter accumulate over about 100 years to a level between 20 and 25 tC ha^{-1}.

The combined contributions to total woodland carbon stocks made by soil, deadwood and litter and living trees are shown by the line denoted "Plus trees" in Figure A2. The contribution to carbon stocks made specifically by living trees is the difference between this line and the line denoted "Plus deadwood and litter" in the figure. The carbon stocks specifically in living trees have already been considered in Section A1.2.1 above and in Section 2.5 in the main body.

Overall, small losses of total carbon stocks are estimated in the years immediately following woodland creation, as losses of soil carbon exceed gains in trees and deadwood and litter. After about 12 years, carbon stocks return to the levels estimated for the period prior to woodland creation. The accumulation of total carbon stocks continues to be quite modest up to about 25 years after the creation of the woodland, when the rate of accumulation (i.e. carbon sequestration) increases rapidly, as the trees forming the woodland approach the “full-vigour” growth phase (see discussion in Section 2.5 of the main body).

Eventually, the rate of carbon sequestration declines, such that a point is reached where an “ultimate carbon stock” is accumulated, after which no further increases or decreases in total carbon stocks occur (this is “saturation”, see Section 2.7 of the main body). However, it is still the case that the accumulation of carbon in soil can continue for many decades (possibly centuries) before the ultimate carbon stock is reached. The estimated ultimate carbon stock in trees, deadwood, litter and soil is estimated at 370 tC ha^{-1}, as indicated by the dashed line in Figure A2.

Arguably, the results as presented in Figure A2 give a misleading picture of the impacts on carbon stocks of creating the example woodland. For instance, the figure might be interpreted as suggesting that the creation of the woodland has caused the accumulation of all of the 370 tC ha^{-1} of land-based carbon stocks, as shown in the figure. However, approximately 100 tC ha^{-1} of this carbon stock already existed in the soil before the woodland was created. A better indication of the cumulative impacts on carbon stocks of creating the woodland is given by considering the cumulative change in carbon stocks on the land, compared to the pre-existing carbon stocks. According to this scheme, the results for carbon stock impacts in year *t* from time of woodland creation are calculated as:

$$\begin{array}{c}\text{Net impacts on}\\ \text{carbon stock in year } t\end{array} = \begin{array}{c}\text{Carbon stock}\\ \text{in year } t\end{array} - \begin{array}{c}\text{Carbon stock existing before}\\ \text{the woodland was created}\end{array}$$

Where t is the number of years since the woodland was created.

The majority of the results presented in figures in this appendix are based on these types of results. Figure A3 shows such results are shown for the example of creating the broadleaf woodland carbon reserve as considered above.

In summary, the results in Figure A3 show:

- An initial loss of carbon (from the soil), as a result of soil disturbance during site preparation and the time taken for the inputs to soil carbon from trees to replace the inputs from the previous grass cover
- Significant long-term accumulation of carbon stocks in living trees, dead wood, litter and (eventually) soil
- Over many decades (more than a century), the rate of carbon stock accumulation slows down and shows signs of levelling off. However, the carbon stock changes resulting from the initial act of tree planting are long-lasting and are still apparent 200 years later.

The general pattern of carbon stock changes in Figure A3 is similar across a wide range of woodland types (site type, tree species, growth rate etc.). However, the details vary considerably (e.g. rate of carbon accumulation, ultimate carbon stock achieved, and extent of losses from soil).

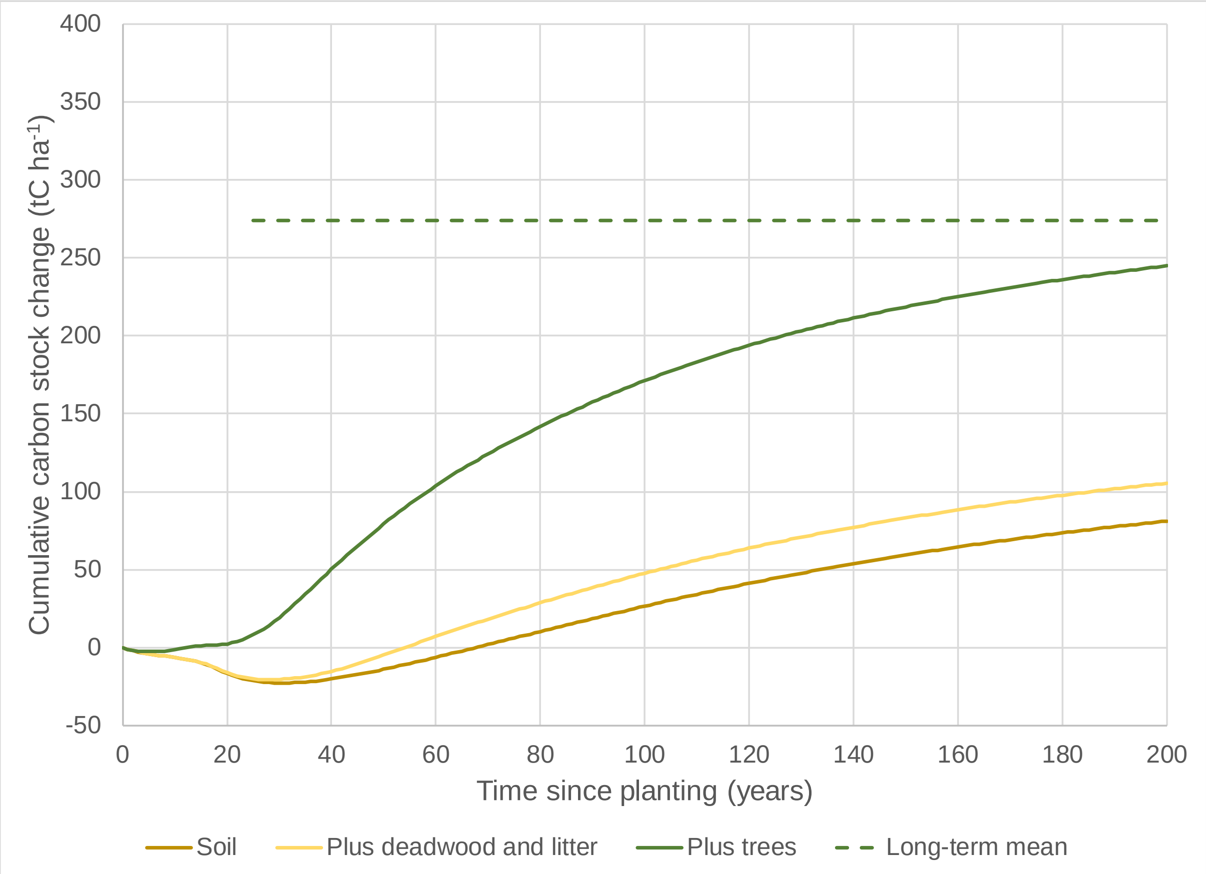

Figure A3 Cumulative net impact on woodland carbon stocks resulting from creating a stand of mixed birch and oak (yield class 4) left undisturbed and protected so as to create a "carbon reserve". "Plus deadwood and litter" = soil carbon stocks + deadwood and litter carbon stocks; "Plus trees" = soil carbon stocks + deadwood and litter carbon stocks + tree carbon stocks (i.e. total woodland carbon stocks).

Viewed over a long timescale, the ultimate carbon stock, calculated for a 300-year period, is indicated in Figure A7 by a dashed horizontal line, taking a value of 274 tC ha^{-1}.

A1.2.3 Factors and issues to consider

It should be noted that several factors have not been considered in the presentation and discussion of the results for the example woodland creation scenario described in this section:

1. It is possible (indeed likely) that the act of creating the woodland would involve some management operations, for example as part of site preparation, weed control, tree planting and/or the protection of the woodland against disturbances such as fire. Some or all of these operations are likely to involve the use of machinery, materials and energy, with associated GHG emissions. Such GHG emissions have not been estimated for this "woodland carbon reserve" case. However, estimates of such emissions for other scenarios,

involving more active woodland management indicate that these are likely to make a small contribution to the overall impact on GHG emissions (see for example relevant results in Section A1.4.3).

2. It should be recalled that the scenario considered in this section involves an assumption that the accumulation of woodland carbon stocks is not disrupted by incidents of natural disturbance (e.g. fire, storms, pests and diseases). In situations where disturbances occur, on some sites, some of the resultant losses may be compensated for if the potential growth rate of regenerating trees is sufficiently high.
3. The scenario considered in this section involves the assumption that no management is carried out in the “carbon reserve woodland” once it is created, other than management aimed at protection of the woodland carbon stocks. In practice, some management, involving the thinning of some trees or felling of patches may be carried out, to meet amenity or ecological objectives, for example, to allow access to visitors for recreation, or to create habitats or encourage the growth of understorey vegetation. These management activities are likely to reduce the carbon stocks in living trees, so that the ultimate carbon stock of the woodland is somewhat lower than that suggested by the results presented above. However, depending on the details of the management practices, there may be some related increases in carbon stocks in deadwood, litter and soil. It may also be noted that, on some sites, some losses may be compensated for if the potential growth rate of the trees (generally broadleaf in this context) are higher than the average rates for existing woodlands. (See Sections A1.4, A1.6 and A1.8 for illustrations of relevant points in the context of managed coniferous woodlands.)
4. There will be a contribution to initial losses of carbon stocks as a result of the removal of the previous vegetation as part of woodland creation. This initial loss of vegetation carbon stocks is not estimated or included in the results. However, it is likely that these carbon stocks will be relatively small, for example in the case of managed grassland which is subjected to grazing or annual mowing (and possibly removal of the biomass). Inputs of carbon to soil from pre-existing vegetation and manure produced by grazing livestock (if present) are included implicitly in the modelling of soil carbon stocks for the for the previous land use (i.e. prior to woodland creation).
5. The modelling of the impacts of woodland creation involves the assumption that the previous vegetation is removed from the site (with consequent loss of pre-existing inputs of carbon to the soil), and that this remains the case until the trees have become sufficiently established to compensate for the lost soil carbon inputs. In practice, the transition involving the loss of previous vegetation cover and the establishment of tree cover may be more gradual, with smaller impacts on soil carbon inputs over this period. This is a subject for further research and potential refinement of modelling.
6. If the land was used previously for agricultural production, the change in land use to create the woodland results in the loss of this production from this area of land. If this agricultural produce was needed, then this implies that agricultural production will need to be increased from some other source (land area). Any consequent changes in agricultural production and land management are likely to involve impacts on GHG emissions (see Section

2.14 in the main body). These impacts (if relevant) have not been estimated or included as part of the results presented here.

It should be further noted that points (1) to (3) above are relevant specifically for the “carbon reserve” woodland creation scenario considered in this section, and also for the scenario considered in also Section A1.3, whilst points (4) to (6) above are potentially more widely relevant to a number of the scenarios considered in this appendix and the main annex body.

A1.3. Natural colonisation

As discussed in Section 2.16.3 of the main body, the option has been suggested of creating carbon-reserve woodlands by abandoning land (e.g. former agricultural land) and passively allowing woodland to regenerate by natural colonisation. The long-term impacts of such an approach on vegetation and soil carbon are likely to be significant. However, there is limited evidence available of the “success rate” of this sort of passive approach to woodland creation. It also seems likely that the process of natural colonisation of land by trees, and subsequent growth and carbon sequestration, will be slow, compared with active approaches to woodland creation, involving the same tree species or otherwise.

There are very few examples of studies investigating the development of woodlands through natural succession.

The Broadbalk and Geescroft trials, undertaken at Rothamsted Research in Southern England (Jenkinson 1971; Poulton et al. 2003), are an exception, regarded as ‘classical’ studies in the reversion of agricultural land to ‘wilderness’ (essentially woodland).

Up until the early 1880s, these two sites had been under agricultural management for a long time. However, management was completely withdrawn at this time and the sites were allowed to regenerate naturally with vegetation. Both sites gradually developed into stands of mixed broadleaved trees, with ash and sycamore being dominant for the Broadbalk site, and oak being dominant for the Geescroft site.

A1.3.1 Tree carbon stocks

Measurements of tree carbon stocks (branches, stemwood and roots) were made at Broadbalk and Geescroft in 1964/5 and 1999, giving two observations for tree carbon stocks for both sites. In Figure A4, the measurements of tree carbon stocks from these trials are shown plotted against the years in which they were measured. Simulations have been made using the CARBINE model, based on the tree species regenerating at Broadbalk and Geescroft, calibrated for consistency with the observed development of the tree carbon stocks over time, as measured in the studies.

The development of carbon stocks simulated by CARBINE are also shown in Figure A4 (solid lines), with projections to 2050 (dashed lines). The input data to the CARBINE model required detailed specification to get a good match to the field observations. In particular:

- It was necessary to assume an exceptionally fast growth rate for the ash and sycamore trees at the Broadbalk site (yield classes between 12 and 14 m^3 ha^{-1} yr^{-1})
- The growth rate (yield class) of the oak at the Geescroft site was estimated at about 5 to 6 m^3 ha^{-1} yr^{-1} (again, relatively fast but in this case within the typical range observed for oak)
- Importantly, it was necessary to assume some delay to the start of tree growth at both sites following abandonment of agricultural management around 1882/3. For each site, this involved assuming two episodes of tree regeneration, taking place between 10 years and 45 years after land abandonment. This appears to be broadly consistent with the observations about the timing of tree regeneration at the two sites reported by Harmer et al. (2001).

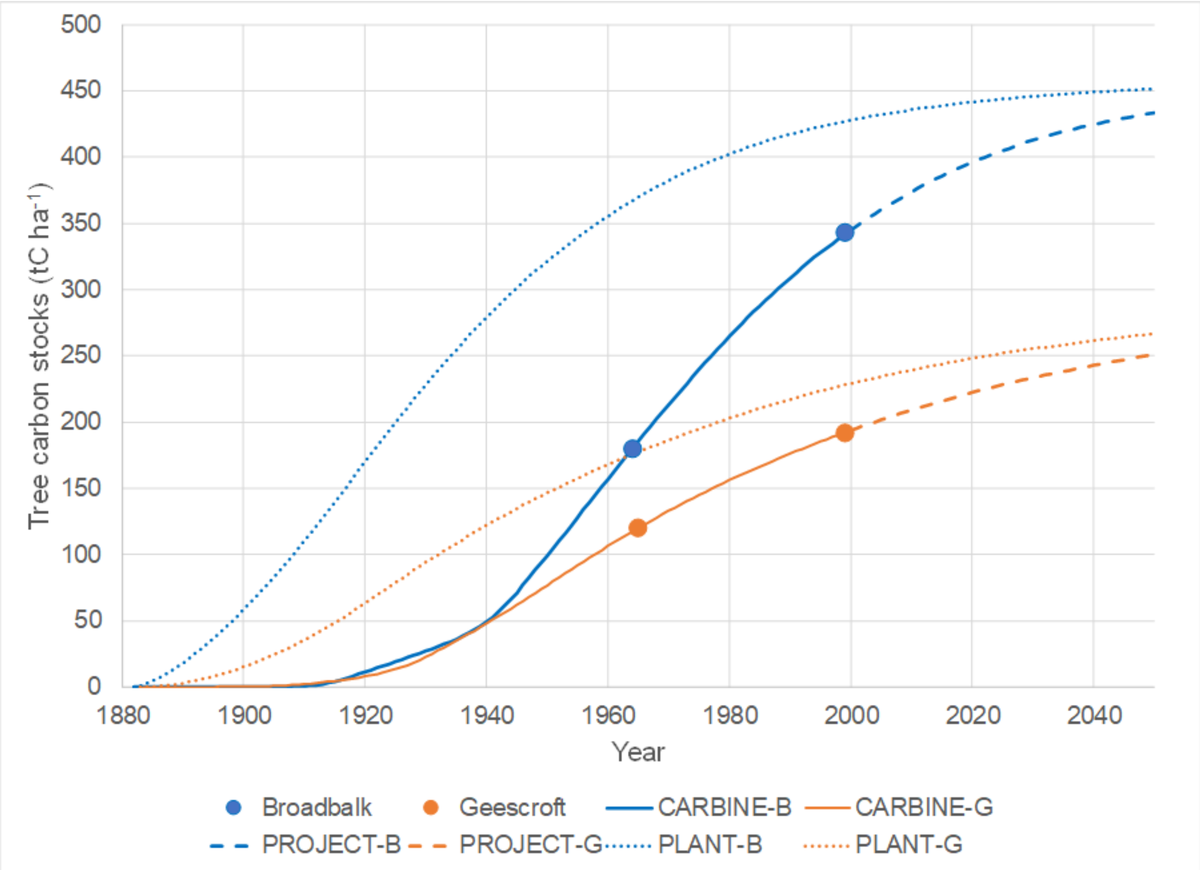

Figure A4 Development of tree carbon stocks (branches, stem, roots) at the Rothamsted study sites (Broadbalk and Geescroft). Points indicate field observations. CARBINE-B and CARBINE-G indicate CARBINE model simulations of carbon stocks, calibrated to fit the data for Broadbalk and Geescroft, respectively. PROJECT-B and PROJECT-G are projections made using the CARBINE model for years subsequent to the last measurements. PLANT-B and PLANT-G indicate CARBINE model simulations assuming all trees were actively planted rather than naturally regenerating. Source of data for field observations: Rothamsted Research (2015ab).

According to Figure A4, the results, the results of the CARBINE simulations are a good fit to the field observations. However, the high uncertainty associated with model input assumptions must be stressed. It must also be recognised that there are just two measurements of tree carbon stocks at each study site, which make any projection of past and future accumulation of carbon stocks very speculative.

To permit comparison, CARBINE simulations were also produced based on the assumptions described earlier but assuming a consistent planting year of 1882 (Broadbalk) and 1883 (Geescroft). These simulations may be representative of carbon stock developments, had the two sites been actively planted, rather than left to recolonise naturally. Results for these simulations are also shown in Figure A4.

A1.3.2 Soil and litter carbon stocks

There is more evidence available from the Rothamsted classical studies on the impacts on soil carbon stocks occurring as a consequence of the abandonment of agricultural land and allowing the land to naturally recolonise with trees. Four measurements of soil carbon stocks have been made in each of the study trials, taken in 1881/3, 1904, 1964/5 and 1999. These results are shown in Figure A5 (points joined by solid trajectories). The estimates of soil carbon stocks are to a consistent soil depth of 69 cm.

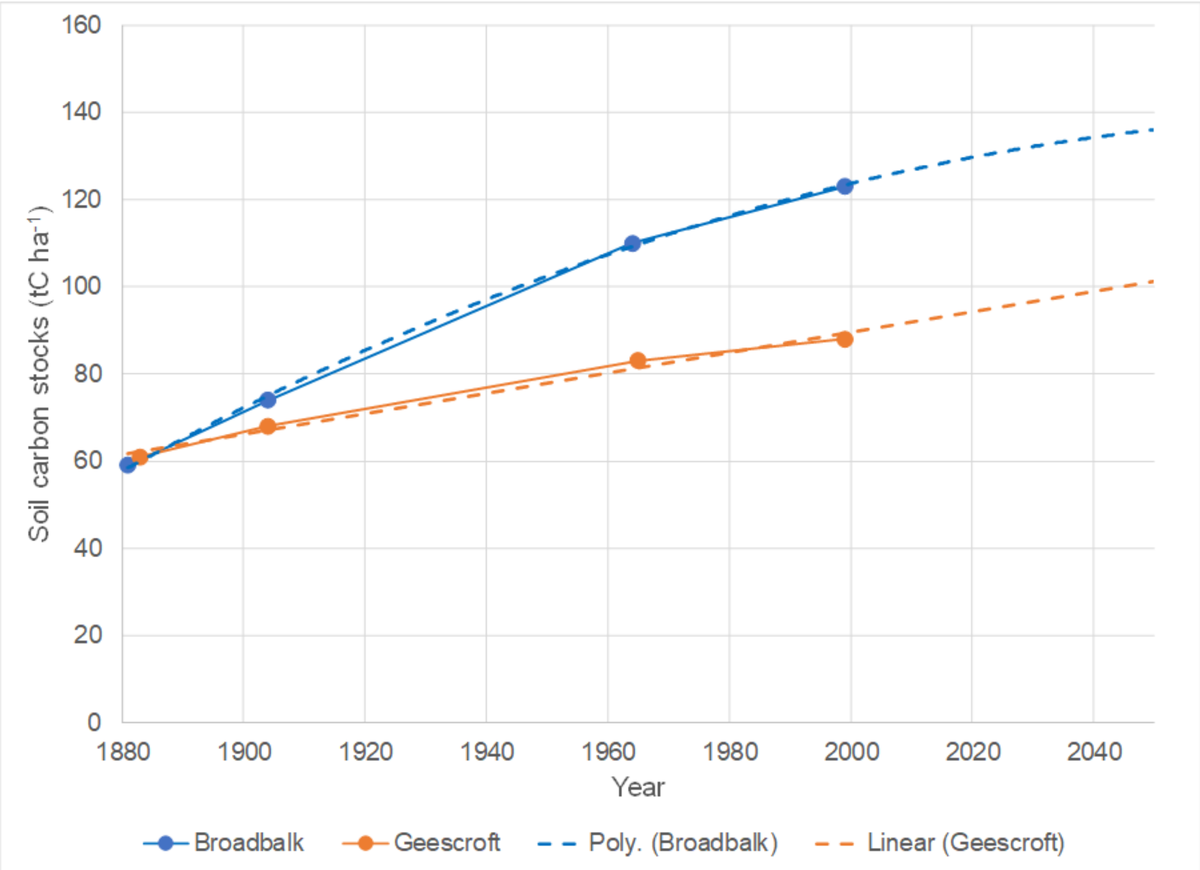

Figure A5 Development of soil carbon stocks at the Rothamsted study sites (Broadbalk and Geescroft). Points indicate field observations. Dashed lines indicate simple quadratic ("Poly.") and linear equations fitted to the data. Source of data for field observations: Rothamsted Research (2015ab).

At the time of abandonment, soil carbon stocks at both sites were around 60 tC ha^{-1}. Over the period from abandonment to the year 1999, soil carbon stocks increased at fairly consistent annual rates of about 0.5 tC ha^{-1} yr^{-1} at Broadbalk and about 0.25 tC ha^{-1} yr^{-1} at Geescroft. The higher rate of carbon accumulation at Broadbalk may reflect the much higher growth rate estimated for this site compared with the Geescroft site (see Section A1.3.1). It may also be noted that the field at Broadbalk is adjacent to a farmyard, whereas the Geescroft site is surrounded by other fields. Poulton et al. (2003) also report contrasting soil conditions at Broadbalk and Geescroft (calcareous and acidic, respectively). It may be further noted that recolonization by trees was observed to occur later at the Geescroft site (Harmer et al. 2001).

The increases in soil carbon stocks in the early years (possibly decades) after abandonment are likely to reflect inputs of carbon to the soil from non-tree vegetation recolonising the land in advance of most trees.

Based on very simple extrapolations of the data (linear and quadratic relationships with respect to year, shown as dashed lines in Figure A5), soil carbon stocks may be expected to exceed 100 tC ha^{-1} at both sites by 2050. There is only the slightest suggestion in the results of a slowing of the rate of soil carbon accumulation over a period of more than 150 years. Poulton et al. (2003) also report an additional but relatively small additional contribution to woodland carbon stocks from deadwood and litter.

The above results and findings for soil and litter carbon stocks are reasonably consistent with the model results presented in Figure A2 and A3 in Section A1.2, allowing for the differences in the scenario considered in that example (tree planting rather than recolonization, and on land that was formerly grassland rather than arable land).

A1.3.3 Assessment of total woodland carbon stock impacts

Whilst the periodic measurements of soil carbon stocks at Broadbalk and Rothamsted are a valuable source of evidence, the two measurements of tree/vegetation biomass and the tentative CARBINE simulations are more difficult to interpret definitively. Furthermore, confounding factors frustrate attempts to draw any definite conclusions from comparisons between the measured and modelled carbon stocks. Relevant factors include uncertainty over the speed of natural succession processes following abandonment, uncertainty over the growth rates of equivalent even-aged stands and the inclusion of understorey vegetation in biomass estimates reported for the Rothamsted studies.

One possible but very tentative interpretation of the results is that woodlands established by natural succession accumulate carbon stocks very slowly initially (compared with planted woodlands, or those in which regeneration is assisted), but that growth rates and carbon accumulation accelerate later on (e.g. between perhaps 50 and 150 years), compared to planted woodlands. Outcomes also appear to vary considerably from site to site, depending on how long the expected broadleaved trees take to start regenerating (assuming this occurs) and the types of trees involved. It should also be noted that the sites at Rothamsted were previously arable fields with relatively high management inputs prior to abandonment, where vegetation might be expected to regenerate relatively quickly. It is not possible to comment on whether such stands of trees would accumulate more carbon stocks at the point of saturation than an equivalent stand of planted trees. On the other hand, there are likely to be significant obstacles to successful woodland creation through natural colonisation on many sites, for example if there is significant pressure from grazing animals such as deer or rabbits. As a consequence, natural colonisation is risky and, on many sites, and it is likely that little, if anything, will happen in terms of woodland development in a reasonable period, say 50 years. It may also be noted (Figure A4) that stands of trees of equivalent tree species and growth rate, established through planting or assisted regeneration, might be expected to sequester carbon more rapidly early on and to reach the ultimate carbon stocks between 10 and 40 years earlier than stands that become established through natural colonisation, where this takes place successfully.

More studies of the vegetation and soil carbon dynamics of land being abandoned appear to be required.

A1.3.4 Factors and issues to consider

Additional points discussed in Section A1.3.3 are also relevant here.

A1.4. Managed spruce woodland

Figures A6 to A8 show an example of the impacts on land-based carbon stocks of establishing a new coniferous woodland (most likely by planting trees) and managing the new woodland for wood production. If newly-created woodlands are managed for production of timber and fuel, there should also be significant positive impacts on GHG emissions in other sectors, as a result of carbon sequestration in wood products and “product substitution” (see Section 2.12 of main body), compared with the option of simply allowing carbon stocks in the new woodlands to accumulate without any harvesting. Estimates of these “off-site” impacts are also included in Figure A8.

The tree species planted is assumed to be Sitka spruce, with a yield class of 12 m^3 ha^{-1} yr^{-1}. This growth rate may be regarded as moderate for new plantings of Sitka spruce but areas of such Sitka spruce stands are quite common as part of coniferous woodlands in Wales. It is assumed that the woodland is managed for wood production involving clearfelling and restocking on a rotation of 50 years, but with no thinning being carried out during the rotation.

A1.4.1 Tree carbon stocks

Figure A6 shows the accumulation and loss of carbon stocks in the living trees forming the woodland over several rotations. The carbon stocks in trees accumulate from the time of planting up to the end of each 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 “cycle” between zero and 170 tC ha^{-1} every 50 years.

Considered from a long-term perspective, planting the Sitka spruce stand and managing with a clearfelling rotation of 50 years is seen to accumulative and maintain a time-averaged (long-term mean) carbon stock in trees of 60 tC ha^{-1}. This is indicated by the dashed horizontal line in Figure A6. (This is an example of "technical saturation", as opposed to "biological saturation", as illustrated in Figure A1 in Section A1.2.1; see also Section 2.7 of the main body.) The cyclical variation in this carbon stock in the individual stand of Sitka spruce trees is considerable. However, such variation can be very much less when populations of stands forming a large area of woodland are considered. In this situation, the peaks and troughs in woodland carbon stocks will be evened out over the population of stands, and carbon stocks per hectare for the complete woodland will be closer to the long-term mean, once all the stands have become established. This point is illustrated and explained in detail in Section A1.5.

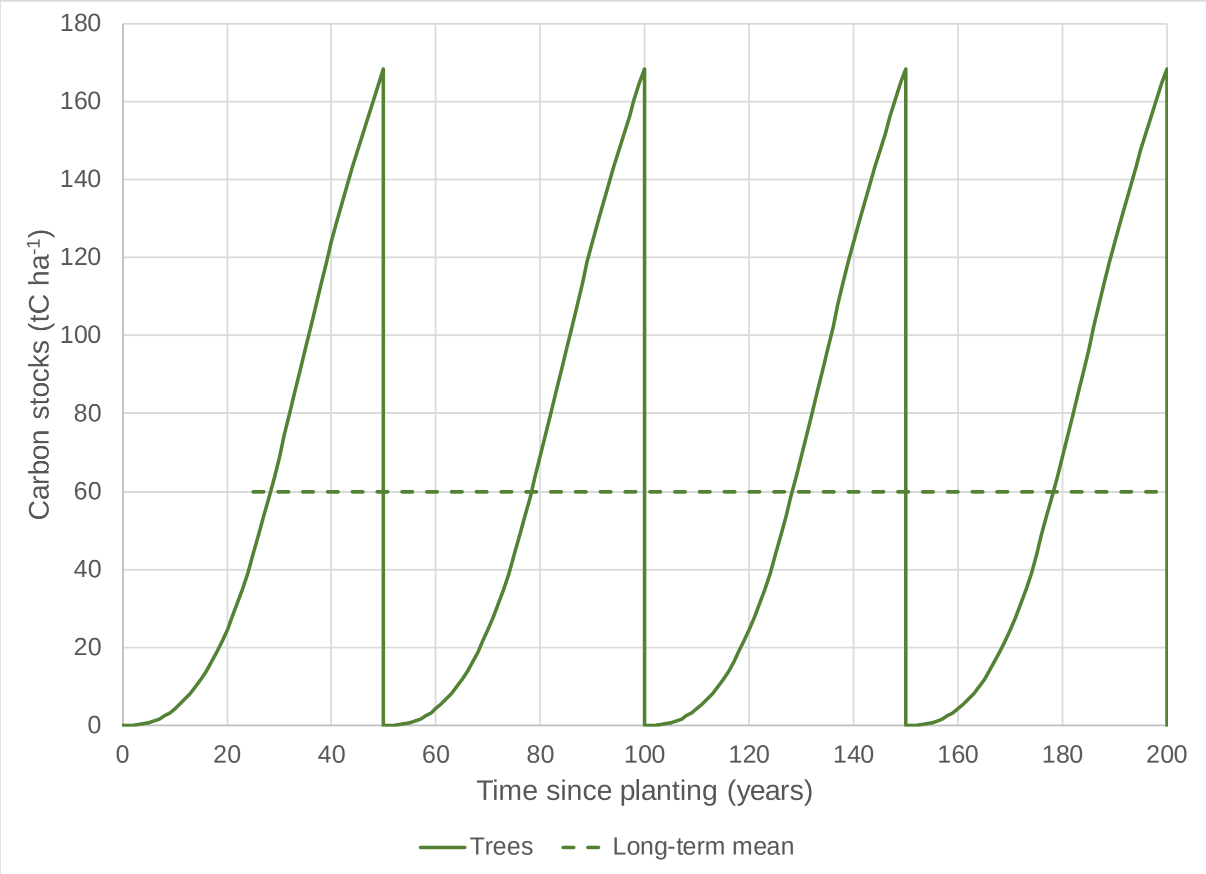

Figure A6 Development of tree carbon stocks in a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation without thinning.

A1.4.2 Total woodland carbon stocks

Figure A7 shows the combined impacts on carbon stocks in living trees, in deadwood and litter and in soil. The figure shows the net impacts on carbon stocks from time of woodland creation, calculated as explained in Section A1.2.2.

The pattern of accumulation and loss of carbon stocks in living trees has already been discussed in Section A1.4.1 above. Figure A7 also shows how tree harvesting results in the significant accumulation of carbon stocks in deadwood and litter (the residues of harvesting), followed by gradual decay. It is assumed in this scenario that the harvesting residues are left to rot on site, rather than being burned, or removed from the site as a source of wood fuel (bioenergy). There is an initial loss of carbon from the soil, as a result of soil disturbance during site preparation and the time taken for the inputs to soil carbon from trees to replace the inputs from the previous grass cover. Eventually, there is a long-term accumulation of carbon stocks in the soil as inputs of carbon from living trees, deadwood and litter increase once the woodland stand has become established.

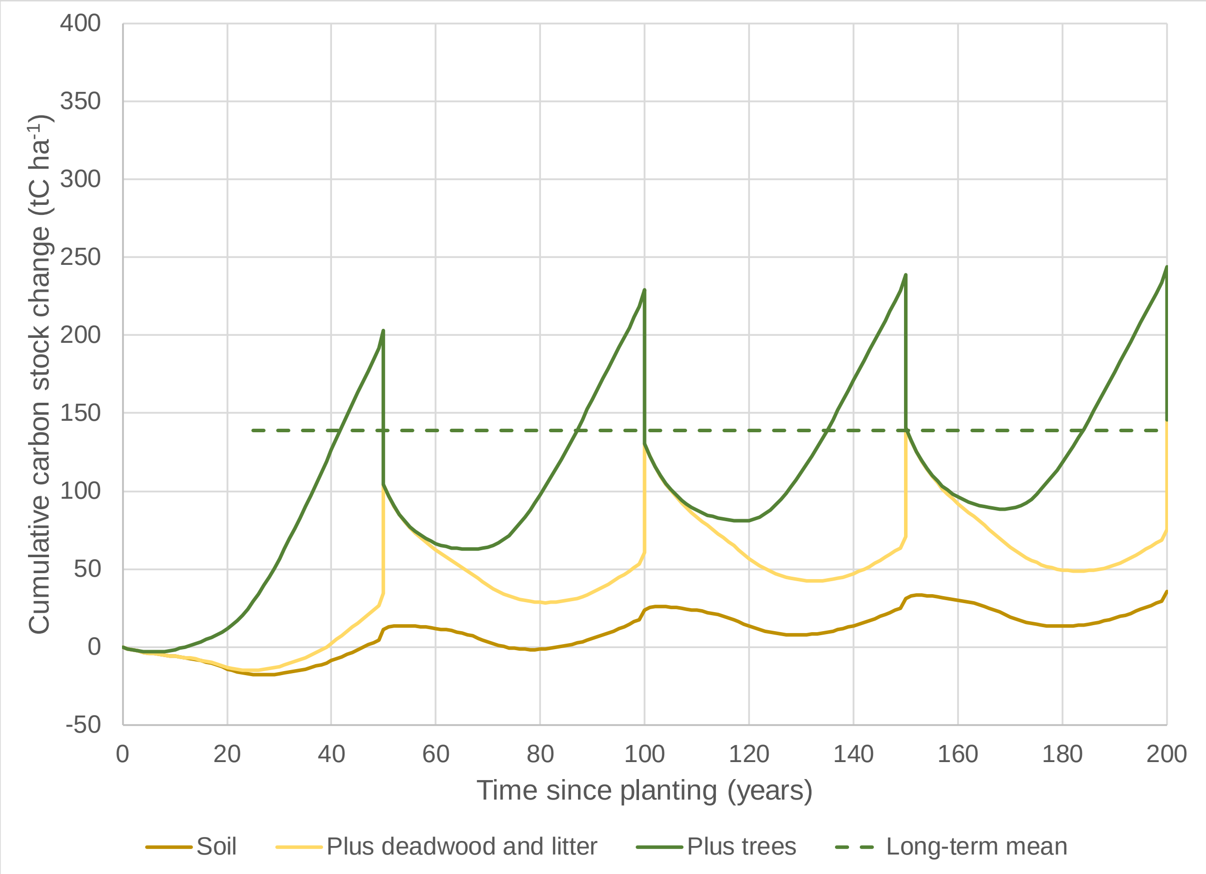

Figure A7 Development of total woodland carbon stocks in a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation without thinning. "Plus deadwood and litter" = soil carbon stocks + deadwood and litter carbon stocks; "Plus trees" = soil carbon stocks + deadwood and litter carbon stocks + tree carbon stocks (i.e. total woodland carbon stocks).

Overall, the development of carbon stocks in the woodland exhibits peaks and troughs, as the woodland stand (re)grows and is clearfelled every 50 years. However, viewed over a long timescale, mean carbon stocks in the woodland are seen to oscillate around a long-term mean carbon stock. This mean carbon stock, calculated for a 300-year period, is indicated in Figure A7 by a dashed horizontal line, taking a value of 140 tC ha^{-1}. This point is particularly pertinent when considering an ensemble of woodland stands, planted over a series of years, rather than all in one year (see Section A1.5).

The long-term mean carbon stocks are lower than those for the ultimate carbon stock of the example unmanaged broadleaf stand with no harvesting (Figure A3, Section A1.2.2), but are still significant, compared with the carbon stocks before tree planting.

It should also be recalled that the high carbon stocks estimated for the unmanaged woodland involve an assumption of no losses occurring as a result of natural disturbance events.

A1.4.3 Total carbon and GHG impacts

In Figure A8, the results in Figure A7 are repeated but, in addition to the development of carbon stocks in trees, deadwood and litter and soil, Figure A8 shows:

- Contributions made by carbon stocks in wood products manufactured from wood harvested from the Sitka spruce stand
- GHG emissions (in units of tC-eq. ha^{-1}) from operations carried out as part of woodland management (e.g. machinery used in tree harvesting). These contributions are expressed cumulatively, for consistency with the estimates of net carbon stock impacts (i.e. rather than carbon stock changes, see Section A1.2.2).
- Potential contributions to reductions in GHG emissions (in units of tC-eq. ha^{-1}) made by using wood fuel in substitution for fossil fuels and through material wood products substituting for more GHG intensive non-wood products. These contributions are expressed also cumulatively, for consistency with the estimates of net carbon stock impacts.

If carbon stocks in wood products are considered as well as carbon stocks in the woodland, the mean cumulative net carbon stock impacts after 300 years resulting from creating the managed woodland are 170 tC ha^{-1}, as indicated by the dashed dark red horizontal line in Figure A8.

If potential GHG emissions displaced by wood products are also considered, the mean cumulative net impacts after 300 years are 580 tC-eq. ha^{-1}, as indicated by the dashed purple horizontal line in Figure A8. Hence, in the longer term, GHG emissions impacts from wood product substitution are the dominant contribution to overall GHG impacts. It may also be noted that the contribution to cumulative GHG emissions from operations carried out as part of woodland management (e.g. from harvesting machinery) are relatively very small.

Whilst carbon sequestration in the woodland and wood products will eventually saturate, in principle the displacement of GHG emissions through product substitution can continue indefinitely. However, uncertainties surrounding these contributions in the longer term have been highlighted in Section 2.12 of the main body text.

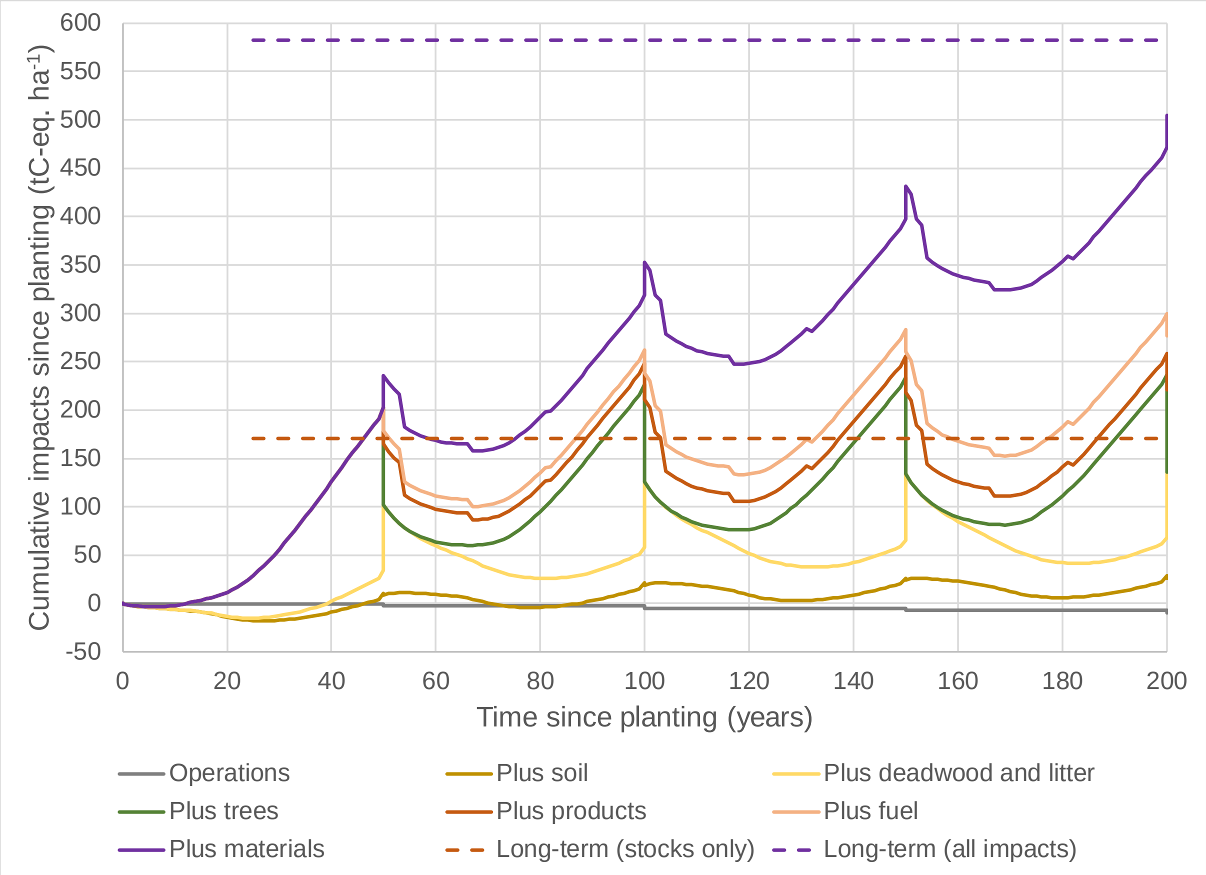

Figure A8 Cumulative net impacts on woodland and "off-site" carbon stocks and "off-site" GHG emissions resulting from planting a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation without thinning. Contributions from different sources are "stacked", e.g. "Plus fuel" = Operations + soil + deadwood and litter + trees + wood products + GHG emissions displaced by wood fuel.

A1.4.4 Factors and issues to consider

Points (4) to (6) in Section A1.2.3 should be recalled here. In addition, Points (2) and (3) in that discussion have some relevance.

A1.5. Populations of managed stands

As highlighted in Section A1.4, large cycles in carbon stocks can occur in individual stands of trees managed for production involving clearfelling, reflecting the periodic growth, felling and regrowth of stands. However, usually, not all of the stands in a population forming a whole woodland or landscape will be the same age or clearfelled at the same time. Hence, at the scale of a whole woodland or landscape, losses of carbon stocks related to harvesting may be counterbalanced by sequestration in the remaining stands which are still growing, as is the case if the relevant woodland area is managed on the basis of sustainable yield. (Sustainable yield is one of the fundamental principles underlying sustainable woodland management.) Figures A9-A13 illustrate how a woodland might be created and then harvested according to sustainable yield principles, also showing the overall consequences for woodland carbon stocks and carbon sequestration. This example is repeated from Section 3.3 of Matthews et al. (2014a), which is based heavily on earlier illustrations presented by Piers Maclaren (see for example Maclaren 1996, 2000).

Figures A9-A13 describe how a 5,600 hectare woodland 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 yield class (potential stem volume growth rate) of 12 m^3 stem volume ha^{-1} yr^{-1}. Harvesting is assumed to involve clearfelling of stands on a rotation of 56 years. (Note that the rotation in this example is slightly longer than the one assumed for the example Sitka spruce stand considered in Section A1.4.)

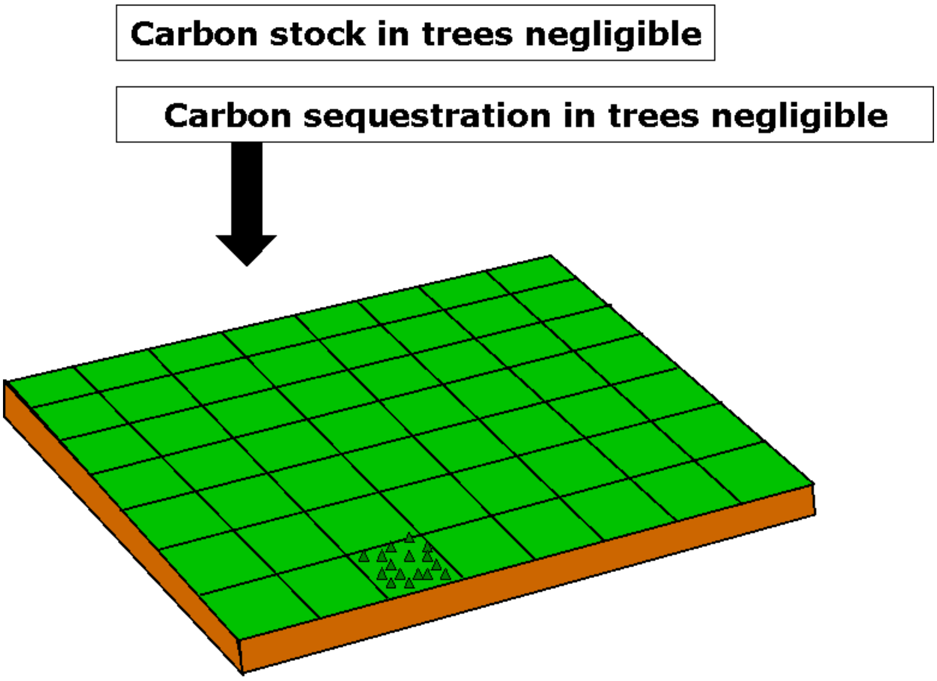

Figure A9 Creating a 5,600 hectare woodland from even-aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 1 year. (Figure repeated from Matthews et al. 2014a and based on the ideas of Piers Maclaren, see Maclaren 1996, 2000.)

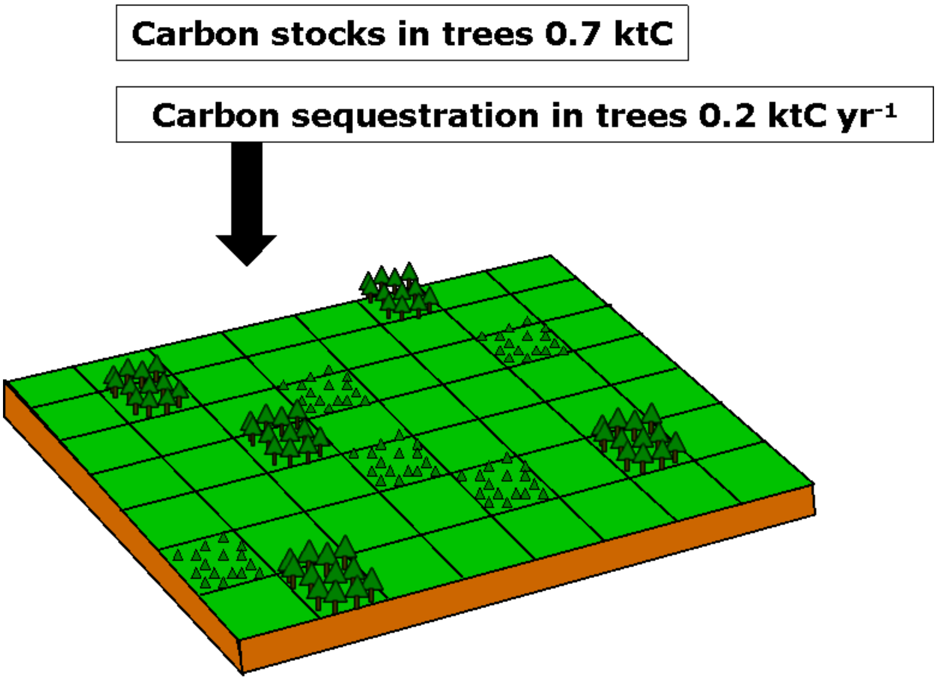

Figure A10 Creating a 5 600 hectare woodland from even-aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 10 years. (Figure repeated from Matthews et al. 2014a and based on the ideas of Piers Maclaren, see Maclaren 1996, 2000.)

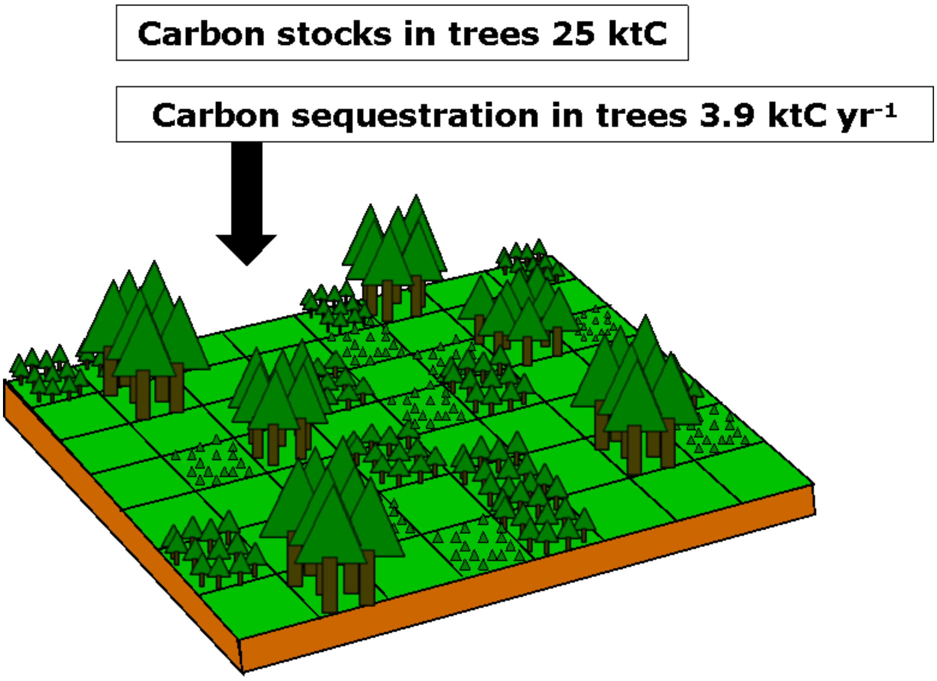

Figure A11 Creating a 5 600 hectare woodland from even-aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 25 years. (Figure repeated from Matthews et al. 2014a and based on the ideas of Piers Maclaren, see Maclaren 1996, 2000.)

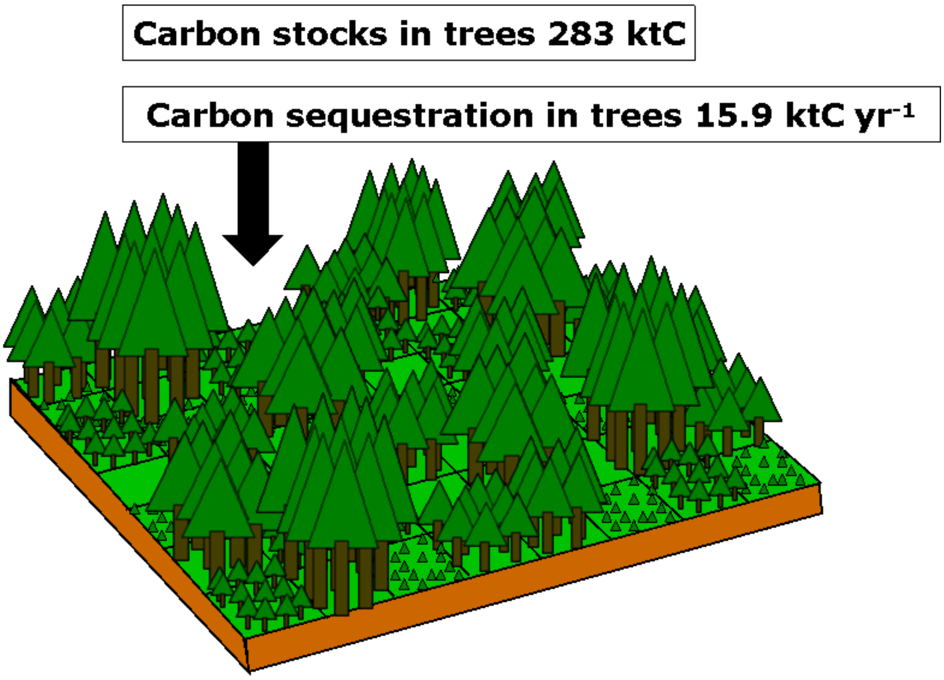

Figure A12 Creating a 5 600 hectare woodland from even-aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 50 years. (Figure repeated from Matthews et al. 2014a and based on the ideas of Piers Maclaren, see Maclaren 1996, 2000.)

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 (similarly to the example woodland stand considered in Section A1.4). Whilst this example is theoretical, a strong parallel with real-world coniferous woodlands in Wales and the UK (and the manner in which these woodlands have been created) should be noted. For simplicity, the results quoted in Figures A9-A13 are for carbon stocks in trees only, i.e. no account is taken of carbon stocks in deadwood, litter and soil, or of the contributions from wood products.

Figure A9 shows the situation after 1 year. Just one hundred hectares of new Sitka spruce stands have been established and, after just one year of growth, levels of carbon stocks and carbon sequestration are negligible. After 10 years (Figure A10), 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 in trees (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 A11), 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 (see Section 2.5 of the main body). Carbon stocks in trees have reached 25 ktC and the rate of carbon sequestration has risen to 3.9 ktC yr^{-1}. After 50 years (Figure A12), 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 in trees have reached 283 ktC and the rate of carbon sequestration has risen to 15.9 ktC yr^{-1}.

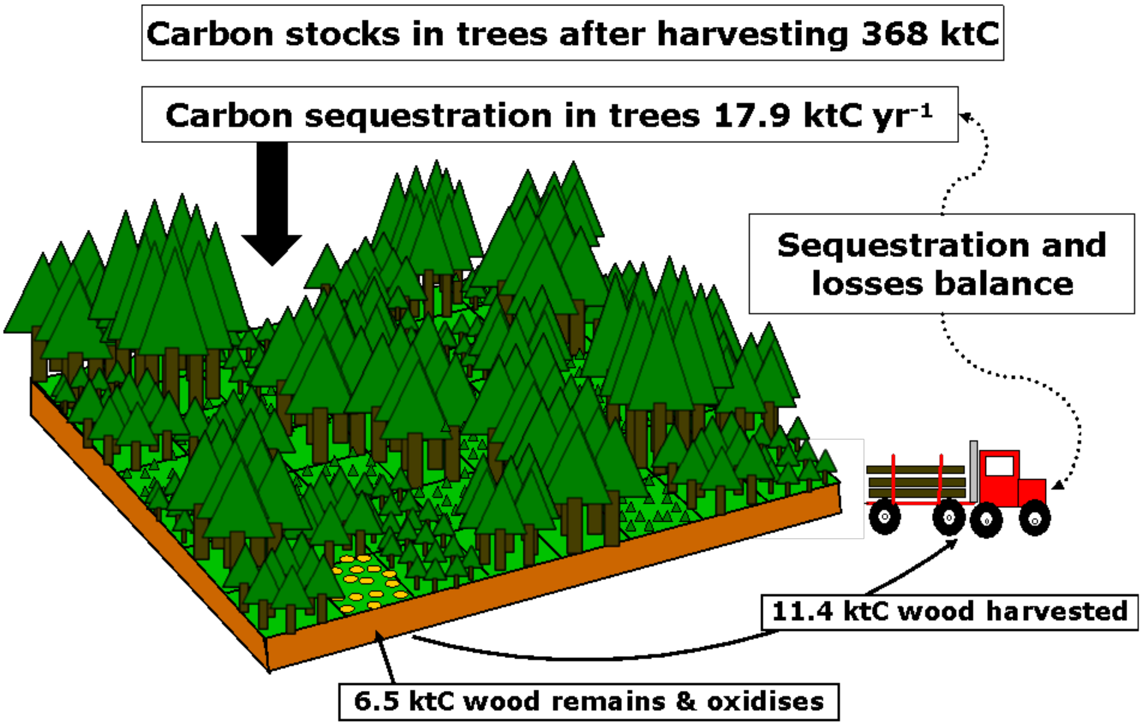

Figure A12. Creating a 5 600 hectare woodland from even-aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration: situation after 56 years. (Figure repeated from Matthews et al. 2014a and based on the ideas of Piers Maclaren, see Maclaren 1996, 2000.)

Figure A13 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.

The development over time of the carbon stocks in the trees comprising the stands described in Figures A9-A13 is shown in Figure A14.

The accumulation of carbon stocks becomes more rapid over a 40-year period, as more stands are established 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 woodland, which is recovered within one year by the continued growth of the remaining woodland stands. In year 57 another cohort of stands is clearfelled but the growth of the remaining woodland stands continues to counterbalance losses of carbon stocks within one year. Provided woodland stands are re-established as soon as they are clearfelled, *overall carbon stocks in the woodland are not reduced, but neither do they increase*, rather *a constant carbon stock is maintained* over time.

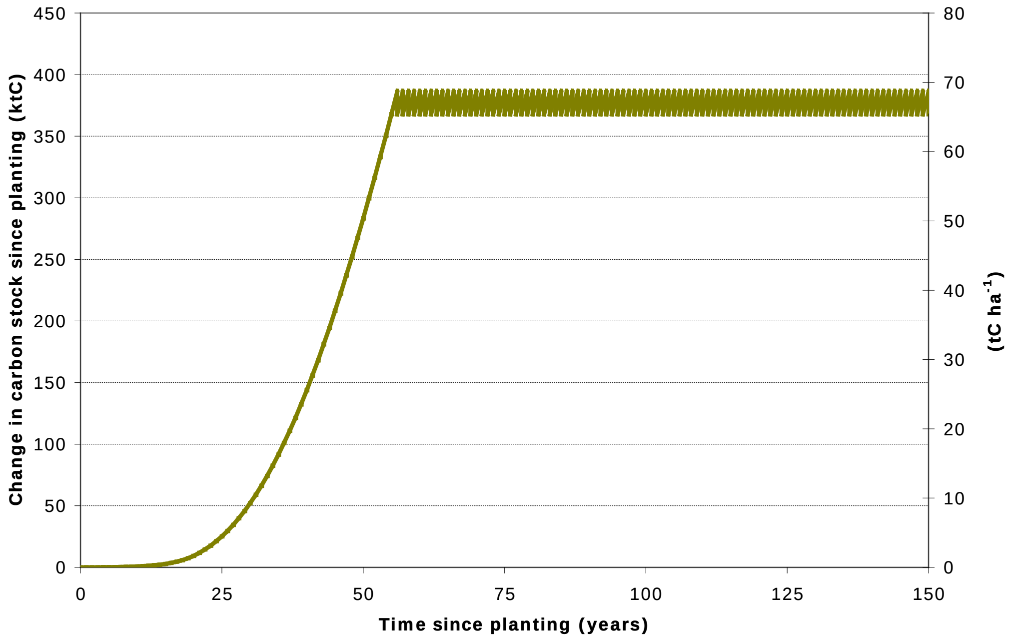

Figure A14. Development of carbon stocks over time in trees forming the stands of the 5 600 hectare woodland created from even-aged Sitka spruce stands over 56 years, as illustrated in Figures A5-A9. The left-hand y-axis shows the change in total carbon stocks for the 5 600 ha area, the right-hand y-axis shows the change in carbon stocks for the area expressed in tC ha^{-1}.

It is interesting to compare the result for the long-term per-hectare carbon stock in trees, resulting from the creation of the 5 600 ha woodland as considered above, with the mean tree carbon stock estimated for the individual Sitka spruce stand in Figure A6 (Section A1.4.1). The per-hectare carbon stocks for the population of stands are indicated by the right-hand y-axis in Figure A14. The long-term mean tree carbon stock in Figure A6 (60 tC ha^{-1}) and that for the population of stands in Figure A14 (65 tC ha^{-1}) are very similar. The difference between the two estimates reflects the slightly longer rotations assumed for the population of stands, compared with the example individual stand (56 years and 50 years, respectively). This is an illustration of how carbon stocks in woodlands are affected by the rotations applied to individual stands, a point discussed further in Section A1.7 below. The results in Figures A6 and A14 also show how estimates of carbon stocks (and stock changes) for an individual stand of trees can be interpreted to assess results for whole woodlands consisting of many stands of trees.

A1.5.1 Factors and issues to consider

Creating a 5 600 ha woodland as described in the preceding example will of course also have impacts on deadwood, litter and soil carbon stocks. Results for total woodland carbon stocks for the example 5 600 ha woodland are not given here, but results for a single stand of trees, based on a similar scenario, have been presented and discussed in Section A1.4.2. Relevant population-scale results were included in the report of Matthews et al. (2014a, Section 3.3) but it should be noted that these were based on results from an older version of the CARBINE model, giving different results for deadwood, litter and soil compared to the current version. Significant improvements have been made to the representation of these carbon stock dynamics in the current version of CARBINE (Matthews et al. 2020a).

It remains the case that managing a newly created woodland 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 Section A1.2.

The discussion presented in this section is based largely on the example of a woodland 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 woodlands 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 woodland growth and in rates of harvesting and, in response, the carbon stock in the stands of trees forming a woodland will fluctuate around a mean level, rather than following the mean level precisely as illustrated in Figure A14. 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 woodland stands, in particular the interplay between growth and sequestration on the one hand, and harvesting and removals of carbon for wood production on the other hand.

A1.6. Influence of thinning

Figures A15 to A17 show an example of the impacts on land-based carbon stocks, and on “off-site” carbon stocks and GHG emissions, of establishing a new coniferous woodland (most likely by planting trees) and managing the new woodland for wood production. The type of woodland and the management are the same as for the example described in Section A1.4, with the exception that the woodland is managed with regular wood harvesting from thinning operations during the life cycle of the stand, as well as being clearfelled on a rotation of 50 years. This is in contrast to the example in Section A1.4, where the woodland was assumed not to be thinned.

A1.6.1 Tree carbon stocks

Figure A15 shows the accumulation and loss of carbon stocks in the living trees forming the woodland over several rotations. The general patter of the development of tree carbon stocks is similar to that describe for the unthinned woodland (Figure A6, Section A1.4.1), but with additional shorter-term losses and increases in tree carbon stocks, as trees are removed (harvested) as thinnings and the remaining trees continue to grow.

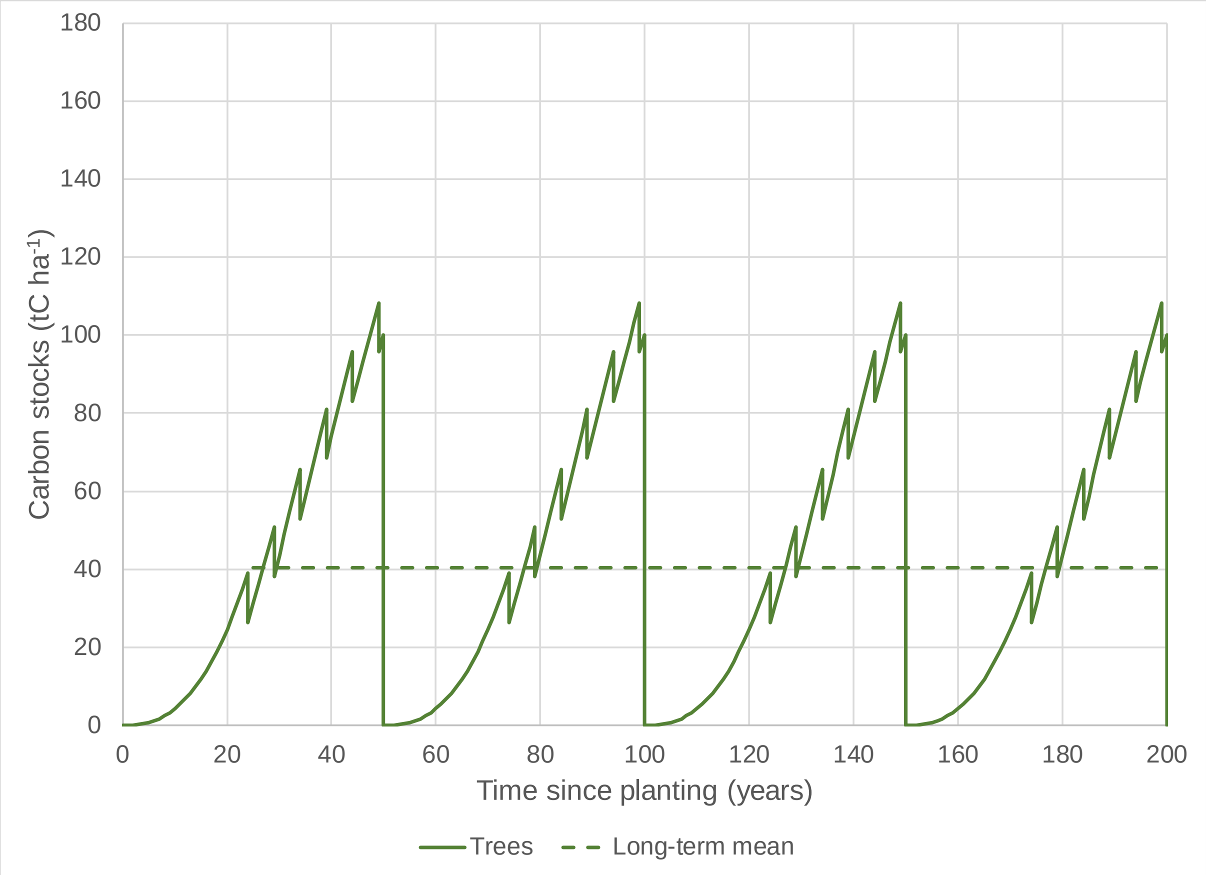

Figure A15 Development of tree carbon stocks in a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation with thinning during the rotation.

It is well accepted that, when some of the trees forming a woodland stand are removed as thinnings, the trees left behind can respond to the greater space available around them and their growth can accelerate. As a consequence, if the types of trees removed in thinnings are carefully selected, and the numbers of trees removed are kept within certain limits, the total wood production over a rotation from a stand of trees can be at least as much as for a stand in which no thinnings removed during the life cycle of the stand (see for example Matthews et al. 2016). Total wood production over a rotation can even be somewhat higher in a thinned stand, if there are significant losses of production in an equivalent unthinned stand, as a result of competition-induced tree mortality. However, this widely accepted fact appears to be misinterpreted sometimes, as meaning that, when trees are removed from a stand as thinnings, the remaining trees can regrow at such a rate that they can fully compensate for the loss of carbon stocks (compared to an unthinned stand), as a result of the thinning operations. It is therefore important to recognise that this is not the case for the example presented in Figure A15, when compared with Figure A1 in Section A1.2.1. This point is understood to apply for the management of woodland stands more generally, although it is conceivable that there may be some exceptions in the case of very fast-growing stands of trees that are not thinned too regularly or intensively.

Considered from a long-term perspective, planting the Sitka spruce stand and managing with thinning on a clearfelling rotation of 50 years is seen to result in the accumulation and maintenance of a long-term mean carbon stock in trees of 40 tC ha^{-1}, i.e. significantly less than for the equivalent unthinned stand (60 tC ha^{-1}, see Section A1.4.1). Nevertheless, the accumulation of carbon stocks in the trees growing in the thinned stand is still significant. The long-term mean carbon stock of the thinned stand is indicated by the dashed horizontal line in Figure A15.

A1.6.2 Total woodland carbon stocks

Figure A16 shows the combined impacts on carbon stocks in living trees, in deadwood and litter and in soil. The figure shows the net impacts on carbon stocks from time of woodland creation, calculated as explained in Section A1.2.2.

The pattern of accumulation and loss of carbon stocks over time is broadly similar to that described for an unthinned stand in Section A1.4.2 (Figure A7), except that additional impacts on carbon stocks related to the thinning operations are apparent.

Compared with the unthinned stand, the additional carbon stocks accumulated in deadwood, litter and soil are smaller. In particular, there is effectively no additional carbon sequestered in soil. This mainly reflects the lower levels of tree growing stock being maintained on the site in the thinned stand, compared with the unthinned stand (hence lower inputs of carbon to the soil). The accumulation of deadwood in the unthinned stand (related to competition-induced mortality) is also more significant than for the thinned stand.

The estimated long-term mean value of total woodland carbon stocks in the thinned stand is just under 90 tC ha^{-1}, i.e. significantly less than for the equivalent unthinned stand (140 tC ha^{-1}, see Section A1.4.2). Nevertheless, the accumulation of total woodland carbon stocks in the thinned stand is still significant. The long-term mean total woodland carbon stock of the thinned stand is indicated by the dashed horizontal line in Figure A16.

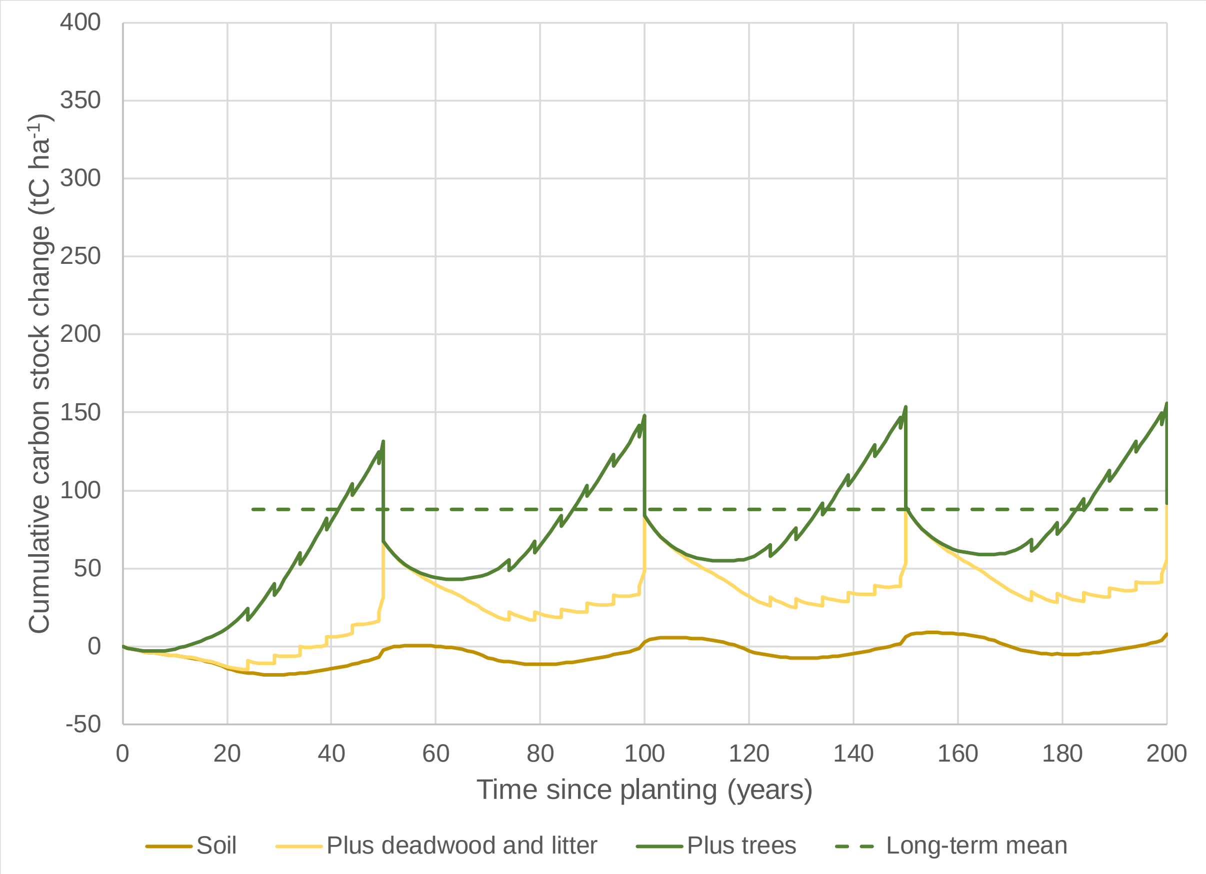

Figure A16 Development of total woodland carbon stocks in a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation with thinning during the rotation. "Plus deadwood and litter" = soil carbon stocks + deadwood and litter carbon stocks; "Plus trees" = soil carbon stocks + deadwood and litter carbon stocks + tree carbon stocks (i.e. total woodland carbon stocks).

A1.6.3 Total carbon and GHG impacts

Figure A17 shows the development of carbon stocks in trees, deadwood and litter and soil, and also:

- The development of "off-site" carbon stocks in wood products, as well as:
- Cumulative GHG emissions from operations carried out as part of woodland management and
- Potential contributions to reductions in GHG emissions made by using wood fuel in substitution for fossil fuels and through material wood products substituting for more GHG intensive non-wood products

The contribution to cumulative GHG impacts made by wood product stocks and GHG emission reductions through product displacement are slightly higher for the thinned stand, compared with the equivalent unthinned stand considered in Section A1.4.3. This occurs because the wood production from the thinned stand is marginally higher than for the unthinned stand. In the unthinned stand, some potential wood production is lost as a result of competition-induced tree mortality. Additionally, sawlog production over a rotation is somewhat higher for the thinned stand, compared with the unthinned stand, because the thinning operations provide space for the remaining trees to grow and increase in diameter. The greater sawlog production in turn enables the manufacture of marginally more long-lived wood products, compared with the wood production from the unthinned stands.

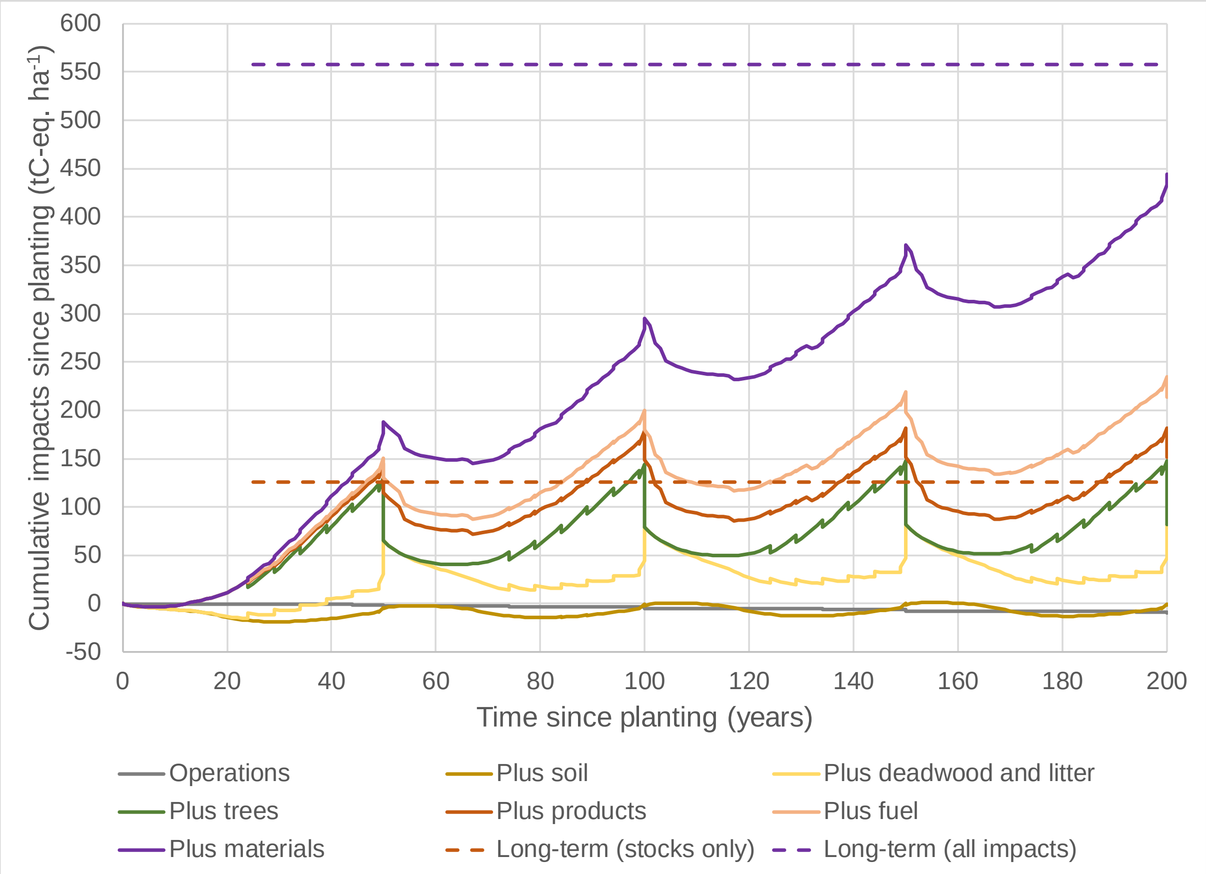

Figure A17 Cumulative net impacts on woodland and "off-site" carbon stocks and "off-site" GHG emissions resulting from planting a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation with thinning during the rotation. Contributions from different sources are "stacked", e.g. "Plus fuel" = Operations + soil + deadwood and litter + trees + wood products + GHG emissions displaced by wood fuel.

Although the contributions to total GHG impacts from wood product carbon stocks and product displacement effects are bigger for the thinned stand, the overall impacts are smaller, because carbon stocks in the thinned woodland are lower than those in the unthinned woodland. If carbon stocks in wood products are considered as well as carbon stocks in the woodland, the mean cumulative net carbon stock impacts after 300 years resulting from creating the example thinned woodland considered here are 125 tC ha^{-1}, as indicated by the dashed dark red horizontal line in Figure A17. If potential GHG emissions displaced by wood products are also considered, the mean cumulative net impacts after 300 years are 560 tC-eq. ha^{-1}, as indicated by the dashed purple horizontal line in Figure A17. These results may be compared with those for the equivalent unthinned stand (Section A1.4.3) of 170 tC ha^{-1} and 580 tC ha^{-1}, respectively.

As was observed in the case of the unthinned managed woodland, in the longer term, GHG emissions impacts from wood product substitution are the dominant contribution to overall GHG impacts. It may also be noted that the contribution to cumulative GHG emissions from operations carried out as part of woodland management (e.g. from harvesting machinery) are relatively very small. Whilst carbon sequestration in the woodland and wood products will eventually saturate, in principle the displacement of GHG emissions through product substitution can continue indefinitely. However, uncertainties surrounding these contributions in the longer term have been highlighted in Section 2.12 of the main body.

A1.6.4 Factors and issues to consider

Points (4) to (6) in Section A1.2.3 should be recalled here. In addition, Points (2) and (3) in that discussion have some relevance.

It has been shown above that, for the example Sitka spruce stand, leaving the stand unthinned results in more carbon being sequestered, and greater GHG impacts (net GHG emissions reductions), when compared with the case in which the stand is thinned. The comparison of these results with those for the example unmanaged broadleaf woodland (Section A1.2) shows that the biggest accumulation of carbon stocks (carbon sequestration) physically in woodland is obtained for the unmanaged woodland, when comparing these particular cases. (However, note that a further option is considered in Section A1.8 and relevant further discussion may be found in Section A1.9.) Conversely, if total impacts are considered (carbon sequestration in woodland and wood products, and GHG emissions reductions from product displacement effects), the biggest impacts are obtained for the examples of managed coniferous woodlands.

In this context, it is very important to recognise that decisions about the management of woodlands are taken with the aim of achieving a balance between a number of objectives. These objectives can address a range of economic, amenity, climate-change, ecological and wider environmental goals. It follows that consideration of the potential impacts on carbon sequestration and “off-site” GHG emissions are just two factors out of many that need to be considered when making decisions about creating new woodlands or managing woodlands. These wider factors are not taken into account when making comparisons such as those discussed above. As a corollary, this highlights the inappropriateness of advocating for or against any particular type of woodland management strategy on the grounds of achieving optimum or maximum carbon sequestration or GHG emissions displacement. It may be further noted that all three of the example scenarios for woodland creation and management, presented in Section A1.2 and A1.4 and in this section, lead to significant carbon sequestration and/or total GHG emissions reductions, albeit with varying magnitudes. Further relevant discussion may be found in Sections A1.9 and A1.11.5.

A1.7. Influence of rotation

The discussion in Section A1.5 illustrated the management of a significant area of Sitka spruce woodland, involving periodic harvesting and regeneration of individual stands forming the woodland, on a rotation of 56 years. The continuous harvesting and regeneration of stands involves a balance between carbon sequestration in trees and the extraction of harvested wood that maintains a constant carbon stock in across the woodland as a whole. The magnitude of this constant tree carbon stock depends on the choice of rotation. For example, this was apparent when the per-hectare carbon stock in the woodland was compared with the long-term mean tree carbon stock in a similar woodland, but managed on a slightly shorter rotation of 50 years (see Section A1.4.1, Figure A6 and the discussion in Section A1.5). The more general dependence of tree carbon stocks on rotation is illustrated for this particular type of Sitka spruce woodland in Figure A18.

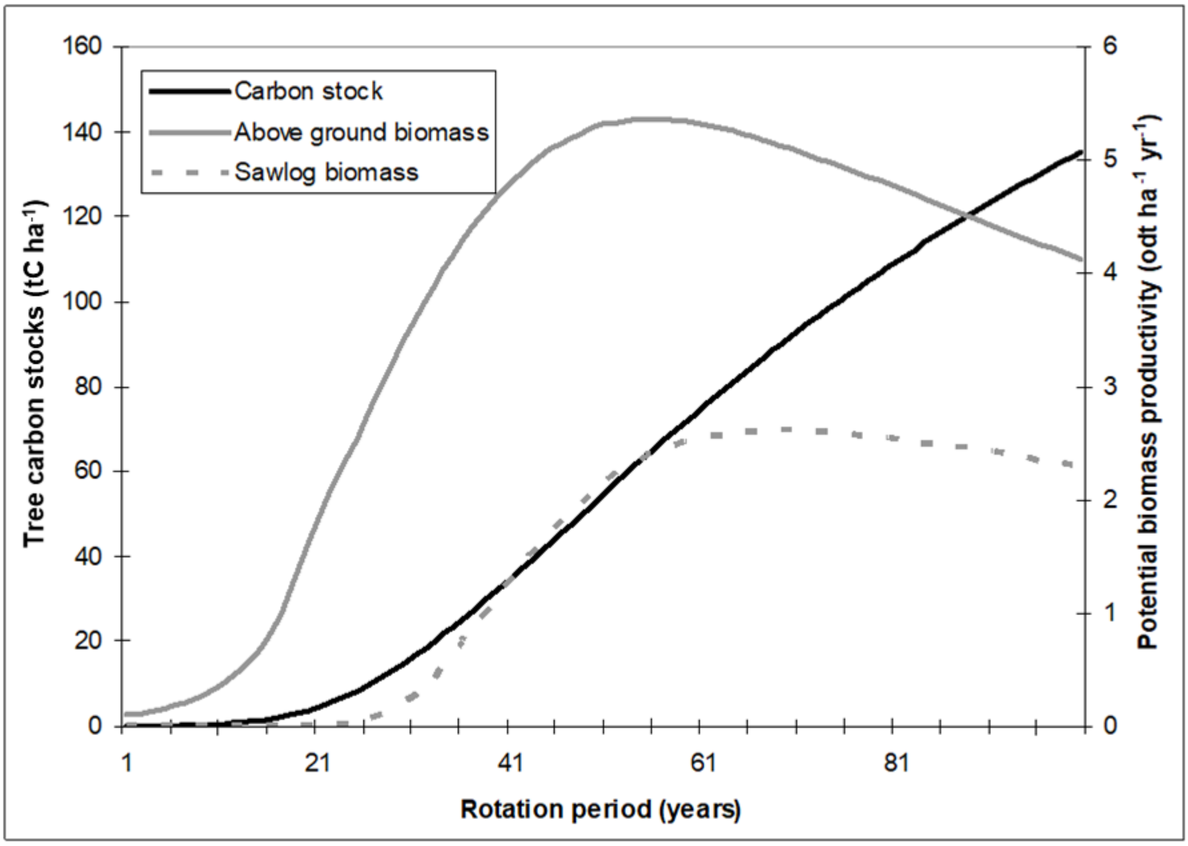

Figure A17 Illustration of the influence of rotation period on forest carbon stocks and biomass productivity. Source: Matthews et al. (2014b).

The figure also shows the biomass productivity (in units of oven-dry tonnes per hectare per year, or odt ha^{-1} yr^{-1}), that can be achieved in the woodland, depending on the selected rotation period. Results for biomass productivity are based on total above ground biomass production and on sawlog biomass production (i.e. biomass of relatively large diameter stemwood).

The estimated carbon stock in the woodland rises monotonically as the rotation applied to the woodland stands is increased. In contrast, biomass productivity initially rises as the rotation is increased but reaches a maximum value, and then declines for longer rotations (see Matthews et al. 2016). In terms of total above ground biomass, managing the Sitka spruce stands forming the woodland on a rotation of 55 years should achieve maximum potential production (5.4 odt ha^{-1} yr^{-1}). Maximum production of biomass suitable for use as sawlogs is achieved at a somewhat longer rotation of 69 years (2.6 odt ha^{-1} yr^{-1}). Potential production of total above ground biomass for a rotation of 69 years is slightly lower than for a rotation of 55 years (5.1

odt ha^{-1} yr^{-1}). The woodland carbon stocks associated with rotations of 55 and 69 years are 64 and 90 tC ha^{-1} respectively.

Figure A18 illustrates how the choice of rotations applied to woodland areas involves trade-offs between achieving high productivity for different types of wood product and high woodland carbon stocks, for example:

- Choosing rotations to maximise total above ground biomass production (which may be desirable if priority is given to raw biomass production) involves reduced potential for sawlog production.
- Choosing relatively long rotations (e.g. greater than 80 years in the case of Figure A18) to achieve high carbon stocks is likely to involve significantly reduced potential total biomass and sawlog production.
- Choosing relatively short rotations (e.g. less than 45 years in the case of Figure A18), perhaps to achieve a quick or economically-optimal return in terms of revenue, generally involves significantly reduced potential total biomass and sawlog productivity, and also relatively low woodland carbon stocks.

Such points are very important when considering the adjustment of rotations in woodland areas in order to increase the climate change mitigation potential of woodlands. For example, many woodland areas are managed on relatively long rotations to achieve a range of economic, environmental and landscape objectives. If a decision were to be taken to shorten rotations to increase total biomass or sawlog production, this would most likely lead to a reduction in the overall level of carbon stocks in these woodland areas (with implied GHG emissions). On the other hand, there are also examples of woodland areas which are managed on relatively short rotations, largely driven by market demands. If a decision were taken to extend rotations to increase total biomass or sawlog production, this would most likely lead to an increase in the overall level of carbon stocks in these woodland areas (with implied carbon sequestration). It follows that actions to ‘intensify’ the management of woodland areas to increase supply of wood, through adjustments to rotations, can have antagonistic or synergistic effects on woodland carbon stocks, and implied GHG emissions or carbon sequestration.

A1.8. Influence of growth rate

Figures A19 to A21 show an example of the impacts on land-based carbon stocks, and on “off-site” carbon stocks and GHG emissions, of establishing a new *fast-growing* coniferous woodland (most likely by planting trees) and managing the new woodland for wood production. The type of woodland and the management are the same as for the example described in Section A1.6, with two exceptions:

- Firstly, the growth rate of the Sitka spruce woodland is assumed to be much higher, with a yield class of 24 m^3 ha^{-1} yr^{-1}, i.e. double the growth rate assumed in the examples of Sitka spruce woodlands in Sections A1.4 and A1.6
- Secondly, the Sitka spruce woodland is assumed to be managed on a shorter clearfell rotation of 35 years (compared with 50 years assumed for the slower-growing Sitka spruce woodlands considered in Sections A1.4 and A1.6).

Generally, rotations applied to stands of trees are shorter in faster-growing stands. This is because optimum stem volume production is typically reached at younger stand ages in faster-growing (higher yield class) stands of trees (see Matthews et al. 2016). Economic considerations also tend to shorten rotations in faster-growing stands of trees, with the aim of obtaining a quicker return on investment.

A1.8.1 Tree carbon stocks

Figure A19 shows the accumulation and loss of carbon stocks in the living trees forming the woodland over several rotations.

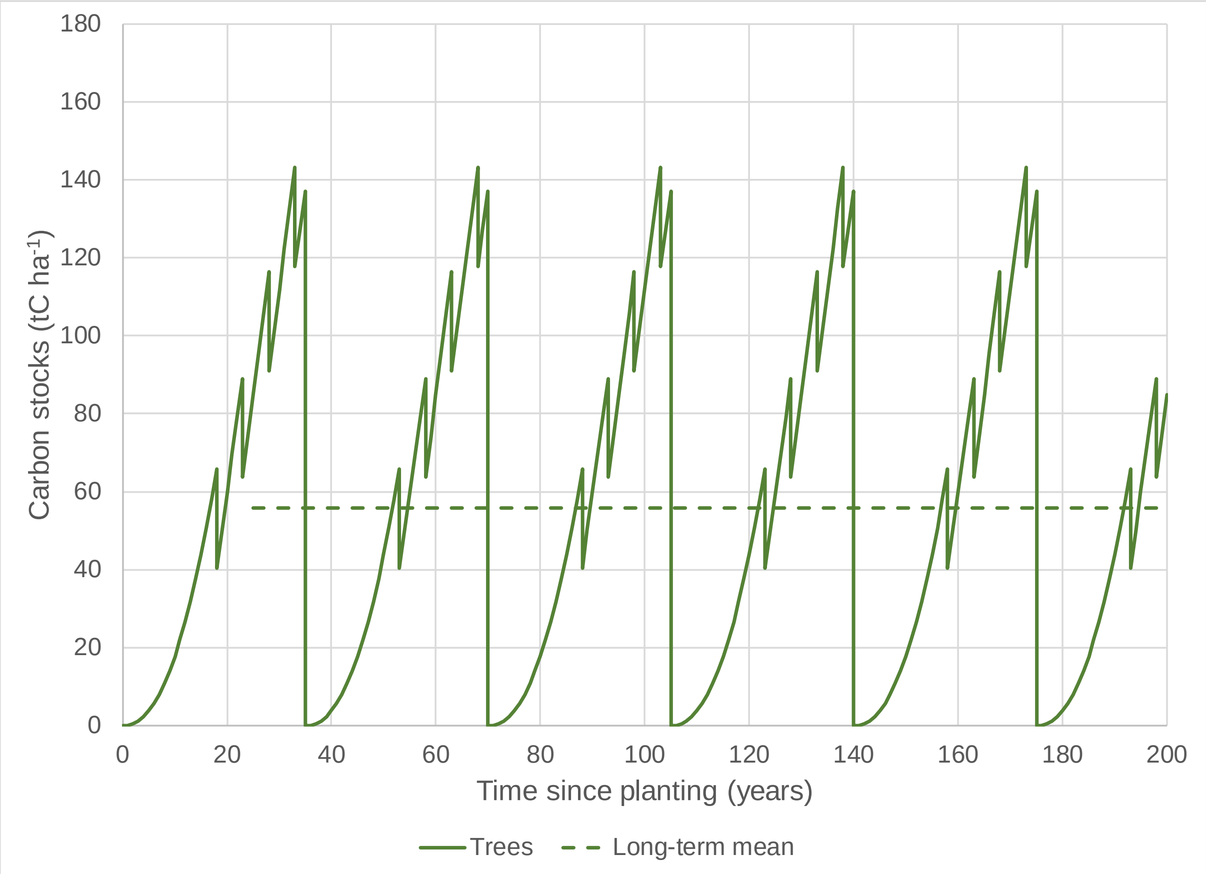

Figure A19 Development of tree carbon stocks in a stand of Sitka spruce with a fast growth rate managed for production on a 35-year rotation with thinning during the rotation.

The general pattern of the development of tree carbon stocks is similar to that described for the slower-growing Sitka spruce woodland (Figure A15, Section A1.6.1), except that:

- The accumulation of carbon stocks is more rapid (reflecting the faster growth rate)
- The cycles between the accumulation of carbon stocks and losses at the time of clearfelling are shorter (reflecting the shorter rotation).

Considered from a long-term perspective, planting the fast-growing Sitka spruce stand and managing with clearfelling and thinning on a rotation of 35 years is seen to sequester and maintain a long-term mean carbon stock in trees of 55 tC ha^{-1}. This is only 15 tC ha^{-1} higher than the estimate for the slower-growing Sitka spruce woodland, despite the growth rate of the faster-growing stand being double that of the slower-growing stand. It follows that faster-growing stands of trees do not automatically sequester significantly more carbon than slower-growing stands, because carbon stocks in the stands of trees will depend on a number of factors, notably the details of stand management. Whilst this may be the case for carbon sequestration in trees, it is necessary to also consider impacts on total woodland carbon stocks (including carbon sequestered "off-site" in wood products) and "off-site" impacts on GHG emissions resulting from product substitution, as discussed below.

A1.8.2 Total woodland carbon stocks

Figure A20 shows the combined impacts on carbon stocks in living trees, in deadwood and litter and in soil. The figure shows the net impacts on carbon stocks from time of woodland creation, calculated as explained in Section A1.2.2.

The pattern of accumulation and loss of carbon stocks over time is broadly similar to that described for the slower-growing Sitka spruce stand in Section A1.6.2 (Figure A16), except that the magnitudes and cycle periods are different.

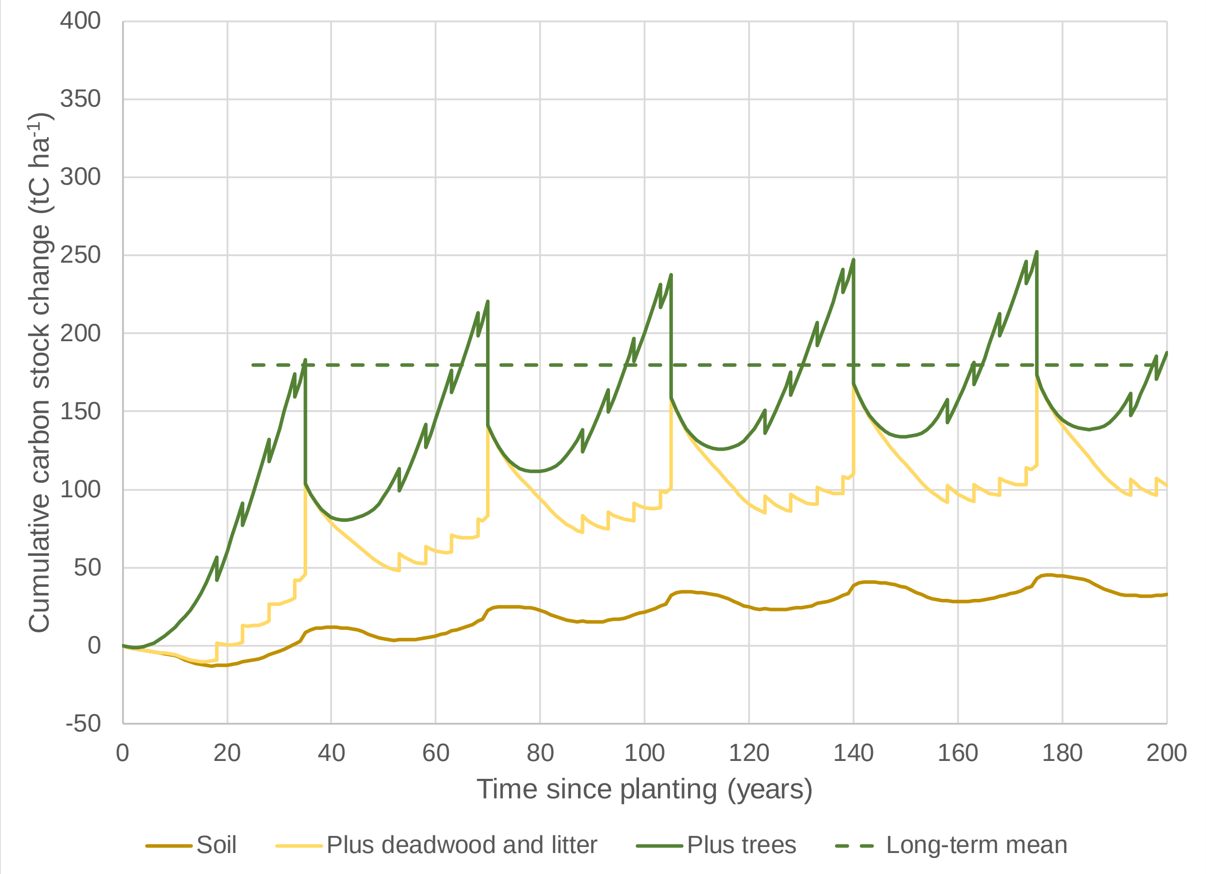

Figure A20 Development of total woodland carbon stocks in a fast-growing stand of Sitka spruce managed for production on a 35-year rotation with thinning during the rotation. "Plus deadwood and litter" = soil carbon stocks + deadwood and litter carbon stocks; "Plus trees" = soil carbon stocks + deadwood and litter carbon stocks + tree carbon stocks (i.e. total woodland carbon stocks).

The carbon stocks accumulated in deadwood and litter are significantly greater than in the case of a slower-growing stand, although some uncertainty must be attached to this estimate (see Section A1.8.4). There is also a significant accumulation of soil carbon stocks under the fast-growing Sitka spruce stand, in contrast to the slower-growing stand. This result reflects the greater inputs of carbon to the soil from the faster-growing trees and also from decaying deadwood and litter. The note of caution about the carbon stocks estimated for deadwood and litter is also relevant here. The consequence of the different contributions from deadwood, litter and soil is a much higher long-term mean value of total woodland carbon stocks in the faster-growing stand, at 180 tC ha^{-1} (dashed line in Figure A20), compared with 90 tC ha^{-1} for the slower-growing stand (see Section A1.8.4).

A1.8.3 Total carbon and GHG impacts

Figure A17shows the development of carbon stocks in trees, deadwood and litter and soil, and also:

- The development of “off-site” carbon stocks in wood products, as well as:
- Cumulative GHG emissions from operations carried out as part of woodland management and
- Potential contributions to reductions in GHG emissions made by using wood fuel in substitution for fossil fuels and through material wood products substituting for more GHG intensive non-wood products

The accumulation of carbon stocks in wood products is significantly greater than for the example slower-growing Sitka spruce stand (Figure A17, Section A1.6.3), reflecting the much higher level of wood production in the faster-growing stand. The long-term mean carbon stock in woodlands and wood products combined is estimated at over 250 tC ha^{-1} (dark red dashed horizontal line in Figure A21), as opposed to 125 tC ha^{-1} for the slower-growing stand.

An accumulated total woodland/wood product carbon stock of 250 tC ha^{-1} is at the lower end of the range estimated for total woodland carbon stocks ultimately accumulated in examples of planted or regenerated broadleaf woodlands managed as a “woodland carbon reserve” (see Sections A1.2 and A1.3).

When GHG impacts from wood product substitution are also included, the cumulative impacts on GHG emissions after 300 years amount to 1 130 tC-eq. ha^{-1} (beyond the scale of the y-axis in Figure A21). This is by far the biggest climate-change mitigation impact amongst the examples considered in this discussion. However, it must be stressed that the main contribution determining this outcome is product substitution, rather than carbon sequestration in woodlands or wood products. Uncertainties surrounding these contributions in the longer term have been highlighted in Section 2.12 of the main body.

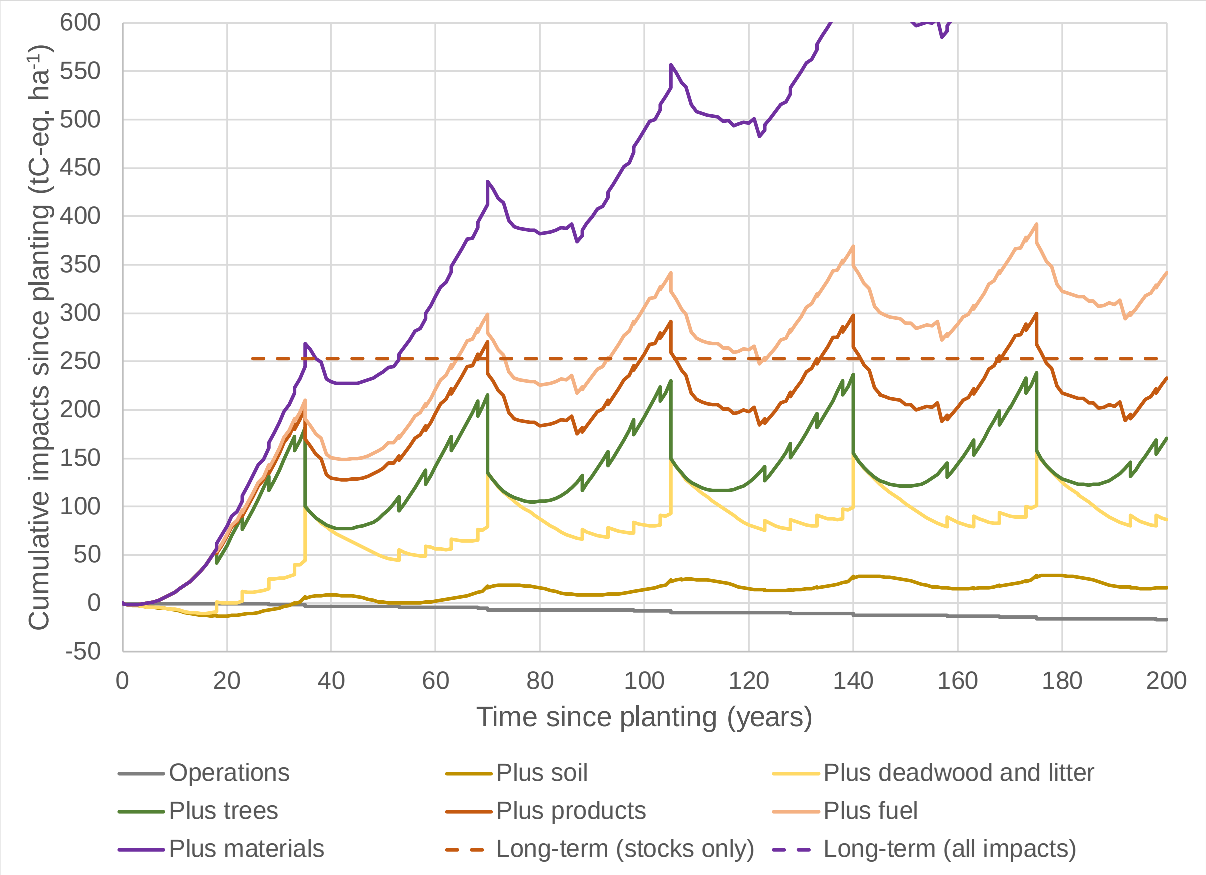

Figure A21 Cumulative net impacts on woodland and "off-site" carbon stocks and "off-site" GHG emissions resulting from planting a stand of Sitka spruce with a fast growth rate managed for production on a 50-year rotation with thinning during the rotation. Contributions from different sources are "stacked", e.g. "Plus fuel" = Operations + soil + deadwood and litter + trees + wood products + GHG emissions displaced by wood fuel.

A1.8.4 Factors and issues to consider

Points (4) to (6) in Section A1.2.3 should be recalled here. In addition, Points (2) and (3) in that discussion have some relevance.

Some caution must be attached to certain estimates for this type of woodland management scenario. Some uncertainties regarding wood-product substitution effects have already been highlighted. Furthermore, the estimates of high carbon stocks in deadwood and litter for this type of woodland must be regarded as speculative and uncertain. In principle, it is possible that the quantities of carbon in dead biomass and litter could be accumulated on site, particularly after thinning operations and especially when clearfelling is carried out. However, it is not clear that this biomass would be left entirely on site after harvesting. If the quantities are very significant, this may attract interest in extracting the residual biomass left over from stemwood harvesting, for example for use as a source of wood fuel (bioenergy). There may also be other reasons for clearing a significant proportion of the residual wood from woodland sites after harvesting, as part of the preparation of sites for the regeneration or planting of trees for the next rotation. The removed residual biomass may be burnt as waste. In such circumstances, the high carbon stocks in deadwood and litter suggested by the results in Figure A21 will not occur, and estimates of total woodland carbon stocks and total GHG impacts would need to be reduced accordingly. However, if the harvesting residues were to be used as a bioenergy source, then potentially there are additional product substitution effects (e.g. replacing fossil fuels) which could make a further contribution to GHG emissions impacts (reductions). A scenario of this type is considered in Section A1.11.

A1.9. Influence of tree species

Often, there is interest in understanding whether some trees are “better” than others for climate change mitigation, or more specifically for carbon sequestration. The relevance of tree species in this context is discussed briefly below.

In effect, the examples already described in Sections A1.2-A1.4, A1.6 and A1.8 have already provided some illustrations of how tree species selection (e.g. for woodland creation) may depend on several objectives relevant to climate change mitigation. However, it should also be apparent from these examples that it is not easy (and possibly not appropriate) to offer simple conclusions about the relative merits of different tree species for addressing such objectives.

To begin with, one key in determining the capacity of trees to sequester carbon is growth rate. The typical growth rate of different tree species, as measured by yield class (Matthews et al. 2016) can display important systematic variations. For example, *in general* (but *not always*), the yield classes of coniferous tree species tend to be higher than those of broadleaf tree species.

Taking some specific examples, oak tends to be amongst the slower growing tree species in UK conditions (rarely exceeding yield class 6). Other broadleaf species such as ash and sycamore can have higher yield classes (see for example Section A1.3), although they may be less enduring trees than oak, and disease issues with ash in current times must be noted. According to the GB National Forest Inventory, the mean yield class of broadleaf tree species is 4.8 in Wales (BEIS, 2020). Scots pine can vary quite widely in yield class but typical values in the UK are around 8 and 10. Sitka spruce is known for being able to grow relatively fast on suitable sites in the UK, with common yield classes perhaps ranging from 12 to 24, and potentially higher in the case of genetically improved Sitka spruce. However, spruce stands may be less enduring than stands of slower-growing coniferous or broadleaf tree species. Douglas fir is an example of a relatively enduring coniferous tree species that can also exhibit relatively high yield classes. According to the GB National Forest Inventory, the mean yield class of coniferous tree species is about 14 in Wales (BEIS, 2020).

Whilst these general patterns in growth rates (in terms of yield classes) can be distinguished for different tree species, the ranges of yield classes that different tree species can exhibit generally overlap. Furthermore, the actual growth performance of a given tree species on a given site will depend on the suitability of the site and the prevailing climate at the site, which can depend on a combination of a number of factors (see for example Pyatt et al. 2001). Other factors potentially affecting the growth of certain tree species may also need to be considered, such as the susceptibility of tree species to disease, their attractiveness to grazing animals or possibly instability in the face of storms.

It must then be recognised that yield class, as a measure of tree growth rate, is not a perfect indicator of the potential for different tree species to sequester carbon. Yield classes as given for different tree species are not absolutely comparable, because the growth rates indicated for different tree species will be realised over different timescales, depending on the tree species being considered (see Matthews et al. 2016). More importantly, yield class is expressed in units of tree stem volume growth or production (per hectare per year). Stem volume growth is not a perfect indicator of total tree biomass growth or of total tree carbon sequestration. Firstly, this is because wood density, although very variable, also tends to vary systematically for different tree species (see for example Lavers and Moore 1983). For example, typical values of stem wood density for broadleaf tree species are above 0.45 odt m^{-3} (oven dry tonnes per unit of fresh wood volume), whereas for coniferous tree species, wood density is typically below this value. More generally (but not always), wood density can display an inverse relationship with tree growth rate. This tends to compensate for the slower growth rates typically displayed by broadleaf tree species in the UK, compared with coniferous tree species. The additional quantities of biomass in branchwood and roots also show some variation with tree species (see for example Matthews et al. 2020a). This has the consequence that the relationships between total tree biomass and stem biomass are different for different tree species. Hence, comparisons of the stemwood growth of different tree species will not be a perfect indicator of differences in total tree biomass growth. The carbon content of the woody biomass of trees can also vary, and it is possible to discern some species-specific variations in wood carbon content, although this appears to be a secondary factor in determining systematic variations in relationships between stemwood growth rates and tree carbon sequestration for different tree species (Matthews, 1993).

All of the above factors make it difficult to draw clear and simple conclusions about the relative performance of different tree species in terms of capacity to sequester carbon.

The examples given earlier in this appendix illustrate how the intended management of woodland areas (e.g. for amenity, production or some combination) is a major determinant of the carbon sequestration potential and GHG emissions impacts of different types of woodland. The choice of tree species and intended management of the woodland therefore need to be considered together. Only very broad conclusions can be reached about tree species selection in this context. Very generally, slower-growing and more enduring tree species (frequently broadleaves) tend to be better suited for meeting the objective of creating a woodland carbon reserve. On the other hand, faster-growing “pioneer” tree species (frequently conifers) tend to be better where the intention is to manage woodlands for wood production. However, such distinctions are somewhat arbitrary and may not be helpful, particularly given that woodlands are usually created and/or managed to meet a range of objectives and provide a range of goods and services (see Section A1.6.4 and A1.11.5).

A1.10. Influence of soil characteristics

A1.10.1 Mineral soils

Examples of the impacts of woodland creation on carbon stocks in mineral soils have already been considered in earlier sections of this appendix. The example CARBINE model simulations discussed in Sections A1.2, A1.4, A1.6 and A1.7 all involve the assumption that the woodlands are planted on a soil typical of the loam type, with a former land use of grassland or pasture. In the case of the field measurements of carbon stocks reported for the Rothamsted classical studies (Section A1.3), the soil types were quite complex (involving combinations of loam, silt and clay components, and in one case calcareous in nature) and the sites were formerly agricultural fields. However, these soils might also be broadly regarded as loam soils.

The establishment of the various woodland types on these loam soils with former grassland cover (i.e. excepting the Rothamsted studies) results in roughly similar effects on soil carbon stocks, specifically:

- An initial loss of some soil carbon stocks, if the site is disturbed significantly and the previous vegetation is removed as part of the site preparation for tree planting. This is particularly the case where soil carbon stocks are high before the establishment of woodland, which can often be the case if the previous land use was grassland.
- Where an initial loss of soil carbon stocks occurs, this can be recovered after some years, as tree cover becomes established and inputs of carbon to the soil from tree roots and litter replace the contributions by the previous vegetation.
- The accumulation of soil carbon stocks tends to be greater in undisturbed woodlands and in woodlands formed of faster-growing trees, reflecting higher inputs of carbon to soil from the trees in both cases. Conversely, soil carbon stocks tend to be lower in managed stands of slower-growing trees.
- Periodic tree harvesting (where carried out) can result in cycles in soil carbon stock levels, as carbon is first lost and then regained, when inputs of carbon from trees are first reduced but then recover (with inputs also from parts of felled trees left behind as deadwood and litter).

The results of the Rothamsted studies also show an accumulation of soil carbon stocks as a result of natural recolonization of the formerly agricultural sites (ultimately) with trees (see Section A1.3.2). There does not appear to be any initial loss of soil carbon at the point when agricultural management was abandoned. This reflects the lower initial soil carbon stocks and the avoidance of soil disturbance because management was simply abandoned at these sites.

These general features are also exhibited by carbon stocks in other kinds of mineral soil (sands and clays), but with different levels of carbon stocks and rates of accumulation (or loss) being associated with these soils. Specific illustrations are not presented here.

The accumulation and/or loss of soil carbon stocks is also affected by the climatic conditions prevalent at woodland sites (notably temperature and rainfall). The CARBINE simulations that produced the results considered in Sections A1.2, A1.4, A1.6 and A1.8 are all based on a characterisation of meteorological conditions for “warm, moist” sites, which occur commonly in Wales (See Section 4.1.4 of the main body text).

The accumulation of carbon stocks in soils is also influenced by the hydrological properties of the soil, i.e. the height of the water table over the course of the year (particularly the growing season), and the extent to which the soil is free-draining or can become waterlogged (and the depth of soil involved). These features are particularly important in the case of organic and organo-mineral soils, as discussed below.

A1.10.2 Organic soils

The impacts of planting woodlands on organic soils, or more specifically peatlands, has been discussed in Section 2.9.2 of the main body. As explained there, new woodland planting on deep peat is not allowed under the UK Forestry Standard (UKFS) and is therefore out of scope in any consideration of future sustainable afforestation. Examples of CARBINE model simulations for tree planting on organic soils are not given here. There is conflicting evidence regarding the extent of soil carbon loses that may result from such activities. The relatively recent and very thorough review by Evans et al. (2017) suggests that CO_2 emissions from peat soils under forests can be significant (see Section 2.9.2 of the main body). However, much of the evidence for this comes from measurements of CO_2 fluxes from the soil. The contributions to these fluxes (e.g. from soil, decaying litter or root respiration) can be difficult to disaggregate. Furthermore, flux measurements can be difficult to compare with net carbon stock changes in soil, because some inputs of carbon to soil may not be allowed for in assessments of net fluxes. Work is ongoing to reconcile soil CO_2 flux measurements, soil carbon stock-change measurements, and the representation of relevant processes in models such as CARBINE. However, this does not alter the conclusion from evidence such as presented in Evans et al. (2017) that CO_2 emissions resulting from planting trees on peatlands can be significant. Although further clarification is needed of the magnitudes of CO_2 emissions and their variation over time is needed, this is unlikely to have further bearing on the established policy of avoiding tree planting on peatlands.

A1.10.2 Organo-mineral soils

Figure A22 shows the impacts on total woodland carbon stocks and on “off-site” carbon stocks and GHG emissions resulting from creating the type of managed Sitka spruce woodland with a moderate growth rate already considered in Section A1.6, except that in this case the woodland is planted on an organo-mineral soil (see Section 2.9.1 of the main body). These types of soils are mineral soils with an overlying organic (peaty) layer (up to 50 cm depth).

The figure shows the results in the same format as for the majority of graphs in this appendix, i.e. it shows the *cumulative change* in carbon stocks (and cumulative GHG impacts) from the initial carbon stocks before the trees were planted (see Section A1.2.2). The initial soil carbon stocks of such soils (prior to tree planting) are typically around 350 tC ha^{-1} (see Table 2.1, Section 2.9.1 of the main body). It should be noted that, by convention, the results for soil carbon stocks reported by CARBINE are for a soil depth of 1 metre (this is consistent with UK National GHG Inventories; the default soil depth referred to in IPCC Guidance is 30 cm, see IPCC, 2006).

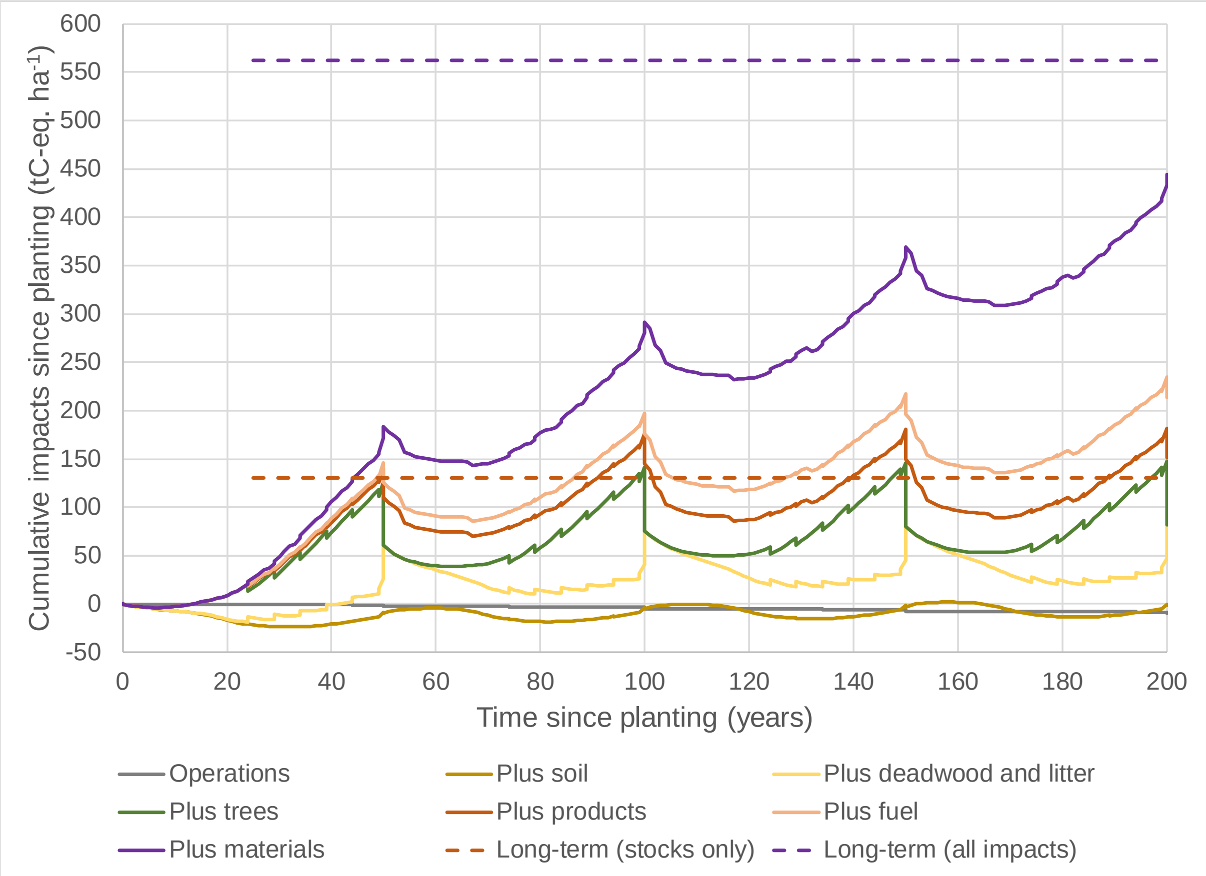

Figure A22 Cumulative net impacts on woodland and "off-site" carbon stocks and "off-site" GHG emissions resulting from planting a stand of Sitka spruce with a moderate growth rate on an organo-mineral soil. The stand is managed for production on a 50-year rotation with thinning during the rotation. Contributions from different sources are "stacked", e.g. "Plus fuel" = Operations + soil + deadwood and litter + trees + wood products + GHG emissions displaced by wood fuel.

Figure A22 indicates that establishing the Sitka spruce woodland on the organic soil initially results in a significant loss of carbon stocks, of nearly 25 tC ha^{-1}. This is eventually compensated for by the accumulation of carbon stocks in tree biomass, losses from soil carbon dominate initially, so that the total system is a net carbon source, rather than a carbon sink, for nearly 20 years from the time of woodland establishment. By the end of the first rotation of the Sitka spruce stand (50 years), the inputs of carbon to the soil from trees and litter are sufficient to result in the initial losses of soil carbon stocks being recovered, but this takes place over a century. The total additional accumulated carbon stocks in the woodland/wood products system and the total GHG emissions impacts after 300 years are estimated at 130 tC ha^{-1} and 560 tC-eq. ha^{-1}, respectively (dark red dashed horizontal line in Figure A22 and purple dashed horizontal line in Figure A22, respectively). The accumulation of carbon stocks in soil after 300 years is actually slightly higher than for the case involving the mineral soil considered in Section A1.6. This is because the mineral component of the organo-mineral soil is assumed to be a gley type, which has greater capacity to retain soil carbon than a loam soil (assumed in Section A1.6), given the same climatic conditions and inputs of soil carbon.

Interaction with tree growth rate

Figure A23 shows the impacts of planting a faster-growing stand of Sitka spruce on the example organo-mineral soil considered above. The example Sitka spruce stand and its management are the same as already considered in Section A1.8, except for the assumption of planting on an organo-mineral soil, as also considered for a slower-growing Sitka spruce stand immediately above.

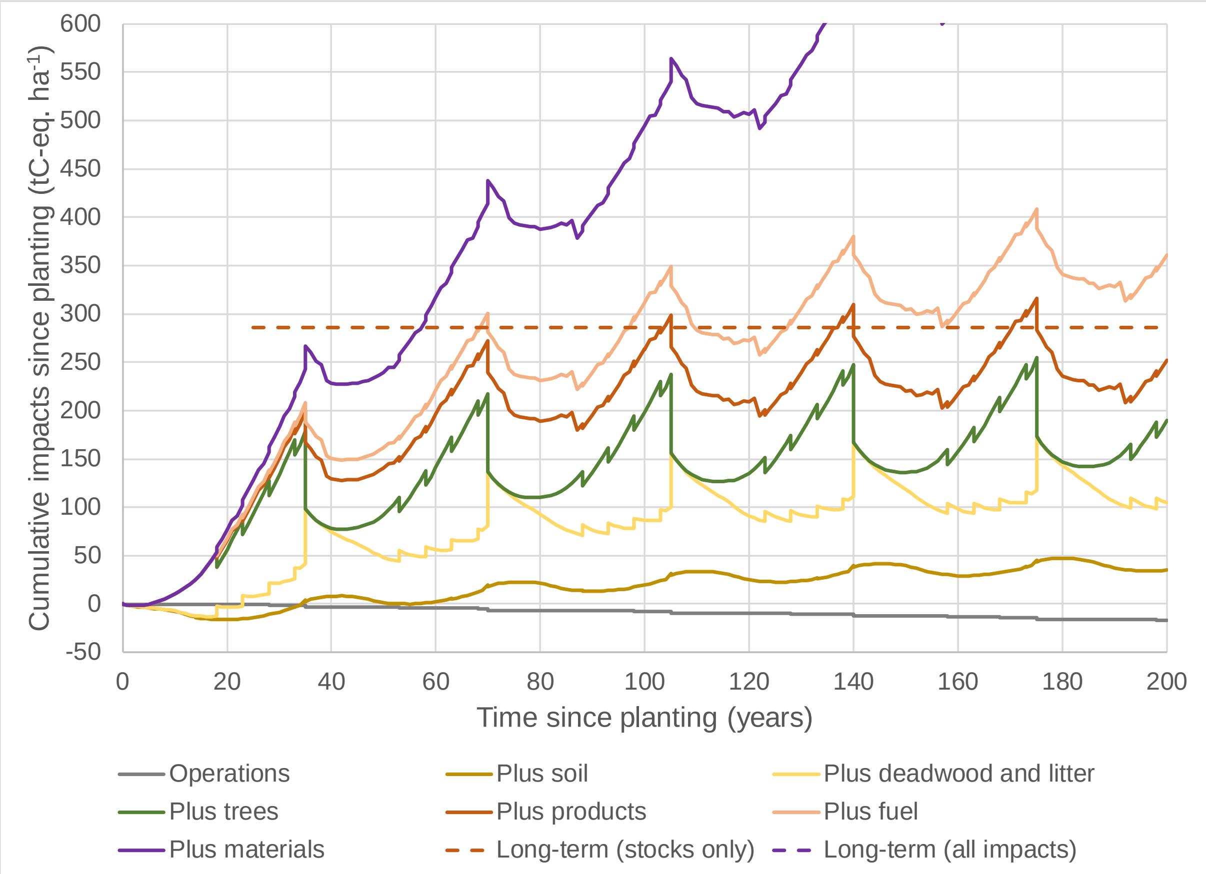

Figure A23 Cumulative net impacts on woodland and "off-site" carbon stocks and "off-site" GHG emissions resulting from planting a stand of Sitka spruce with a fast growth rate on an organo-mineral soil. The stand is managed for production on a 50-year rotation with thinning during the rotation. Contributions from different sources are "stacked", e.g. "Plus fuel" = Operations + soil + deadwood and litter + trees + wood products + GHG emissions displaced by wood fuel.

The general pattern of soil carbon stock changes has some similarities to those observed for the slower-growing Sitka spruce stand in Figure A22. However, the initial period during which there are soil carbon losses is shorter (about 10 years). Furthermore, eventually, soil carbon stocks are recovered within 35 years and then subsequently marginally increased when compared with pre-existing levels. However, this recovery of soil carbon stocks takes place over about a century. The differences for the faster-growing Sitka spruce stand reflect the higher inputs of carbon to the soil from the faster-growing trees (which also means shorter rotations) and from deadwood and litter.

The total additional accumulated carbon stocks in the woodland/wood products system and the total GHG emissions impacts after 300 years are estimated at 285 tC ha^{-1} and 1 162 tC-eq. ha^{-1}, respectively (dark red dashed horizontal line in Figure A23 shows long-term accumulation of carbon stocks, equivalent line for GHG impacts is off the scale of the graph in Figure A23). The accumulation of carbon stocks in soil after 300 years is actually slightly higher than for the case involving the mineral soil considered in Section A1.8. This is because the mineral component of the organo-mineral soil is assumed to be a gley type, which has greater capacity to retain soil carbon than a loam soil (assumed in Section A1.8), given the same climatic conditions and inputs of soil carbon.

Caveats concerning certain assumptions made in the modelling of the faster-growing Sitka spruce stand should also be borne in mind here (see Section A1.8.4).

A1.10.3 Factors and issues to consider

Points 4 to 6 in Section A1.2.3 and the discussions in Sections A1.6.4 and A1.8.4 should be recalled here. In addition, some other cautionary remarks should be made regarding the simulations of soil carbon stock changes on different soil types, produced using the CARBINE model, and the implications for decisions about woodland creation and management on different soils.

Firstly, data on soil carbon stock changes in response to tree planting are limited, the simulations made by the CARBINE model are consistent with the available evidence on the soil carbon stock changes that have occurred when woodlands are planted on different kinds of soils under UK conditions, including mineral, organo-mineral and organic soils (Bradley et al. 2005; Hargreaves et al. 2003; Vanguelova et al. 2019; Matthews et al. 2020b). The representation of soil carbon processes in the CARBINE model is derived from a leading soil carbon model (Smith et al. 2010). However, some aspects of the CARBINE version have been identified as having scope for further improvement, notably in the representation of significant layers of litter and organic matter that can accumulative under woodlands. These aspects of the soil carbon model are the subject of ongoing development. It follows that there are uncertainties in the results for soil carbon stock changes, such as illustrated in this appendix and referred to more widely in this assessment, hence these aspects of the results should be assessed and interpreted with care.

Secondly, uptake and emission of non-CO_2 GHGs (methane and nitrous oxide) can also occur in soils, notably in organic and organo-mineral soils. The impacts of woodland creation and management on the fluxes of non-CO_2 GHGs to and from soils have not been assessed here, but the likely contributions of non-CO_2 GHGs to the overall GHG impacts of woodland creation and management are discussed in Section 2.10 of the main body.

Finally, it is again important to stress that decisions about woodland creation and management, and decisions about wider land use, are made by considering a number of factors and objectives, not just carbon stocks, GHG emissions and climate change mitigation. For example, in the case of peatlands with high ecological value, the conservation of the existing ecosystem and the associated water resources are likely to be preeminent considerations.

A1.11. Extraction of harvesting residues

A1.11.1 An example of the extraction and utilisation of harvesting residues

Figure A24 shows the impacts on woodland carbon stocks, “off-site” carbon stocks in wood products and impacts on GHG emissions (through product substitution) for the woodland creation scenario similar to the one illustrated in Section A1.4 (Sitka spruce managed for production without thinning). The difference in the scenario considered here is that, as an additional activity, a proportion of the biomass residues created as part of harvesting (“harvesting residues”) are extracted for utilisation as a feedstock for energy generation (wood chips or wood pellets).

The extraction of harvesting residues is assumed to consist of 80% of branchwood and 80% of stem offcuts (produced as part of the conversion of stemwood into uniform small roundwood and sawlog products). Foliage biomass and fine woody debris are assumed to be unsuitable for extraction and utilisation. Stump and root biomass is assumed to be left unextracted to avoid disruption to the soil and consequent loss of soil carbon. These assumptions mean that a relatively small proportion of the total quantity of harvesting residues is extracted, amounting to 43 odt ha^{-1} (oven-dry tonnes of biomass per hectare) at time of clearfelling. (Note that, under this scenario, the Sitka spruce stand is assumed to be clearfelled on a rotation of 50 years with no thinning operations during the life cycle of the stand.)

If the results in Figure A24 are compared with the results in Figure A7 (representing no extraction of residues), the two sets of results are difficult to tell apart. However, close scrutiny reveals that, for the scenario of residue extraction considered here:

- The accumulation of carbon stocks in deadwood, litter and soil is slightly lower (by between about 3 and 19 tC ha^{-1}), during the period of the second rotation (following the first clearfelling) and between 4 and 23 tC ha^{-1} during the period of the third rotation, with the difference tending to be maximal immediately after extraction of the residues, and declining over the period of the rotation.
- The accumulation of total woodland and “off-site” carbon stocks is slightly lower compared to the case where harvesting residues are not extracted. The difference in carbon stocks between the two scenarios is largest immediately after each harvesting event (every 50 years), but the difference gets smaller between clearfelling events. This is because some of the carbon in the residues left on site is lost as these residues decay, bringing the carbon stock in the remaining residues closer to that in the scenario in which the residues are extracted After 300 years, the difference in accumulated carbon stocks between the two scenarios is between 7 tC ha^{-1} at minimum and 26 tC ha^{-1} at maximum, with a mean difference over a rotation of 12 tC ha^{-1}. However, a large proportion of the carbon stock difference occurs at the end of the first stand rotation (50 years after woodland planting), with smaller net losses in subsequent rotations.
- Cumulative GHG emissions associated with forest operations are slightly increased, by 0.5 tC ha^{-1} per rotation. These additional GHG emissions are associated with the collection and extraction of the harvesting residues.
- Cumulative GHG emissions “saved” as a result of using some harvested wood and an energy source are increased by 14.5 tC-eq. ha^{-1} per rotation.

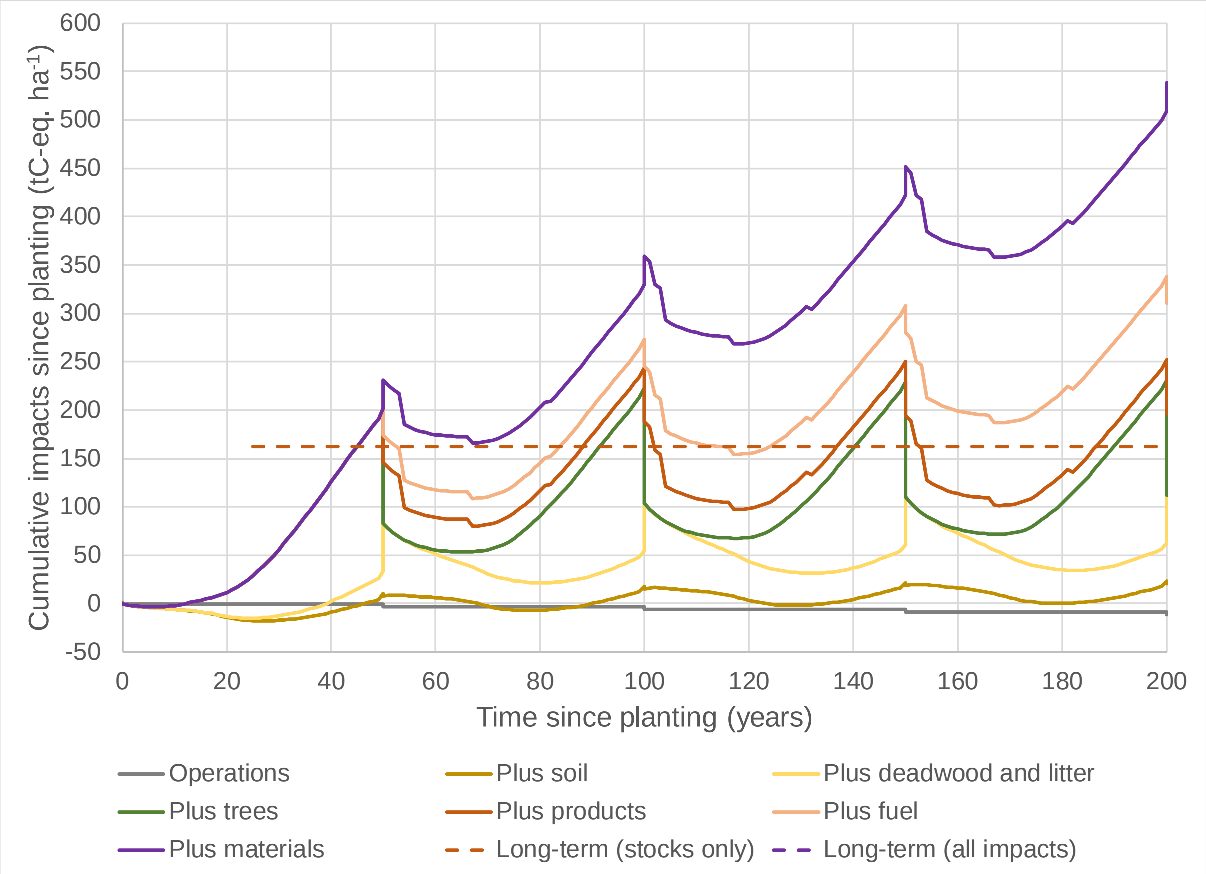

Figure A24 Cumulative net impacts on woodland and "off-site" carbon stocks and "off-site" GHG emissions resulting from planting a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation with no thinning during the rotation. Additionally, some harvesting residues are extracted for use as wood fuel (bioenergy). Contributions from different sources are "stacked", e.g. "Plus fuel" = Operations + soil + deadwood and litter + trees + wood products + GHG emissions displaced by wood fuel.

The time-averaged impacts on carbon stocks and cumulative GHG emissions over a 300-year timescale from woodland establishment are summarised in Table A1.

These results show that, compared with a scenario in which harvesting residues are left to rot in the woodland, the extraction of harvesting residues for utilisation as an energy source has the following impacts on carbon sequestration and GHG emissions:

- Lower total carbon sequestration in the woodland (hence the total for woodland and wood products is also lower, since the latter result is unchanged)
- Deeper potential reductions in GHG emissions through product substitution
- Overall, cumulative total net impacts on GHG emissions (mitigation) is greater by 77 tC-eq. ha^{-1}.

However, the picture is different if a shorter timescale is considered, specifically if results for the end of the first rotation (year 50) are considered, as shown in Table A2.

Table A1 Estimated impacts after 300 years on carbon stocks and cumulative GHG emissions avoided of a decision to extract some harvesting residues for utilisation as an energy source

Scenario	*Accumulated carbon stock in woodland and wood products (tC ha^{-1})*	*Cumulative GHG emissions displaced through product substitution products (tC-eq. ha^{-1})*	*Total cumulative net GHG impacts (tC-eq. ha^{-1})*
Extract some of residues (use for energy)	162	497	659
Leave residues to rot in the woodland	170	412	582
Difference	-8	+85	+77

Table A2 Estimated impacts in year 50 (time of first clearfelling) on carbon stocks and cumulative GHG emissions avoided of a decision to extract some harvesting residues for utilisation as an energy source

Scenario	*Accumulated carbon stock in woodland and wood products (tC ha^{-1})*	*Cumulative GHG emissions displaced through product substitution products (tC-eq. ha^{-1})*	*Total cumulative net GHG impacts (tC-eq. ha^{-1})*
Extract some of residues (use for energy)	149	83	231
Leave residues to rot in the woodland	167	68	236
Difference	-19	+14	-5

It is apparent from Table A2 that, specifically in year 50, the decision to extract some of the harvesting residues as a source of bioenergy has resulted in a less beneficial outcome, in terms of the overall net impacts on GHG emissions. However, further detailed inspection of the results for the two scenarios considered here reveals that:

- By year 55, the cumulative total net GHG emissions of the two scenarios are roughly the same (the “extract residues scenario is now slightly more beneficial). This situation arises because a proportion of the residues left to rot on site (under the “leave in woodland” scenario) have now decayed, and so have released CO_2 to the atmosphere, but without the corresponding benefits of having been burnt to produce useful energy, as was the case in year 50 for the “extract residues” scenario.

- After year 55, the cumulative total net GHG emissions reductions become progressively deeper for the “extract residues” scenario, compared with the “leave in woodland” scenario, giving the time-averaged cumulative results over a 300-year scenario as shown in Table A1.

These findings illustrate an example of how using woody biomass to produce energy can have time-dependent impacts on GHG emissions. In this example, the extraction of the harvesting residues and burning them to produce energy initially results in less benefits in terms of net impacts on GHG emission reductions than the alternative of leaving the residues to rot in the woodland. However, after some years, this situation is reversed and greater net GHG emissions reductions are provided by extracting and burning the residues to produce energy, compared to the alternative of not using them. Such a pattern, which can be associated with decisions to increase harvesting to produce additional wood fuel (bioenergy), i.e. an initial period of reduced GHG benefits (or increased GHG emissions in some cases), followed by longer-term increased GHG benefits, is the phenomenon that has been labelled by some as the “carbon debt” of bioenergy. In the example illustrated here, the “debt” is “paid off” relatively quickly, within 5 years. However, there are other situations where the “payback period” can be much longer, including over centuries, whilst in some cases the “debt” is never fully paid off (see for example Matthews et al. 2014b, particularly Section 5). It should be noted that this issue can apply equally to wood harvesting to produce timber and other wood-based products. It is clear from the example presented here that there is a substantive issue that needs to be addressed. However, the “carbon debt” issue is the subject of conflicting accounts in the scientific literature and there is still strong disagreement amongst different stakeholder groups about its relevance, importance and even its meaningful existence. This critical point requires further exploration, as discussed below.

A1.11.2 “Carbon neutral” or “carbon debt”?

The ensuing discussion considers the question of the “carbon debt” that is sometimes associated with biomass harvested from woodlands, and used for energy or other wood-based products. Three questions are addressed:

1. Is “carbon debt” a real phenomenon?
2. Why can there be strongly different perceptions and disagreements amongst stakeholders about the existence and importance of the “carbon debt” issue?
3. Are there any implications for the role of woodland management, and in particular wood production and utilisation, in meeting climate change objectives?

The discussion addresses these questions collectively rather than sequentially. Before starting, it should be noted that the use of the term “carbon debt” is regarded as unhelpful by some researchers and stakeholders (including the authors of this annex). This is partly because of the apparent attachment of a value judgement to what should be a technical term. However, the term has “stuck”, and stakeholders generally understand the issue being raised when it is used, even if they do not necessarily understand or accept the actual technical issue being referred to. The intention of the decision below is to attempt to clarify this technical issue.

A1.11.3 The riddle of the counterfactual

Matthews et al. (2018) report that an experienced forestry and bioenergy researcher has commented, *'when someone asks the question, "What are the impacts on GHG emissions of using forest bioenergy?" I always reply, "Compared to what?"…'*.

This comment is derived from a fundamental principle in life cycle assessment (LCA), which is particularly relevant to the methods of so-called consequential LCA, which is applied for the purposes of policy analysis (see Section 2.2 of the main body). The consequential LCA methodology requires that the impacts of a policy decision (or equally possibly a business decision) are assessed by comparing against a scenario in which the policy or business decision *is not taken and is not implemented*. This scenario is referred to as the "counterfactual" scenario for the scenario in which he policy or business decision *is taken and is implemented*.

The choice of counterfactual scenario (i.e. the interpretation of what the counterfactual scenario should consist of) strongly affects the results of assessments of GHG emissions impacts (or climate change mitigation impacts) for different options involving woodland creation and woodland management. This is the case, even when the reference to a counterfactual scenario is not explicit. For example, in this appendix, results have been presented for different examples of options involving woodland creation. In all cases, an *implicit* assumption has been made that the counterfactual scenario involves *not creating the example woodland*, or more specifically, the counterfactual scenario involves continuing with the existing land use. (This is generally assumed to be grassland, with the exception of the discussion in Section A1.3, which considers woodland regeneration on former agricultural crop land.) Occasionally, two scenarios for woodland creation (involving differences in some other factor, such as growth rate or management) have been compared with each other. For example, in Section A1.6, a scenario in which a Sitka spruce woodland is created, and managed within thinning and clearfelling on a 50-year rotation, is compared with a scenario involving creating the same woodland but without thinning (Section A1.4). This is described as an assessment of the "influence of thinning". In this case the scenario involving thinning is being compared against an implicit counterfactual scenario involving not thinning (with the type of woodland and management the same in all other respects). It follows that any assessment of the GHG and climate impacts of different woodland management options generally involves a comparison against a counterfactual scenario, even when this is not explicitly stated, or perhaps even recognised by the analyst.

As with the issue of "carbon debt", not all stakeholders understand or accept the requirement for (or validity of) referring to a counterfactual scenario when assessing woodland management options. This point has been observed by Matthews et al. (2018), who also point out that, by analogy, when deciding whether to make a commercial investment using economic analysis, "*it is standard practice to include the opportunity costs of the investment decision as part of the balance of costs and revenues, i.e. to take account of the counterfactual scenario of not making the investment. The counterfactual scenario in [consequential LCA] serves a similar* *purpose and not referring to one would mean that the full impacts of a policy or commercial decision would not be properly evaluated*". Furthermore, as the discussion immediately above highlights, everyone making assessments or statements about the benefits (or otherwise) of an activity involving woodland creation or management (or the use of woody biomass) must be referring to a counterfactual scenario, even if they do not realise they are doing so.

Much of the disagreement amongst commentators on the GHG impacts of woody biomass as an energy source appears to stem from different viewpoints on the most appropriate counterfactual scenario to refer to when assessing particular options. This point is illustrated by the two example viewpoints below.

The "forest sector" viewpoint

Consider the results for cumulative total net GHG impacts for the two woodland creation scenarios:

1. Sitka spruce plantation, yield class 12, not thinned, clearfelled every 50 years, without extracting any harvesting residues for use as bioenergy (Section A1.4.3)
2. Sitka spruce plantation, yield class 12, not thinned, clearfelled every 50 years, with a proportion of the woody harvesting residues extracted for use as bioenergy (Section A1.11.1).

Putting carbon and GHG impacts aside for a moment, it is entirely possible that the management of such woodlands according to either of these two scenarios could meet the highest standards of sustainable forest management, as judged by a range of sustainability criteria. Woodland managers and wood processors are likely to take the view that these well-managed productive woodlands only exist because of their stewardship and management of the woodlands, and through providing markets for the wood products harvested from them. Sometimes, this may be literally the case, in that the woodlands may have been created in the first place through private or public investment in afforestation or reforestation.

It follows that those working in the forest sector are likely to view the counterfactual scenario for their management activities as being, "no woodland", i.e. either the woodland is not maintained, or it would not have been created in the first place. (N.B. This comparison may be made explicitly or consciously.) If this viewpoint is taken, results such as those shown in Figure A8 (Section A1.4.3) and Figure A24 (Section A1.11.1) can be referred to directly to evaluate two possible (and effectively independent) scenarios for woodland management in terms of climate change mitigation potential. Consideration of Figures A8 and A24 in this way suggests that:

- Both woodland management options result in significant accumulation of carbon stocks and cumulative reductions in GHG emissions, i.e. both scenarios are beneficial in terms of climate change mitigation
- The differences in the benefits provided by the two scenarios can be quite small, but over the longer timescales it becomes apparent that the option of extracting some of the woody harvesting residues for use as bioenergy provides greater benefits (cumulative GHG emissions reductions).

Given this perspective, it is possible to see why the forestry and wood processing sectors may consider that their efforts towards the responsible and sustainable management and use of woodlands, including the promotion of the use of some harvested wood and a renewable bioenergy source, are not always understood or fairly portrayed, when it is suggested that some of these practices are damaging in terms of climate change.

The "environmentalist" viewpoint

There are other possible ways of viewing the GHG impacts of the two woodland scenarios described above. For example, consider the following situation:

- The woodland areas (even if created through afforestation or reforestation) have been in existence for a long time, perhaps 50 years or more
- The practice of extracting woody harvesting residues for use as a bioenergy source has only started recently, perhaps as a result of new incentives to produce and/or consume bioenergy.

From this viewpoint, the existence of the woodlands is long-established and is a "given", whereas the practice of extracting residues for bioenergy production is a new activity. In such a context, the case may be argued for assessing the impacts on carbon stocks and GHG emissions of introducing this new practice (i.e. residue extraction) in comparison to pre-existing practice (i.e. leaving the residues to rot in the woodland). Hence, the "leave in woodland" scenario is regarded as the counterfactual scenario to the "extract residues" scenario. This is the viewpoint frequently taken by environmental groups and also by many forestry and bioenergy researchers (see for example, Matthews 2014b, Section 4.10).

Influence of counterfactual scenario on bioenergy emissions estimates

The discussion above described two possible viewpoints that can be taken when assessing the impacts of an example decision that might be taken about woodland management and wood use. Specifically, the example involved a decision to extract harvesting residues, in order to use the biomass as an energy source. The question now arises: what are the GHG emissions resulting from burning this bioenergy source, for example, is the bioenergy effectively "carbon-neutral" or are the emissions so high that the bioenergy is effectively as bad as burning coal? (See Sections 2.16.4 to 2.16.6 in the main annex text). Unfortunately, it is possible to arrive at very widely varying estimates, depending on the choice of counterfactual scenario.

If the "forest sector" viewpoint is taken, the "extract residues" scenario is compared against a "no woodland" counterfactual scenario. The "extract residues" scenario is then assess as resulting in significant net carbon sequestration in woodlands (i.e. "negative CO_2 emissions"). Conceivably, therefore, producing energy from the residues could be viewed as involving negative GHG emissions. However, if the carbon sequestration by the woodlands is viewed as a product or service in its own right (and perhaps used for claiming carbon credits), then the bioenergy is a by-product of this carbon sequestration. This leads to the conclusion that, whilst the sequestered carbon should not be attributed to the bioenergy, neither should any CO_2 emissions be attributed when the bioenergy is burnt. Hence, the (net) GHG emissions from burning bioenergy produced from the woodland may be assessed as being zero.

If the "environmentalist" viewpoint is taken, the "extract residues" scenario is compared against a "leave in woodland" counterfactual scenario. The "extract residues" scenario is then assessed as resulting in some initial losses of carbon stocks from the woodland, compared with the "leave in woodland" scenario (i.e. a net increase in CO_2 emissions). However, the carbon stocks in the woodland under the "extract residues" scenario eventually stabilise at a new, somewhat lower level than for the "leave in woodland" scenario, so that, after some time, there are no further net losses of carbon stocks. Hence, the (net) GHG emissions resulting from burning the bioenergy produced from residues extracted from the woodland are assessed as initially relatively high, but dropping to much lower levels over time. This is illustrated in Table A3, which shows the estimates CO_2 emissions per unit of energy generated by burning the bioenergy produced at the end of each successive rotation of the example Sitka spruce woodland discussed in Section A1.11.1.

The CO_2 emissions are expressed as a factor with respect to the energy generated from burning the bioenergy, such that

$$\text{Bioenergy } CO_2 \text{ emissions factor} = \frac{CO_2 \text{ emissions (as a result of net woodland carbon stock changes from extracting the residues)}}{\text{Energy generated by burning the bioenergy produced from the residues}}$$

The emissions factors are expressed in units of $gCO_2\ MJ^{-1}$, i.e. grams CO_2 effectively emitted per megajoule of energy produced by burning the bioenergy.

It is apparent that the CO_2 emissions factor for the bioenergy derived from the residues harvested at the end of the first rotation is relatively high, at 93 $gCO_2\ MJ^{-1}$. This is very comparable to an equivalent emissions factor for coal and is an example of the kind of result that has led to bioenergy produced from woody biomass sources having been called "dirtier than coal" by some environmental groups. However, by the time of the second extraction of residues, i.e. at the end of the next rotation, the CO_2 emissions factor has dropped to 7.4 $gCO_2\ MJ^{-1}$, much lower than for any fossil energy source. The emissions factor continues to get smaller with each extraction at the end of each successive rotation such that, by the fifth rotation, the emissions factor is less than 1 $gCO_2\ MJ^{-1}$.

Given these kinds of results, in particular the very high CO_2 emissions factor when the activity of extracting residues for bioenergy is just starting, it is possible to see why some environmental groups have issues with the increased harvesting and extraction of biomass for use as a bioenergy source (and sometimes for the manufacture of timber and other wood-based material products). This is particularly the case for scenarios where it takes many decades or centuries for the initially high

CO_2 emission factor to decline to the point where it is small enough for the harvested wood to make a significant contribution to GHG emissions reductions.

Table A3 CO_2 emissions factors estimated for bioenergy produced from harvesting residues when the counterfactual scenario involves leaving the residues in the woodland

Rotation number	*CO_2 emissions factor (gCO2 MJ^{-1})*
1	93.0
2	7.4
3	2.3
4	1.1
5	0.7
6	0.4

What are the "true" CO_2 emissions?

The question posed here is the essence of the riddle of the counterfactual:

- The preceding discussion has shown how, depending on the choice of counterfactual scenario, it is possible to arrive at two very contrasting results for the CO_2 emissions from extracting woody harvesting residues and burning them as a source of energy
- It is possible to "argue the case" for selecting one or other of the counterfactual scenarios, depending on one's viewpoint
- If so, how is it possible to arrive at a "true" CO_2 emissions for wood production systems or wood products?

An answer to this question would appear to require an approach for selecting a "definitive" counterfactual for any scenario for woodland creation, and/or management or wood utilisation under consideration. However, equally, it would appear very challenging to define counterfactual scenarios that can be widely agreed upon or accepted, in all possible cases (or perhaps in any possible cases). Is there any prospect of being able to arrive at a widely accepted assessment?

One way of solving this riddle might involve taking a different approach to assessing different woodland creation and management options, involving framing the question of interest differently, and potentially with greater relevance to the intended ultimate goal, i.e. the mitigation of climate change. Such an approach is outlined tentatively below.

A1.11.4 Carbon budgeting as an approach for assessing options

At the outset, it must be stressed that the approach to assessment described here does not represent a fully worked-out methodology. Rather, the essential features of a tentative possible methodology are discussed. In some respects, the approach does not appear to be particularly innovative and could almost be regarded as self-evident. Nevertheless, this possible approach does not appear to have received explicit or detailed attention until now.

The method is based on the assessment of different options for woodland creation and/or management.in terms of their potential contribution towards a specified carbon budget. The carbon budget is defined by a target, or sequence of targets, for limits on GHG emissions. Depending on the purpose of the assessment, conceivably, these targets could be real or theoretical. The approach is illustrated by taking a hypothetical example of a “body” (such as a commercial company or a municipality) which is evaluating options for meeting a carbon budget, consisting of planned reductions in GHG emissions, starting in the year 2020. Suppose this body intends to reduce annual GHG emissions by 25,000 tC-eq. and intends to achieve this target after 50 years, in 2070. Between 2020 and 2070, the aim is to achieve a linear reduction in GHG emissions. No further reductions in GHG emissions are planned after 2070, at this stage. This leads to annual targets for reduced GHG emissions (compared to the base year of 2020), as shown in Table A4 for some example years.

Table A4 Planned targets for emissions reductions (compared to emissions in 2020) for a hypothetical carbon budget devised by a body

Year	***Target for GHG emissions reduction (tC-eq.)***
2025	2,500
2030	5,000
2040	10,000
2050	15,000
2060	20,000
2070	25,000
2080	25,000
2090	25,000
2100	25,000

Now suppose that the body decides to use woodland creation as a key component of its plan to meet the annual targets. Two options are considered. Under “Option 1”, a 5,000 ha woodland would be created by planting 100 ha of woodland each year for 50 years, starting in 2020. The individual stands of trees forming these woodlands would be the same as for the scenario in Section A1.4, that is:

- Sitka spruce plantations
- Planting on former grassland
- Loam soils
- Growth rate (yield class) 12 m^3 ha^{-1} yr^{-1}
- Harvested by clearfelling every 50 years (50-year rotation)
- No thinning during the rotation

- Harvesting residues left to rot in the woodland stands
- Immediate restocking of stands after clearfelling, either by natural or assisted regeneration or by planting.

Under “Option 2”, the plan would be the same as for Option 1 above, except that 80% of branchwood and stem offcuts left behind after clearfelling would be extracted for use as wood fuel (bioenergy). This is the same scenario as described in Section A1.11.1.

Figure A25 shows the cumulative total net impacts on GHG emission resulting from the two woodland creation options defined above. The results are presented in a similar format to those considered in earlier sections of this appendix (e.g. similarly to Figure A8 in Section A1.4.3 and Figure A24 in Section A1.11.1), except that:

- The x-axis shows the years between 2020 and 2100, rather than “time since planting”
- The results for cumulative total net GHG impacts (y-axis) are total results for the complete woodland area (5,000 ha when fully planted in 2069), expressed in units of MtC-eq. (million tonnes carbon-equivalent).
- The individual contributions to the cumulative total net GHG impacts (from tree, deadwood, litter and soil carbon stocks, wood product carbon stocks and from product substitution effects) are not shown; only the totals are shown for the two options.

The units needed to express the results in Figure A25 indicate that the GHG impacts of the two woodland creation options are very significant, but it must be borne in mind that the results consist of cumulative impacts over an 80-year period for a 5,000 ha area of woodland. For the purpose of carbon budgeting, the body planning to create the woodland needs to know what contribution each woodland option is expected to make to the annual target for GHG emissions reductions in each year from 2020. For this purpose, results are needed for the total net GHG impacts each year, rather than the cumulative impacts from 2020. These results are shown for the two woodland options in Figure A26.

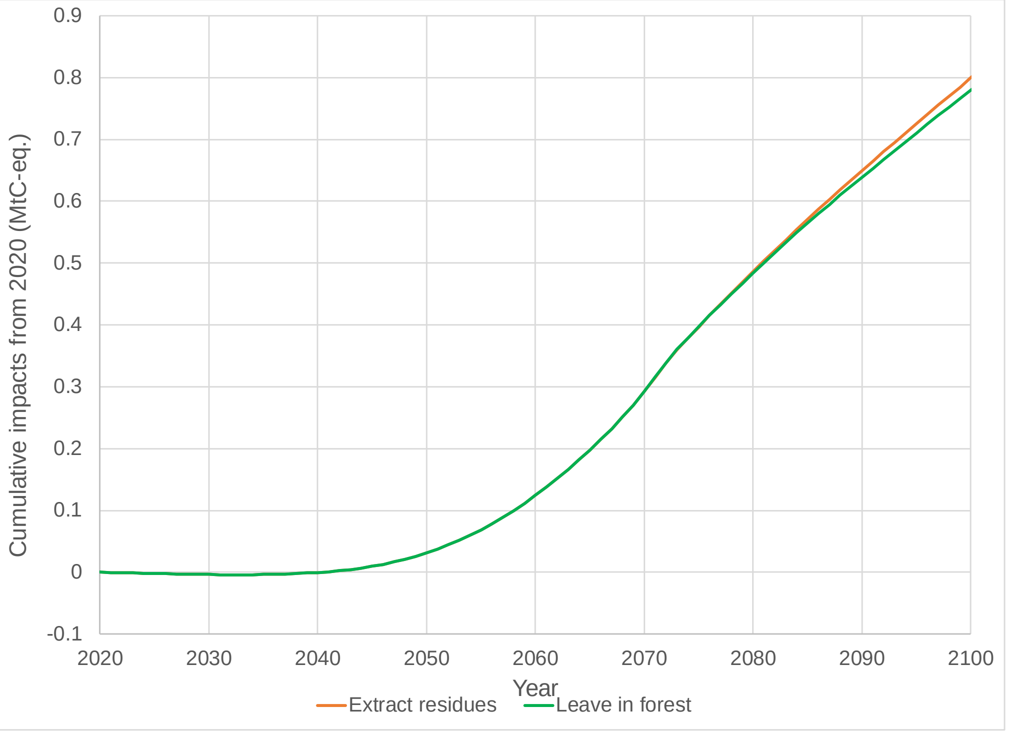

Figure A25 Cumulative total net impacts on GHG emissions contributed by two woodland options. Both involve planting a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation with no thinning during the rotation. Additionally, under one option ("Extract residues"), some harvesting residues are extracted for use as wood fuel (bioenergy).

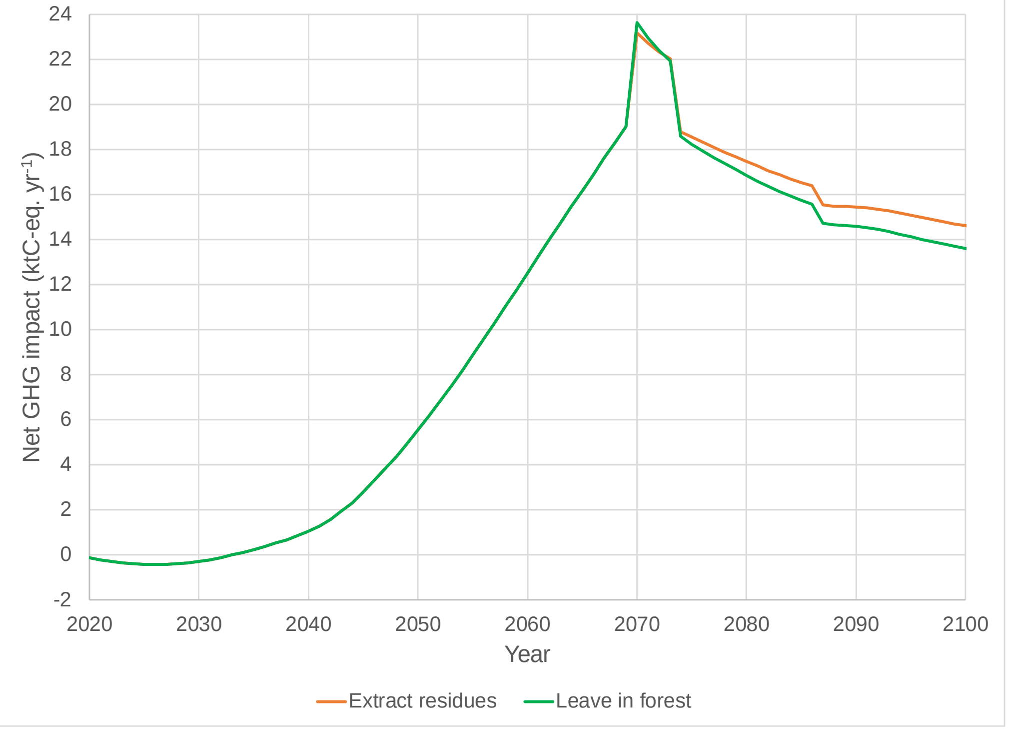

Figure A26 Annual total net impacts on GHG emissions contributed by two woodland options. Both involve planting a stand of Sitka spruce with a moderate growth rate managed for production on a 50-year rotation with no thinning during the rotation. Additionally, under one option ("Extract residues"), some harvesting residues are extracted for use as wood fuel (bioenergy).

The units for the annual contributions to GHG emissions reductions on the y-axis in Figure A26 are thousand tonnes carbon-equivalent (ktC-eq.).

A number of features in the results are apparent from Figures A25 and A26:

- The GHG impacts of the two woodland options are the same up to the year 2070 – this is the year when the stands planted in 2020 are clearfelled, and some harvesting residues are either extracted or left in the woodland, according to the two options for woodland management.
- In the initial period from 2020, whilst the woodland is being created, there are net GHG emissions, mainly as a consequence of losses of carbon stocks from soil during site preparation and tree establishment (see Section 2.10.1)
- After about 2040, the rate of carbon sequestration increases significantly under both scenarios (see Section 2.5 of the main body)
- After 2070, the contributions to net GHG emissions reductions made by the woodlands start to decline, as a result of the technical saturation of carbon sequestration in the trees (see Section A1.4.1), and more gradual saturation of carbon sequestration in the soil. Carbon sequestration in wood products compensates for this to an extent. The discontinuities displayed in the results in Figure A26 are related to short-lived wood products (e.g. paper, bark mulch) reaching the end of their service lives. These discontinuities do not appear in results in later years, i.e. once the complete 5,000 ha woodland has been established and is contributing to wood production.
- In the longer term, the contributions to GHG emissions reductions do not decline to zero, rather there should be a sustained contribution to GHG emissions reductions as a result of wood product displacement effects, provided that these products substitute for more GHG-intensive alternative products.
- By 2080 and later, the option of extracting harvesting residues and using them as a source of energy makes a bigger contribution to net GHG emissions reductions than the option of leaving the residues to rot on site. This is a consequence of the additional energy produced using the residues, which is assumed to avoid the consumption of other more GHG-intensive energy sources. This difference in the contributions made by the two woodland management options gets bigger over longer timescales.

On the basis of the above assessment, the body planning to create the 5,000 ha woodland might conclude that the “extract residues” option is the better option for woodland management, for contributing towards future GHG emissions reductions targets. Unfortunately, there is a snag.

Further inspection of Figure A26 reveals that, in 2070 and for a few years afterwards, the “extract residues” scenario contributes smaller GHG emissions reductions than the “leave in the woodland” scenario. This difference is not visible in the graph of cumulative impacts in Figure A25 but it is also present in these results.

The contributions made by the two woodland creation options to the planned GHG emissions reductions are further explored in Table A5, which shows the outcomes for a selection of years (the targets have been considered already in Table A4). For example, the first row in the table shows the target set by the body for the GHG emissions reductions in the year 2025 (compared to GHG emissions in the year 2020). The target in 2025 is 10% of the target to be achieved in 2070, i.e. 2,500 tC-eq. The contributions made to the 2025 target by the two woodland creation options are also given in Table A5, and are seen to be the same, at -324 tC-eq. This means that the initial activities to create the woodlands are leading to net losses of carbon stocks and, initially, these losses detract from achieving the target emissions reductions. As a consequence, in order to meet the target, bigger contributions to GHG emissions reductions need to be achieved through other mitigation activities (not discussed here), as also shown in Table A5 (2,500 + 324 = 2 824 tC-eq.).

The general situation is still the case in the year 2030, although the losses of carbon stocks from woodland creation have declined and the additional mitigation activities do not need to make up quite so big a deficit.

By 2040, the new woodlands are making a positive contribution towards meeting the target for GHG emissions reductions, which by now is set at 10,000 tC-eq. Carbon sequestration by the new woodlands is projected to contribute just over 11% (1 143 tC-eq.) of the required emissions reduction. Other mitigation activities still need to contribute the majority of the required reductions (8 857 tC-eq.).

Table A5 contributions made by two woodland options towards planned targets for annual GHG emissions reductions in some example years

Year	Target for GHG emissions reduction (tC-eq.)	Contribution from woodland options (tC-eq.)		Contribution required from other mitigation activities (tC-eq.)	
		Extract residues	Leave in woodland	Extract residues	Leave in woodland
2025	2,500	-428	-428	2,928	2,928
2030	5,000	-292	-292	5,292	5,292
2040	10,000	1,039	1,039	8,961	8,961
2050	15,000	5,532	5,532	9,468	9,468
2060	20,000	12,509	12,509	7,491	7,491
2070	25,000	23,158	23,613	1,842	1,387
2080	25,000	17,462	16,841	7,538	8,159
2090	25,000	15,446	14,569	9,554	10,431
2100	25,000	14,608	13,596	10,392	11,404

In 2060, the majority of the stands forming the new woodlands are in the full-vigour phase of growth and carbon sequestration is contributing more than 60% (12 612 tC-eq.) of the planned emissions reductions, the target for which is now set at 20,000 tC-eq.

In 2070, the projected contribution from the woodland options is more than 90% of the full target of 25,000 tC-eq. (greater than 23,000 tC-eq.).

After 2070 (2080 to 2100), the contribution made by the woodland options declines so that slightly more than half of the target GHG emissions reductions are provided by the woodland. This decline occurs because of the (technical) saturation of carbon sequestration in the trees (Section A1.4.1) and litter, and a gradually declining net carbon sink in wood products and the woodland soils. The GHG emissions reductions are sustained mainly by product substitution from the use of additional wood materials and fuel being supplied by the woodland that has been created. It is also apparent during this period that extracting the harvesting residues and using them to generate energy results in bigger GHG emissions reductions, compared to the option of leaving the residues to rot in the woodland.

The smaller contributions made to GHG emissions reductions by the “extract residues” woodland option in 2070 is also apparent in the results in Table A5, specifically, in 2070:

- Under the “extract residues” scenario, the GHG emissions reductions contributed by the woodland are 23 156 tC-eq., requiring a further 1 844 tC-eq. to be contributed by other mitigation activities.
- Under the “leave in woodland” scenario, the GHG emissions reductions contributed by the woodland are 23 611 tC-eq., requiring a further 1 e89 tC-eq. to be contributed by other mitigation activities.
- Hence, if the option of extracting the harvesting residues is chosen by the body, it I necessary to find a further 455 tC-eq. of reductions through other mitigation activities, which would not have been needed if the option of leaving the residues to rot in the woodland had been chosen.

This difference of GHG 455 tC-eq. may seem small but it amounts to nearly 2% of the GHG emissions reduction target that needs to be met in 2070, and these reductions need to come from some other mitigation activities, placing a burden on the body that has set the target to identify and take these additional activities. It should also be recalled that this example of harvesting residues extraction involves a relatively small magnitude of biomass extraction from the woodland (for example, compared to scenarios such as where additional thinning is carried out, see for example Sections A1.6 and A1.8).

At this point, some very important observations may be made:

- The longer-term benefits of extracting and utilising harvesting residues, in terms of net reductions in GHG emissions, are clear from this example. This can be regarded as a *fact*, provided that using the harvesting residues for energy avoids the use of more GHG-intensive energy sources (which should be the case under current conditions).
- The short-term impact on the contribution to GHG emissions reductions (around 2070), resulting from consequent carbon stock changes in woodland litter and soil, is also clear.
- In terms of meeting the targets set for GHG emissions reductions in 2070, managing the woodlands with extraction of harvesting residues for energy will make a smaller contribution towards the target reductions than the option of leaving the residues to rot in the woodland. This is also a *fact*, regardless of

whether the "leave in woodland" scenario is considered to be the "counterfactual" scenario for the option of extracting the residues or not.

- It is also interesting to note that this result is obtained, regardless of the time when the decision is taken to extract the harvesting residues for use as bioenergy, e.g. as part of the original plan for woodland management made now (in 2020), at the time when the clearfelling in the woodlands is started (in 2070), or at some point after that. Hence, this is an "absolute" result, i.e. it is not assessed "relatively" to a subjectively determined or an assumed "base year" for making the assessment.

It follows that the body aiming to achieve the target reductions in GHG emissions has a choice to make:

- The option of extracting residues for energy may be chosen, in which case the challenge of finding more GHG emissions reductions through other types of mitigation activities for several years around 2070 must be faced
- The option of leaving the harvesting residues to rot on site in the woodland may be chosen, in which case there is a longer-term challenge of finding more GHG emissions reductions through other types of mitigation activities, from as early as 2080, and going forward.

In conclusion, considering the two scenarios for woodland management in the way presented here, the meaningfulness of characterising the "extract residues" option as incurring a "carbon debt", attributable to the decision to produce some additional bioenergy from the harvesting residues, is questionable. The characterisation of bioenergy sources produced from woodlands as always innately "carbon neutral" is seen to be equally questionable.

Each of the two woodland creation/management scenarios is seen to have advantages and disadvantages. The choice between them would depend on what options are available for other types of mitigation activity that the body can take in order to meet its targets for GHG emissions reductions in a given year. This suggests the use of woodland creation and management activities to meet climate change mitigation targets should not be considered in isolation from other mitigation measures. Rather, the challenge is to develop a programme of integrated climate change mitigation activities that, when taken together, provide a sustainable and cost-effective solution over policy-relevant timescales, including the very long term.

A1.11.5 Factors and issues to consider

The analysis presented in Sections A1.11.2 to A.11.4 raises a number of issues, some of which are relevant to the specific issue of residue extraction and other approaches to bioenergy production from woodlands, and some of more general significance to the role of woodland creation and management as an option for mitigating climate change.

Issues specific to harvesting residues extraction

Several additional points should be borne in mind when considering the results in Sections A1.11.1 to A1.11.4 and their interpretation:

- The scenario for extraction of harvesting residues considered involves a relatively low-impact intervention, in that residue extraction was restricted to branchwood and stem offcuts (i.e. no stumps or roots extracted), further constrained by limiting branchwood and stem offcut removal to 80% of the available biomass. Scenarios involving more intensive extraction of residues (e.g. 100% of biomass, potentially including stumps and roots) would result in bigger negative impacts on woodland carbon stocks and a longer recovery period.
- The model results presented above involve the assumption that the woodland is on a loam soil. Outcomes for other soil types are different, for example, losses of carbon stocks from soil related to residue extraction are likely to be higher when organic soils are involved.
- The GHG emissions of wood fuel production are influenced by a number of other factors, apart from those associated with woodland carbon stock changes, including losses of biomass along the supply chain and biomass processing chain emission (e.g. energy consumed in drying and pelleting wood). These factors have been allowed for in the calculations and results in Sections A1.11.1 to A1.11.4 (and more generally in this appendix and the main body). However, analyses generally show that the biggest contribution to emissions from wood fuel arises from associated woodland carbon stock changes (where these are relevant).
- Efficiency of wood combustion is also an important factor in determining the GHG emissions impacts. The calculations and results in this appendix and the main body text involve an assumption that wood is burnt with relatively efficient conversion to useful energy. Consequently, the results are not representative of situations where wood is burnt with poor efficiency, for example when wood logs are burnt on an open fire or wood chips with relatively high moisture content are burnt.
- Other possible scenarios for the management of harvesting residues can occur in forestry practice. For example, in some regions, it is common practice to remove harvesting residues from clearfelling sites and sometimes to burn them (without energy recovery) as part of woodland maintenance and the preparation of clearfelling sites for natural regeneration or replanting. There are also some situations in which these practices are carried out as part of the control of pests and diseases, e.g. to prevent the spread of fungal infections that may be transmitted by dead tree roots. These scenarios will involve similar impacts on woodland carbon stocks to those described for the “extract residues” scenario considered in this section, but without the potential substitution benefits provided by burning the residues to produce energy.
- In some situations, considerations other than GHG emission impacts will be more important in determining whether to extract harvesting residues as a source of energy. An example has been given immediately above. As a further example, environmental constraints include requirements not to deplete the nutrient status of soils through residue extraction. Risks of soil acidification and physical damage to soils during forest operations also need to be considered. In many situations it may simply be uneconomic to extract residues for bioenergy production. Feedstock quality is a further consideration, for example, harvesting residues are quite variable in properties and may be

contaminated (e.g. with attached soil), making them less suitable for converting into wood fuel products with a consistent quality (such as wood pellets).

Issues of wider relevance of biomass/bioenergy production

As already noted in Section A1.11.4, the pattern of GHG impacts associated with a decision to extract harvesting residues and use them to produce energy applies more generally to other scenarios involving wood production from woodlands to provide energy, and indeed to provide materials. This includes scenarios in which woodland management is left unchanged, but changes are made in the way harvested wood is utilised, e.g. when wood is diverted from the manufacture of wood-based panels to be used for fuel instead. However, the details for individual scenarios can vary considerably, from effectively no impacts or positive impacts on woodland carbon stocks, to significant negative impacts on woodland carbon stocks or permanently increased GHG emissions. The pattern of net GHG emissions impacts over time (either positive or negative) can also be very variable, depending on the scenario. These issues are discussed further in numerous research studies and examples of further relevant discussions can be found in the reviews of Marelli et al. (2013) and Matthews et al. (2014b).

Issues of wider relevance to woodland creation/management options

A partially developed method was tentatively outlined in Section A1.11.4, involving the assessment of the potential contributions of two woodland management options to climate change mitigation, by placing the assessment in the context of their contributions to meeting stated future targets for GHG emissions reductions. This method may have potential as a tool for more general assessment of different options for woodland creation and/or management from the perspective of climate change mitigation. The approach also appears to bring some clarity to the evaluation of the potential impacts on GHG emissions of different options for woodland management and for harvesting and using wood for energy and/or materials.

An important point that emerges from the analysis presented in Section A1.11.4 (e.g. Table A5) reinforces a fundamental issue highlighted in Sections 2.3 and 2.5 of the main body. Specifically, woodland carbon dynamics are very variable over time and depend on a combination of biological and environmental processes and management interventions. The biological and environmental processes are not entirely under human control. Importantly, the general pattern of carbon sequestration over time, demonstrated by the many examples in this appendix and in Section 2.5 of the main body, is an innate feature of woodland carbon dynamics. In particular, there can be periods when the creation or management of new woodlands can result in net GHG emissions increases because of losses of carbon stocks (e.g. from soil, when sites are disturbed as part of tree planting and before the trees become established). There can also be periods where carbon sequestration in woodlands can be very significant (when woodlands are going through the “full-vigour” phase of growth). Ultimately, carbon sequestration in woodlands generally “saturates” (Section 2.7 or the main body). The consequence is that woodlands are likely to make very variable contributions over time towards fixed targets for GHG emissions reductions. This can present challenges when trying to develop plans to meet carbon budgets, which usually need to deliver progressive and simply-defined reductions in GHG emissions over time. This point is illustrated by the example in Table A5 above.

Finally, generalising the conclusion reached at the end of Section A1.11.4, in the context of the type of assessment suggested above, it may be noted that different scenarios for woodland creation and/or management generally exhibit advantages and disadvantages, which can also be variable over time. As already observed but now stated more generally, decisions about the role of woodlands in climate change mitigation, including their creation and management, depend on how their contributions can combine with those of other available other types of mitigation activity, with the aim of meeting targets for GHG emissions reductions over time. To reiterate, this suggests the use of woodland creation and management activities to meet climate change mitigation targets should not be considered in isolation from other mitigation measures. Rather, the challenge is to develop a programme of integrated climate change mitigation activities that, when taken together, provide a sustainable and cost-effective solution over policy-relevant timescales, including the very long term.

A2. Results for GHG Impacts of Woodland Creation Options Obtained from ERAMMP Study

Tables A2-2 to A2-17 present the calculated change in carbon stock associated with planting seven tree species on land that was previously grassland, for three different soil classes of relevance to Wales (soil class 2 = loam, class 3 = gley, and class 4 = organo-mineral soil), for a warm moist climate (climate zone 7).

The results are presented looking over a time horizon of 5, 30, 80 and 200 years for four different management regimes:

Tables A2-2 to A2-5 show the impact for the Reserve option, with no thinning and no felling

Tables A2-6 to A2-9 are for Continuous Cover Forestry (CCF)

Tables A2-10 to A2-13 are for conventional Thin and fell management

Tables A2-14 to A2-17 are for Short Rotation Forestry (SRF).

Table A2-1: Not used.

Table A2-1 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Reserve forestry (no thin, no fell). 5 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	N/A	2	-0.01	2.45	0.00	0.00	0.00	0.00	2.44	2.44
BE	2	N/A	3	-0.01	2.09	0.00	0.00	0.00	0.00	2.08	2.08
BE	2	N/A	4	-0.01	2.87	0.00	0.00	0.00	0.00	2.87	2.87
BE	6	N/A	2	-0.02	2.45	0.00	0.00	0.00	0.00	2.43	2.43
BE	6	N/A	3	-0.02	2.05	0.00	0.00	0.00	0.00	2.03	2.03
BE	6	N/A	4	-0.02	2.87	0.00	0.00	0.00	0.00	2.85	2.85
OK	2	N/A	2	-0.02	2.43	0.00	0.00	0.00	0.00	2.42	2.42
OK	2	N/A	3	-0.02	2.07	0.00	0.00	0.00	0.00	2.05	2.05
OK	2	N/A	4	-0.02	2.88	0.00	0.00	0.00	0.00	2.86	2.86
OK	4	N/A	2	-0.04	2.45	0.00	0.00	0.00	0.00	2.41	2.41
OK	4	N/A	3	-0.04	2.13	0.00	0.00	0.00	0.00	2.09	2.09
OK	4	N/A	4	-0.04	2.91	0.00	0.00	0.00	0.00	2.87	2.87
OK	6	N/A	2	-0.13	2.43	0.00	0.00	0.00	0.00	2.30	2.30
OK	6	N/A	3	-0.13	2.06	0.00	0.00	0.00	0.00	1.93	1.93
OK	6	N/A	4	-0.13	2.90	0.00	0.00	0.00	0.00	2.77	2.77
BI	4	N/A	2	-0.08	2.43	0.00	0.00	0.00	0.00	2.35	2.35
BI	4	N/A	3	-0.08	2.12	0.00	0.00	0.00	0.00	2.04	2.04
BI	4	N/A	4	-0.08	2.92	0.00	0.00	0.00	0.00	2.83	2.83
BI	6	N/A	2	-0.08	2.45	0.00	0.00	0.00	0.00	2.37	2.37

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	N/A	3	-0.08	2.10	0.00	0.00	0.00	0.00	2.02	2.02
BI	6	N/A	4	-0.08	2.91	0.00	0.00	0.00	0.00	2.83	2.83
BI	8	N/A	2	-0.26	2.49	0.00	0.00	0.00	0.00	2.22	2.22
BI	8	N/A	3	-0.26	2.10	0.00	0.00	0.00	0.00	1.84	1.84
BI	8	N/A	4	-0.26	2.96	0.00	0.00	0.00	0.00	2.69	2.69
BI	10	N/A	2	-0.24	2.53	0.00	0.00	0.00	0.00	2.29	2.29
BI	10	N/A	3	-0.24	2.18	0.00	0.00	0.00	0.00	1.93	1.93
BI	10	N/A	4	-0.24	3.01	0.00	0.00	0.00	0.00	2.77	2.77
PO	2	N/A	3	-0.03	2.21	0.00	0.00	0.00	0.00	2.18	2.18
PO	2	N/A	4	-0.03	2.95	0.00	0.00	0.00	0.00	2.92	2.92
PO	4	N/A	2	-0.06	2.50	0.00	0.00	0.00	0.00	2.44	2.44
PO	4	N/A	3	-0.06	2.18	0.00	0.00	0.00	0.00	2.12	2.12
PO	4	N/A	4	-0.06	2.97	0.00	0.00	0.00	0.00	2.91	2.91
PO	6	N/A	2	-0.06	2.65	0.00	0.00	0.00	0.00	2.58	2.58
PO	6	N/A	3	-0.06	2.31	0.00	0.00	0.00	0.00	2.25	2.25
PO	6	N/A	4	-0.06	3.15	0.00	0.00	0.00	0.00	3.09	3.09
PO	8	N/A	2	-0.20	2.78	0.00	0.00	0.00	0.00	2.58	2.58
PO	8	N/A	3	-0.20	2.44	0.00	0.00	0.00	0.00	2.24	2.24
PO	8	N/A	4	-0.20	3.26	0.00	0.00	0.00	0.00	3.05	3.05
SP	8	N/A	2	-0.06	2.43	0.00	0.00	0.00	0.00	2.37	2.37
SP	8	N/A	3	-0.06	2.05	0.00	0.00	0.00	0.00	1.98	1.98

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	N/A	4	-0.06	2.88	0.00	0.00	0.00	0.00	2.81	2.81
SP	10	N/A	2	-0.18	2.47	0.00	0.00	0.00	0.00	2.29	2.29
SP	10	N/A	3	-0.18	2.06	0.00	0.00	0.00	0.00	1.88	1.88
SP	10	N/A	4	-0.18	2.89	0.00	0.00	0.00	0.00	2.71	2.71
SS	12	N/A	2	-0.15	2.43	0.00	0.00	0.00	0.00	2.27	2.27
SS	12	N/A	3	-0.15	2.06	0.00	0.00	0.00	0.00	1.91	1.91
SS	12	N/A	4	-0.15	2.89	0.00	0.00	0.00	0.00	2.74	2.74
SS	20	N/A	2	-0.09	2.44	0.00	0.00	0.00	0.00	2.36	2.36
SS	20	N/A	3	-0.09	2.10	0.00	0.00	0.00	0.00	2.02	2.02
SS	20	N/A	4	-0.09	2.87	0.00	0.00	0.00	0.00	2.78	2.78
DF	8	N/A	2	-0.01	2.45	0.00	0.00	0.00	0.00	2.44	2.44
DF	8	N/A	3	-0.01	2.05	0.00	0.00	0.00	0.00	2.04	2.04
DF	8	N/A	4	-0.01	2.93	0.00	0.00	0.00	0.00	2.92	2.92
DF	10	N/A	2	-0.14	2.43	0.00	0.00	0.00	0.00	2.28	2.28
DF	10	N/A	3	-0.14	2.06	0.00	0.00	0.00	0.00	1.91	1.91
DF	10	N/A	4	-0.14	2.91	0.00	0.00	0.00	0.00	2.77	2.77
DF	12	N/A	2	-0.16	2.44	0.00	0.00	0.00	0.00	2.27	2.27
DF	12	N/A	3	-0.16	2.04	0.00	0.00	0.00	0.00	1.88	1.88
DF	12	N/A	4	-0.16	2.89	0.00	0.00	0.00	0.00	2.72	2.72

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-2 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Reserve forestry (no thin, no fell). 30 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	N/A	2	-0.63	2.41	0.00	0.00	0.00	0.00	1.79	1.79
BE	2	N/A	3	-0.63	2.47	0.00	0.00	0.00	0.00	1.84	1.84
BE	2	N/A	4	-0.63	3.05	0.00	0.00	0.00	0.00	2.42	2.42
BE	6	N/A	2	-3.54	2.41	0.00	0.00	0.00	0.00	-1.13	-1.13
BE	6	N/A	3	-3.54	2.53	0.00	0.00	0.00	0.00	-1.01	-1.01
BE	6	N/A	4	-3.54	3.17	0.00	0.00	0.00	0.00	-0.37	-0.37
OK	2	N/A	2	-1.31	2.57	0.00	0.00	0.00	0.00	1.26	1.26
OK	2	N/A	3	-1.31	2.67	0.00	0.00	0.00	0.00	1.36	1.36
OK	2	N/A	4	-1.31	3.29	0.00	0.00	0.00	0.00	1.99	1.99
OK	4	N/A	2	-2.62	2.37	0.00	0.00	0.00	0.00	-0.25	-0.25
OK	4	N/A	3	-2.62	2.44	0.00	0.00	0.00	0.00	-0.17	-0.17
OK	4	N/A	4	-2.62	3.06	0.00	0.00	0.00	0.00	0.45	0.45
OK	6	N/A	2	-5.17	2.23	0.00	0.00	0.00	0.00	-2.94	-2.94
OK	6	N/A	3	-5.17	2.35	0.00	0.00	0.00	0.00	-2.82	-2.82
OK	6	N/A	4	-5.17	3.00	0.00	0.00	0.00	0.00	-2.17	-2.17
BI	4	N/A	2	-4.33	2.40	0.00	0.00	0.00	0.00	-1.93	-1.93
BI	4	N/A	3	-4.33	2.53	0.00	0.00	0.00	0.00	-1.80	-1.80
BI	4	N/A	4	-4.33	3.19	0.00	0.00	0.00	0.00	-1.14	-1.14

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	N/A	2	-7.27	2.02	0.00	0.00	0.00	0.00	-5.25	-5.25
BI	6	N/A	3	-7.27	2.16	0.00	0.00	0.00	0.00	-5.10	-5.10
BI	6	N/A	4	-7.27	2.82	0.00	0.00	0.00	0.00	-4.45	-4.45
BI	8	N/A	2	-10.19	1.39	0.00	0.00	0.00	0.00	-8.79	-8.79
BI	8	N/A	3	-10.19	1.47	0.00	0.00	0.00	0.00	-8.72	-8.72
BI	8	N/A	4	-10.19	2.11	0.00	0.00	0.00	0.00	-8.07	-8.07
BI	10	N/A	2	-12.95	0.88	0.00	0.00	0.00	0.00	-12.07	-12.07
BI	10	N/A	3	-12.95	0.94	0.00	0.00	0.00	0.00	-12.01	-12.01
BI	10	N/A	4	-12.95	1.55	0.00	0.00	0.00	0.00	-11.40	-11.40
PO	2	N/A	2	-1.68	3.19	0.00	0.00	0.00	0.00	1.51	1.51
PO	2	N/A	3	-1.68	3.46	0.00	0.00	0.00	0.00	1.78	1.78
PO	2	N/A	4	-1.68	4.18	0.00	0.00	0.00	0.00	2.50	2.50
PO	4	N/A	2	-3.36	2.96	0.00	0.00	0.00	0.00	-0.39	-0.39
PO	4	N/A	3	-3.36	3.21	0.00	0.00	0.00	0.00	-0.15	-0.15
PO	4	N/A	4	-3.36	3.91	0.00	0.00	0.00	0.00	0.55	0.55
PO	6	N/A	2	-5.64	2.69	0.00	0.00	0.00	0.00	-2.95	-2.95
PO	6	N/A	3	-5.64	2.94	0.00	0.00	0.00	0.00	-2.70	-2.70
PO	6	N/A	4	-5.64	3.64	0.00	0.00	0.00	0.00	-2.00	-2.00
PO	8	N/A	2	-7.91	2.27	0.00	0.00	0.00	0.00	-5.65	-5.65
PO	8	N/A	3	-7.91	2.48	0.00	0.00	0.00	0.00	-5.43	-5.43

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
PO	8	N/A	4	-7.91	3.18	0.00	0.00	0.00	0.00	-4.73	-4.73
SP	8	N/A	2	-4.57	2.30	0.00	0.00	0.00	0.00	-2.27	-2.27
SP	8	N/A	3	-4.57	2.39	0.00	0.00	0.00	0.00	-2.18	-2.18
SP	8	N/A	4	-4.57	3.04	0.00	0.00	0.00	0.00	-1.53	-1.53
SP	10	N/A	2	-6.80	1.98	0.00	0.00	0.00	0.00	-4.81	-4.81
SP	10	N/A	3	-6.80	2.08	0.00	0.00	0.00	0.00	-4.72	-4.72
SP	10	N/A	4	-6.80	2.71	0.00	0.00	0.00	0.00	-4.09	-4.09
SS	12	N/A	2	-7.64	1.89	0.00	0.00	0.00	0.00	-5.74	-5.74
SS	12	N/A	3	-7.64	1.97	0.00	0.00	0.00	0.00	-5.67	-5.67
SS	12	N/A	4	-7.64	2.60	0.00	0.00	0.00	0.00	-5.04	-5.04
SS	20	N/A	2	-16.17	0.62	0.00	0.00	0.00	0.00	-15.55	-15.55
SS	20	N/A	3	-16.17	0.63	0.00	0.00	0.00	0.00	-15.54	-15.54
SS	20	N/A	4	-16.17	1.23	0.00	0.00	0.00	0.00	-14.94	-14.94
DF	8	N/A	2	-4.81	2.09	0.00	0.00	0.00	0.00	-2.72	-2.72
DF	8	N/A	3	-4.81	2.15	0.00	0.00	0.00	0.00	-2.66	-2.66
DF	8	N/A	4	-4.81	2.77	0.00	0.00	0.00	0.00	-2.04	-2.04
DF	10	N/A	2	-7.00	1.87	0.00	0.00	0.00	0.00	-5.13	-5.13
DF	10	N/A	3	-7.00	1.95	0.00	0.00	0.00	0.00	-5.05	-5.05

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	10	N/A	4	-7.00	2.58	0.00	0.00	0.00	0.00	-4.41	-4.41
DF	12	N/A	2	-9.26	1.51	0.00	0.00	0.00	0.00	-7.75	-7.75
DF	12	N/A	3	-9.26	1.58	0.00	0.00	0.00	0.00	-7.68	-7.68
DF	12	N/A	4	-9.26	2.21	0.00	0.00	0.00	0.00	-7.05	-7.05

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-3 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Reserve forestry (no thin, no fell). 80 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	N/A	2	-2.70	1.15	0.00	0.00	0.00	0.00	-1.55	-1.55
BE	2	N/A	3	-2.70	1.26	0.00	0.00	0.00	0.00	-1.44	-1.44
BE	2	N/A	4	-2.70	1.70	0.00	0.00	0.00	0.00	-1.00	-1.00
BE	6	N/A	2	-8.25	-1.13	0.00	0.00	0.00	0.00	-9.37	-9.37
BE	6	N/A	3	-8.25	-1.36	0.00	0.00	0.00	0.00	-9.61	-9.61
BE	6	N/A	4	-8.25	-1.05	0.00	0.00	0.00	0.00	-9.30	-9.30
OK	2	N/A	2	-2.88	1.03	0.00	0.00	0.00	0.00	-1.85	-1.85
OK	2	N/A	3	-2.88	1.13	0.00	0.00	0.00	0.00	-1.75	-1.75
OK	2	N/A	4	-2.88	1.56	0.00	0.00	0.00	0.00	-1.32	-1.32
OK	4	N/A	2	-5.76	-0.19	0.00	0.00	0.00	0.00	-5.95	-5.95
OK	4	N/A	3	-5.76	-0.27	0.00	0.00	0.00	0.00	-6.03	-6.03
OK	4	N/A	4	-5.76	0.09	0.00	0.00	0.00	0.00	-5.67	-5.67
OK	6	N/A	2	-8.46	-1.35	0.00	0.00	0.00	0.00	-9.81	-9.81
OK	6	N/A	3	-8.46	-1.60	0.00	0.00	0.00	0.00	-10.06	-10.06
OK	6	N/A	4	-8.46	-1.33	0.00	0.00	0.00	0.00	-9.79	-9.79
BI	4	N/A	2	-4.91	-0.25	0.00	0.00	0.00	0.00	-5.16	-5.16
BI	4	N/A	3	-4.91	-0.36	0.00	0.00	0.00	0.00	-5.27	-5.27
BI	4	N/A	4	-4.91	-0.01	0.00	0.00	0.00	0.00	-4.92	-4.92

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	N/A	2	-6.83	-1.30	0.00	0.00	0.00	0.00	-8.14	-8.14
BI	6	N/A	3	-6.83	-1.55	0.00	0.00	0.00	0.00	-8.39	-8.39
BI	6	N/A	4	-6.83	-1.31	0.00	0.00	0.00	0.00	-8.14	-8.14
BI	8	N/A	2	-8.68	-2.26	0.00	0.00	0.00	0.00	-10.94	-10.94
BI	8	N/A	3	-8.68	-2.67	0.00	0.00	0.00	0.00	-11.35	-11.35
BI	8	N/A	4	-8.68	-2.50	0.00	0.00	0.00	0.00	-11.18	-11.18
BI	10	N/A	2	-10.40	-2.78	0.00	0.00	0.00	0.00	-13.18	-13.18
BI	10	N/A	3	-10.40	-3.27	0.00	0.00	0.00	0.00	-13.68	-13.68
BI	10	N/A	4	-10.40	-3.18	0.00	0.00	0.00	0.00	-13.58	-13.58
PO	2	N/A	2	-1.93	1.50	0.00	0.00	0.00	0.00	-0.43	-0.43
PO	2	N/A	3	-1.93	1.67	0.00	0.00	0.00	0.00	-0.25	-0.25
PO	2	N/A	4	-1.93	2.13	0.00	0.00	0.00	0.00	0.21	0.21
PO	4	N/A	2	-3.85	0.62	0.00	0.00	0.00	0.00	-3.23	-3.23
PO	4	N/A	3	-3.85	0.67	0.00	0.00	0.00	0.00	-3.18	-3.18
PO	4	N/A	4	-3.85	1.07	0.00	0.00	0.00	0.00	-2.78	-2.78
PO	6	N/A	2	-5.36	-0.10	0.00	0.00	0.00	0.00	-5.47	-5.47
PO	6	N/A	3	-5.36	-0.16	0.00	0.00	0.00	0.00	-5.52	-5.52
PO	6	N/A	4	-5.36	0.19	0.00	0.00	0.00	0.00	-5.17	-5.17
PO	8	N/A	2	-6.82	-0.82	0.00	0.00	0.00	0.00	-7.63	-7.63
PO	8	N/A	3	-6.82	-0.97	0.00	0.00	0.00	0.00	-7.79	-7.79

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
PO	8	N/A	4	-6.82	-0.68	0.00	0.00	0.00	0.00	-7.50	-7.50
SP	8	N/A	2	-9.08	-1.38	0.00	0.00	0.00	0.00	-10.45	-10.45
SP	8	N/A	3	-9.08	-1.61	0.00	0.00	0.00	0.00	-10.69	-10.69
SP	8	N/A	4	-9.08	-1.35	0.00	0.00	0.00	0.00	-10.43	-10.43
SP	10	N/A	2	-11.09	-1.98	0.00	0.00	0.00	0.00	-13.08	-13.08
SP	10	N/A	3	-11.09	-2.30	0.00	0.00	0.00	0.00	-13.40	-13.40
SP	10	N/A	4	-11.09	-2.10	0.00	0.00	0.00	0.00	-13.20	-13.20
SS	12	N/A	2	-11.38	-2.10	0.00	0.00	0.00	0.00	-13.48	-13.48
SS	12	N/A	3	-11.38	-2.46	0.00	0.00	0.00	0.00	-13.84	-13.84
SS	12	N/A	4	-11.38	-2.28	0.00	0.00	0.00	0.00	-13.66	-13.66
SS	20	N/A	2	-17.15	-3.32	0.00	0.00	0.00	0.00	-20.46	-20.46
SS	20	N/A	3	-17.15	-3.84	0.00	0.00	0.00	0.00	-20.99	-20.99
SS	20	N/A	4	-17.15	-3.83	0.00	0.00	0.00	0.00	-20.98	-20.98
DF	8	N/A	2	-8.17	-1.59	0.00	0.00	0.00	0.00	-9.75	-9.75
DF	8	N/A	3	-8.17	-1.86	0.00	0.00	0.00	0.00	-10.02	-10.02
DF	8	N/A	4	-8.17	-1.62	0.00	0.00	0.00	0.00	-9.78	-9.78
DF	10	N/A	2	-9.92	-2.13	0.00	0.00	0.00	0.00	-12.05	-12.05
DF	10	N/A	3	-9.92	-2.45	0.00	0.00	0.00	0.00	-12.37	-12.37

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	10	N/A	4	-9.92	-2.30	0.00	0.00	0.00	0.00	-12.22	-12.22
DF	12	N/A	2	-11.68	-2.57	0.00	0.00	0.00	0.00	-14.25	-14.25
DF	12	N/A	3	-11.68	-2.96	0.00	0.00	0.00	0.00	-14.64	-14.64
DF	12	N/A	4	-11.68	-2.86	0.00	0.00	0.00	0.00	-14.53	-14.53

Key*: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-4 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Reserve forestry (no thin, no fell). 200 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	N/A	2	-1.97	-0.44	0.00	0.00	0.00	0.00	-2.41	-2.41
BE	2	N/A	3	-1.97	-0.56	0.00	0.00	0.00	0.00	-2.53	-2.53
BE	2	N/A	4	-1.97	-0.37	0.00	0.00	0.00	0.00	-2.33	-2.33
BE	6	N/A	2	-5.56	-2.19	0.00	0.00	0.00	0.00	-7.75	-7.75
BE	6	N/A	3	-5.56	-2.72	0.00	0.00	0.00	0.00	-8.28	-8.28
BE	6	N/A	4	-5.56	-2.91	0.00	0.00	0.00	0.00	-8.47	-8.47
OK	2	N/A	2	-1.90	-0.41	0.00	0.00	0.00	0.00	-2.30	-2.30
OK	2	N/A	3	-1.90	-0.52	0.00	0.00	0.00	0.00	-2.42	-2.42
OK	2	N/A	4	-1.90	-0.34	0.00	0.00	0.00	0.00	-2.23	-2.23
OK	4	N/A	2	-3.78	-1.73	0.00	0.00	0.00	0.00	-5.51	-5.51
OK	4	N/A	3	-3.78	-2.15	0.00	0.00	0.00	0.00	-5.93	-5.93
OK	4	N/A	4	-3.78	-2.21	0.00	0.00	0.00	0.00	-5.99	-5.99
OK	6	N/A	2	-5.42	-2.20	0.00	0.00	0.00	0.00	-7.62	-7.62
OK	6	N/A	3	-5.42	-2.70	0.00	0.00	0.00	0.00	-8.12	-8.12
OK	6	N/A	4	-5.42	-2.96	0.00	0.00	0.00	0.00	-8.38	-8.38
BI	4	N/A	2	-2.35	-1.05	0.00	0.00	0.00	0.00	-3.40	-3.40
BI	4	N/A	3	-2.35	-1.35	0.00	0.00	0.00	0.00	-3.70	-3.70
BI	4	N/A	4	-2.35	-1.32	0.00	0.00	0.00	0.00	-3.67	-3.67

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	N/A	2	-3.20	-1.94	0.00	0.00	0.00	0.00	-5.14	-5.14
BI	6	N/A	3	-3.20	-2.43	0.00	0.00	0.00	0.00	-5.63	-5.63
BI	6	N/A	4	-3.20	-2.60	0.00	0.00	0.00	0.00	-5.80	-5.80
BI	8	N/A	2	-4.01	-2.28	0.00	0.00	0.00	0.00	-6.29	-6.29
BI	8	N/A	3	-4.01	-2.85	0.00	0.00	0.00	0.00	-6.86	-6.86
BI	8	N/A	4	-4.01	-3.16	0.00	0.00	0.00	0.00	-7.17	-7.17
BI	10	N/A	2	-4.75	-2.52	0.00	0.00	0.00	0.00	-7.27	-7.27
BI	10	N/A	3	-4.75	-3.13	0.00	0.00	0.00	0.00	-7.88	-7.88
BI	10	N/A	4	-4.75	-3.55	0.00	0.00	0.00	0.00	-8.31	-8.31
PO	2	N/A	3	-0.93	0.65	0.00	0.00	0.00	0.00	-0.28	-0.28
PO	2	N/A	4	-0.93	0.93	0.00	0.00	0.00	0.00	0.00	0.00
PO	4	N/A	2	-1.85	-0.30	0.00	0.00	0.00	0.00	-2.15	-2.15
PO	4	N/A	3	-1.85	-0.41	0.00	0.00	0.00	0.00	-2.26	-2.26
PO	4	N/A	4	-1.85	-0.24	0.00	0.00	0.00	0.00	-2.10	-2.10
PO	6	N/A	2	-2.52	-0.91	0.00	0.00	0.00	0.00	-3.44	-3.44
PO	6	N/A	3	-2.52	-1.16	0.00	0.00	0.00	0.00	-3.68	-3.68
PO	6	N/A	4	-2.52	-1.12	0.00	0.00	0.00	0.00	-3.64	-3.64
PO	8	N/A	2	-3.17	-1.50	0.00	0.00	0.00	0.00	-4.67	-4.67
PO	8	N/A	3	-3.17	-1.88	0.00	0.00	0.00	0.00	-5.05	-5.05
PO	8	N/A	4	-3.17	-1.97	0.00	0.00	0.00	0.00	-5.14	-5.14

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	N/A	2	-4.75	-2.22	0.00	0.00	0.00	0.00	-6.97	-6.97
SP	8	N/A	3	-4.75	-2.70	0.00	0.00	0.00	0.00	-7.44	-7.44
SP	8	N/A	4	-4.75	-3.02	0.00	0.00	0.00	0.00	-7.77	-7.77
SP	10	N/A	2	-5.67	-2.51	0.00	0.00	0.00	0.00	-8.18	-8.18
SP	10	N/A	3	-5.67	-3.04	0.00	0.00	0.00	0.00	-8.71	-8.71
SP	10	N/A	4	-5.67	-3.49	0.00	0.00	0.00	0.00	-9.15	-9.15
SS	12	N/A	2	-5.76	-2.44	0.00	0.00	0.00	0.00	-8.20	-8.20
SS	12	N/A	3	-5.76	-3.01	0.00	0.00	0.00	0.00	-8.77	-8.77
SS	12	N/A	4	-5.76	-3.38	0.00	0.00	0.00	0.00	-9.14	-9.14
SS	20	N/A	2	-8.28	-3.13	0.00	0.00	0.00	0.00	-11.41	-11.41
SS	20	N/A	3	-8.28	-3.75	0.00	0.00	0.00	0.00	-12.03	-12.03
SS	20	N/A	4	-8.28	-4.48	0.00	0.00	0.00	0.00	-12.76	-12.76
DF	8	N/A	2	-4.44	-2.27	0.00	0.00	0.00	0.00	-6.71	-6.71
DF	8	N/A	3	-4.44	-2.76	0.00	0.00	0.00	0.00	-7.20	-7.20
DF	8	N/A	4	-4.44	-3.11	0.00	0.00	0.00	0.00	-7.55	-7.55
DF	10	N/A	2	-5.29	-2.56	0.00	0.00	0.00	0.00	-7.86	-7.86
DF	10	N/A	3	-5.29	-3.08	0.00	0.00	0.00	0.00	-8.37	-8.37
DF	10	N/A	4	-5.29	-3.57	0.00	0.00	0.00	0.00	-8.86	-8.86

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	12	N/A	2	-6.18	-2.85	0.00	0.00	0.00	0.00	-9.03	-9.03
DF	12	N/A	3	-6.18	-3.38	0.00	0.00	0.00	0.00	-9.56	-9.56
DF	12	N/A	4	-6.18	-4.02	0.00	0.00	0.00	0.00	-10.19	-10.19

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-5 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Continuous Cover Forestry (CCF). 5 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	N/A	2	-0.01	2.45	0.00	0.01	0.00	0.00	2.44	2.45
BE	2	N/A	3	-0.01	2.09	0.00	0.01	0.00	0.00	2.08	2.09
BE	2	N/A	4	-0.01	2.87	0.00	0.01	0.00	0.00	2.87	2.87
BE	6	N/A	2	-0.02	2.45	0.00	0.01	0.00	0.00	2.43	2.43
BE	6	N/A	3	-0.02	2.05	0.00	0.01	0.00	0.00	2.03	2.03
BE	6	N/A	4	-0.02	2.87	0.00	0.01	0.00	0.00	2.85	2.86
OK	2	N/A	2	-0.02	2.43	0.00	0.01	0.00	0.00	2.42	2.42
OK	2	N/A	3	-0.02	2.07	0.00	0.01	0.00	0.00	2.05	2.06
OK	2	N/A	4	-0.02	2.88	0.00	0.01	0.00	0.00	2.86	2.87
OK	4	N/A	2	-0.04	2.45	0.00	0.01	0.00	0.00	2.41	2.42
OK	4	N/A	3	-0.04	2.13	0.00	0.01	0.00	0.00	2.09	2.09
OK	4	N/A	4	-0.04	2.91	0.00	0.01	0.00	0.00	2.87	2.88
OK	6	N/A	2	-0.13	2.43	0.00	0.01	0.00	0.00	2.30	2.31
OK	6	N/A	3	-0.13	2.06	0.00	0.01	0.00	0.00	1.93	1.94
OK	6	N/A	4	-0.13	2.90	0.00	0.01	0.00	0.00	2.77	2.78
BI	4	N/A	2	-0.08	2.43	0.00	0.01	0.00	0.00	2.35	2.35
BI	4	N/A	3	-0.08	2.12	0.00	0.01	0.00	0.00	2.04	2.04
BI	4	N/A	4	-0.08	2.92	0.00	0.01	0.00	0.00	2.83	2.84

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	N/A	2	-0.08	2.45	0.00	0.01	0.00	0.00	2.37	2.38
BI	6	N/A	3	-0.08	2.10	0.00	0.01	0.00	0.00	2.02	2.02
BI	6	N/A	4	-0.08	2.91	0.00	0.01	0.00	0.00	2.83	2.84
BI	8	N/A	2	-0.26	2.49	0.00	0.01	0.00	0.00	2.22	2.23
BI	8	N/A	3	-0.26	2.10	0.00	0.01	0.00	0.00	1.84	1.84
BI	8	N/A	4	-0.26	2.96	0.00	0.01	0.00	0.00	2.69	2.70
BI	10	N/A	2	-0.24	2.53	0.00	0.01	0.00	0.00	2.29	2.29
BI	10	N/A	3	-0.24	2.18	0.00	0.01	0.00	0.00	1.93	1.94
BI	10	N/A	4	-0.24	3.01	0.00	0.01	0.00	0.00	2.77	2.78
PO	2	N/A	2	-0.03	2.51	0.00	0.01	0.00	0.00	2.47	2.48
PO	2	N/A	3	-0.03	2.21	0.00	0.01	0.00	0.00	2.18	2.19
PO	2	N/A	4	-0.03	2.95	0.00	0.01	0.00	0.00	2.92	2.93
PO	4	N/A	2	-0.06	2.50	0.00	0.01	0.00	0.00	2.44	2.45
PO	4	N/A	3	-0.06	2.18	0.00	0.01	0.00	0.00	2.12	2.12
PO	4	N/A	4	-0.06	2.97	0.00	0.01	0.00	0.00	2.91	2.91
PO	6	N/A	2	-0.06	2.65	0.00	0.01	0.00	0.00	2.58	2.59
PO	6	N/A	3	-0.06	2.31	0.00	0.01	0.00	0.00	2.25	2.26
PO	6	N/A	4	-0.06	3.15	0.00	0.01	0.00	0.00	3.09	3.09
PO	8	N/A	2	-0.20	2.78	0.00	0.01	0.00	0.00	2.58	2.59
PO	8	N/A	3	-0.20	2.44	0.00	0.01	0.00	0.00	2.24	2.24

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
PO	8	N/A	4	-0.20	3.26	0.00	0.01	0.00	0.00	3.05	3.06
SP	8	N/A	2	-0.06	2.43	0.00	0.01	0.00	0.00	2.37	2.37
SP	8	N/A	3	-0.06	2.05	0.00	0.01	0.00	0.00	1.98	1.99
SP	8	N/A	4	-0.06	2.88	0.00	0.01	0.00	0.00	2.81	2.82
SP	10	N/A	2	-0.18	2.47	0.00	0.01	0.00	0.00	2.29	2.29
SP	10	N/A	3	-0.18	2.06	0.00	0.01	0.00	0.00	1.88	1.89
SP	10	N/A	4	-0.18	2.89	0.00	0.01	0.00	0.00	2.71	2.71
SS	12	N/A	2	-0.15	2.43	0.00	0.01	0.00	0.00	2.27	2.28
SS	12	N/A	3	-0.15	2.06	0.00	0.01	0.00	0.00	1.91	1.92
SS	12	N/A	4	-0.15	2.89	0.00	0.01	0.00	0.00	2.74	2.74
SS	20	N/A	2	-0.09	2.44	0.00	0.01	0.00	0.00	2.36	2.36
SS	20	N/A	3	-0.09	2.10	0.00	0.01	0.00	0.00	2.02	2.02
SS	20	N/A	4	-0.09	2.87	0.00	0.01	0.00	0.00	2.78	2.79
DF	8	N/A	2	-0.01	2.45	0.00	0.01	0.00	0.00	2.44	2.44
DF	8	N/A	3	-0.01	2.05	0.00	0.01	0.00	0.00	2.04	2.05
DF	8	N/A	4	-0.01	2.93	0.00	0.01	0.00	0.00	2.92	2.93
DF	10	N/A	2	-0.14	2.43	0.00	0.01	0.00	0.00	2.28	2.29
DF	10	N/A	3	-0.14	2.06	0.00	0.01	0.00	0.00	1.91	1.92

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	10	N/A	4	-0.14	2.91	0.00	0.01	0.00	0.00	2.77	2.77
DF	12	N/A	2	-0.16	2.44	0.00	0.01	0.00	0.00	2.27	2.28
DF	12	N/A	3	-0.16	2.04	0.00	0.01	0.00	0.00	1.88	1.88
DF	12	N/A	4	-0.16	2.89	0.00	0.01	0.00	0.00	2.72	2.73

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-6 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Continuous Cover Forestry (CCF). 30 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	N/A	2	-0.63	2.41	0.00	0.01	0.00	0.00	1.79	1.79
BE	2	N/A	3	-0.63	2.47	0.00	0.01	0.00	0.00	1.84	1.85
BE	2	N/A	4	-0.63	3.05	0.00	0.01	0.00	0.00	2.42	2.43
BE	6	N/A	2	-3.15	2.41	-0.22	0.01	-0.10	-0.14	-0.96	-1.18
BE	6	N/A	3	-3.15	2.53	-0.22	0.01	-0.10	-0.14	-0.84	-1.06
BE	6	N/A	4	-3.15	3.17	-0.22	0.01	-0.10	-0.14	-0.20	-0.42
OK	2	N/A	2	-1.31	2.57	0.00	0.01	0.00	0.00	1.26	1.27
OK	2	N/A	3	-1.31	2.67	0.00	0.01	0.00	0.00	1.36	1.37
OK	2	N/A	4	-1.31	3.29	0.00	0.01	0.00	0.00	1.99	1.99
OK	4	N/A	2	-2.62	2.37	0.00	0.01	0.00	0.00	-0.25	-0.24
OK	4	N/A	3	-2.62	2.44	0.00	0.01	0.00	0.00	-0.17	-0.17
OK	4	N/A	4	-2.62	3.06	0.00	0.01	0.00	0.00	0.45	0.45
OK	6	N/A	2	-4.16	2.25	-0.51	0.02	-0.20	-0.26	-2.42	-2.87
OK	6	N/A	3	-4.16	2.37	-0.51	0.02	-0.20	-0.26	-2.30	-2.74
OK	6	N/A	4	-4.16	3.03	-0.51	0.02	-0.20	-0.26	-1.64	-2.08
BI	4	N/A	2	-3.26	2.48	-0.40	0.02	-0.24	-0.32	-1.18	-1.72
BI	4	N/A	3	-3.26	2.63	-0.40	0.02	-0.24	-0.32	-1.03	-1.58
BI	4	N/A	4	-3.26	3.27	-0.40	0.02	-0.24	-0.32	-0.39	-0.93

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	N/A	2	-5.03	2.28	-0.77	0.04	-0.51	-0.69	-3.53	-4.69
BI	6	N/A	3	-5.03	2.42	-0.77	0.04	-0.51	-0.69	-3.38	-4.54
BI	6	N/A	4	-5.03	3.10	-0.77	0.04	-0.51	-0.69	-2.70	-3.86
BI	8	N/A	2	-6.61	1.29	-1.27	0.06	-0.84	-1.26	-6.59	-8.62
BI	8	N/A	3	-6.61	1.33	-1.27	0.06	-0.84	-1.26	-6.55	-8.58
BI	8	N/A	4	-6.61	1.92	-1.27	0.06	-0.84	-1.26	-5.96	-8.00
BI	10	N/A	2	-8.06	0.92	-1.80	0.07	-1.08	-1.79	-8.94	-11.74
BI	10	N/A	3	-8.06	0.94	-1.80	0.07	-1.08	-1.79	-8.92	-11.72
BI	10	N/A	4	-8.06	1.52	-1.80	0.07	-1.08	-1.79	-8.35	-11.15
PO	2	N/A	2	-1.28	3.21	-0.14	0.01	-0.09	-0.11	1.78	1.60
PO	2	N/A	3	-1.28	3.48	-0.14	0.01	-0.09	-0.11	2.06	1.87
PO	2	N/A	4	-1.28	4.21	-0.14	0.01	-0.09	-0.11	2.78	2.59
PO	4	N/A	2	-2.57	3.01	-0.29	0.02	-0.18	-0.23	0.16	-0.23
PO	4	N/A	3	-2.57	3.25	-0.29	0.02	-0.18	-0.23	0.39	0.01
PO	4	N/A	4	-2.57	3.97	-0.29	0.02	-0.18	-0.23	1.11	0.73
PO	6	N/A	2	-3.98	2.84	-0.55	0.04	-0.37	-0.49	-1.69	-2.52
PO	6	N/A	3	-3.98	3.09	-0.55	0.04	-0.37	-0.49	-1.44	-2.27
PO	6	N/A	4	-3.98	3.80	-0.55	0.04	-0.37	-0.49	-0.73	-1.55
PO	8	N/A	2	-5.25	2.57	-0.90	0.05	-0.61	-0.90	-3.58	-5.03
PO	8	N/A	3	-5.25	2.81	-0.90	0.05	-0.61	-0.90	-3.34	-4.80

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
PO	8	N/A	4	-5.25	3.52	-0.90	0.05	-0.61	-0.90	-2.63	-4.09
SP	8	N/A	2	-3.79	2.30	-0.44	0.02	-0.15	-0.18	-1.93	-2.24
SP	8	N/A	3	-3.79	2.40	-0.44	0.02	-0.15	-0.18	-1.83	-2.14
SP	8	N/A	4	-3.79	3.05	-0.44	0.02	-0.15	-0.18	-1.18	-1.49
SP	10	N/A	2	-4.78	2.07	-0.71	0.04	-0.41	-0.53	-3.43	-4.33
SP	10	N/A	3	-4.78	2.17	-0.71	0.04	-0.41	-0.53	-3.32	-4.23
SP	10	N/A	4	-4.78	2.80	-0.71	0.04	-0.41	-0.53	-2.69	-3.60
SS	12	N/A	2	-5.64	2.00	-0.76	0.05	-0.43	-0.69	-4.39	-5.47
SS	12	N/A	3	-5.64	2.09	-0.76	0.05	-0.43	-0.69	-4.31	-5.39
SS	12	N/A	4	-5.64	2.71	-0.76	0.05	-0.43	-0.69	-3.69	-4.77
SS	20	N/A	2	-10.95	1.16	-1.90	0.10	-1.06	-1.87	-11.70	-14.53
SS	20	N/A	3	-10.95	1.20	-1.90	0.10	-1.06	-1.87	-11.65	-14.48
SS	20	N/A	4	-10.95	1.82	-1.90	0.10	-1.06	-1.87	-11.04	-13.86
DF	8	N/A	2	-4.05	2.11	-0.40	0.02	-0.15	-0.23	-2.33	-2.69
DF	8	N/A	3	-4.05	2.18	-0.40	0.02	-0.15	-0.23	-2.27	-2.63
DF	8	N/A	4	-4.05	2.80	-0.40	0.02	-0.15	-0.23	-1.65	-2.00
DF	10	N/A	2	-5.12	1.95	-0.78	0.04	-0.36	-0.57	-3.94	-4.84
DF	10	N/A	3	-5.12	2.04	-0.78	0.04	-0.36	-0.57	-3.86	-4.76

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	10	N/A	4	-5.12	2.68	-0.78	0.04	-0.36	-0.57	-3.22	-4.11
DF	12	N/A	2	-6.88	1.72	-0.94	0.05	-0.45	-0.72	-6.09	-7.22
DF	12	N/A	3	-6.88	1.81	-0.94	0.05	-0.45	-0.72	-6.01	-7.14
DF	12	N/A	4	-6.88	2.45	-0.94	0.05	-0.45	-0.72	-5.37	-6.50

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-7 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Continuous Cover Forestry (CCF). 80 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	N/A	2	-1.76	1.35	-0.28	0.02	-0.22	-0.35	-0.69	-1.25
BE	2	N/A	3	-1.76	1.48	-0.28	0.02	-0.22	-0.35	-0.57	-1.12
BE	2	N/A	4	-1.76	1.92	-0.28	0.02	-0.22	-0.35	-0.13	-0.68
BE	6	N/A	2	-5.29	-0.14	-0.94	0.05	-0.71	-1.20	-6.37	-8.24
BE	6	N/A	3	-5.29	-0.23	-0.94	0.05	-0.71	-1.20	-6.46	-8.32
BE	6	N/A	4	-5.29	0.14	-0.94	0.05	-0.71	-1.20	-6.09	-7.96
OK	2	N/A	2	-1.90	1.37	-0.26	0.02	-0.21	-0.32	-0.79	-1.30
OK	2	N/A	3	-1.90	1.50	-0.26	0.02	-0.21	-0.32	-0.65	-1.16
OK	2	N/A	4	-1.90	1.95	-0.26	0.02	-0.21	-0.32	-0.21	-0.71
OK	4	N/A	2	-3.79	0.47	-0.52	0.03	-0.43	-0.63	-3.84	-4.87
OK	4	N/A	3	-3.79	0.48	-0.52	0.03	-0.43	-0.63	-3.83	-4.86
OK	4	N/A	4	-3.79	0.87	-0.52	0.03	-0.43	-0.63	-3.44	-4.47
OK	6	N/A	2	-5.22	-0.28	-0.92	0.05	-0.71	-1.19	-6.42	-8.27
OK	6	N/A	3	-5.22	-0.39	-0.92	0.05	-0.71	-1.19	-6.53	-8.38
OK	6	N/A	4	-5.22	-0.04	-0.92	0.05	-0.71	-1.19	-6.18	-8.03
BI	4	N/A	2	-2.18	0.43	-0.58	0.04	-0.52	-0.83	-2.33	-3.64
BI	4	N/A	3	-2.18	0.42	-0.58	0.04	-0.52	-0.83	-2.35	-3.66
BI	4	N/A	4	-2.18	0.76	-0.58	0.04	-0.52	-0.83	-2.00	-3.31

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	N/A	2	-2.63	0.00	-0.92	0.06	-0.79	-1.40	-3.54	-5.67
BI	6	N/A	3	-2.63	-0.09	-0.92	0.06	-0.79	-1.40	-3.64	-5.77
BI	6	N/A	4	-2.63	0.24	-0.92	0.06	-0.79	-1.40	-3.30	-5.43
BI	8	N/A	2	-3.05	-1.06	-1.09	0.08	-0.88	-2.37	-5.20	-8.37
BI	8	N/A	3	-3.05	-1.37	-1.09	0.08	-0.88	-2.37	-5.51	-8.68
BI	8	N/A	4	-3.05	-1.16	-1.09	0.08	-0.88	-2.37	-5.30	-8.47
BI	10	N/A	2	-3.50	-1.33	-1.32	0.10	-1.09	-3.09	-6.15	-10.23
BI	10	N/A	3	-3.50	-1.71	-1.32	0.10	-1.09	-3.09	-6.53	-10.61
BI	10	N/A	4	-3.50	-1.55	-1.32	0.10	-1.09	-3.09	-6.37	-10.45
PO	2	N/A	2	-0.88	1.86	-0.21	0.02	-0.19	-0.29	0.78	0.31
PO	2	N/A	3	-0.88	2.07	-0.21	0.02	-0.19	-0.29	0.99	0.52
PO	2	N/A	4	-0.88	2.56	-0.21	0.02	-0.19	-0.29	1.47	1.01
PO	4	N/A	2	-1.76	1.35	-0.42	0.04	-0.39	-0.59	-0.82	-1.76
PO	4	N/A	3	-1.76	1.48	-0.42	0.04	-0.39	-0.59	-0.69	-1.63
PO	4	N/A	4	-1.76	1.93	-0.42	0.04	-0.39	-0.59	-0.24	-1.18
PO	6	N/A	2	-2.13	0.95	-0.65	0.06	-0.58	-1.00	-1.83	-3.36
PO	6	N/A	3	-2.13	1.03	-0.65	0.06	-0.58	-1.00	-1.75	-3.28
PO	6	N/A	4	-2.13	1.45	-0.65	0.06	-0.58	-1.00	-1.33	-2.86
PO	8	N/A	2	-2.49	0.22	-0.78	0.08	-0.66	-1.69	-3.05	-5.32
PO	8	N/A	3	-2.49	0.18	-0.78	0.08	-0.66	-1.69	-3.09	-5.36

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
PO	8	N/A	4	-2.49	0.53	-0.78	0.08	-0.66	-1.69	-2.74	-5.01
SP	8	N/A	2	-5.71	-0.32	-0.98	0.06	-0.59	-1.38	-7.02	-8.92
SP	8	N/A	3	-5.71	-0.42	-0.98	0.06	-0.59	-1.38	-7.11	-9.02
SP	8	N/A	4	-5.71	-0.08	-0.98	0.06	-0.59	-1.38	-6.78	-8.68
SP	10	N/A	2	-6.59	-0.87	-1.20	0.08	-0.73	-2.05	-8.67	-11.37
SP	10	N/A	3	-6.59	-1.04	-1.20	0.08	-0.73	-2.05	-8.84	-11.54
SP	10	N/A	4	-6.59	-0.76	-1.20	0.08	-0.73	-2.05	-8.55	-11.26
SS	12	N/A	2	-6.05	-0.74	-1.22	0.09	-0.70	-2.06	-8.02	-10.68
SS	12	N/A	3	-6.05	-0.93	-1.22	0.09	-0.70	-2.06	-8.21	-10.87
SS	12	N/A	4	-6.05	-0.64	-1.22	0.09	-0.70	-2.06	-7.91	-10.58
SS	20	N/A	2	-7.89	-2.14	-1.91	0.16	-1.12	-3.97	-11.95	-16.88
SS	20	N/A	3	-7.89	-2.56	-1.91	0.16	-1.12	-3.97	-12.37	-17.30
SS	20	N/A	4	-7.89	-2.41	-1.91	0.16	-1.12	-3.97	-12.22	-17.15
DF	8	N/A	2	-4.77	-0.37	-0.82	0.06	-0.51	-1.33	-5.96	-7.74
DF	8	N/A	3	-4.77	-0.48	-0.82	0.06	-0.51	-1.33	-6.07	-7.85
DF	8	N/A	4	-4.77	-0.16	-0.82	0.06	-0.51	-1.33	-5.75	-7.53
DF	10	N/A	2	-5.38	-0.88	-1.20	0.08	-0.64	-1.93	-7.46	-9.96
DF	10	N/A	3	-5.38	-1.07	-1.20	0.08	-0.64	-1.93	-7.65	-10.14

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	10	N/A	4	-5.38	-0.78	-1.20	0.08	-0.64	-1.93	-7.36	-9.85
DF	12	N/A	2	-6.24	-1.38	-1.17	0.10	-0.74	-2.39	-8.79	-11.83
DF	12	N/A	3	-6.24	-1.65	-1.17	0.10	-0.74	-2.39	-9.05	-12.09
DF	12	N/A	4	-6.24	-1.42	-1.17	0.10	-0.74	-2.39	-8.82	-11.86

Key*: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-8 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Continuous Cover Forestry (CCF). 200 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	N/A	2	-0.67	-0.03	-0.13	0.03	-0.23	-0.65	-0.82	-1.68
BE	2	N/A	3	-0.67	-0.09	-0.13	0.03	-0.23	-0.65	-0.89	-1.74
BE	2	N/A	4	-0.67	0.13	-0.13	0.03	-0.23	-0.65	-0.67	-1.53
BE	6	N/A	2	-1.52	-1.32	-0.40	0.06	-0.70	-2.03	-3.24	-5.91
BE	6	N/A	3	-1.52	-1.72	-0.40	0.06	-0.70	-2.03	-3.64	-6.31
BE	6	N/A	4	-1.52	-1.71	-0.40	0.06	-0.70	-2.03	-3.63	-6.30
OK	2	N/A	2	-0.35	0.17	-0.13	0.03	-0.23	-0.59	-0.31	-1.10
OK	2	N/A	3	-0.35	0.15	-0.13	0.03	-0.23	-0.59	-0.33	-1.12
OK	2	N/A	4	-0.35	0.38	-0.13	0.03	-0.23	-0.59	-0.10	-0.89
OK	4	N/A	2	-0.71	-0.53	-0.25	0.04	-0.47	-1.17	-1.48	-3.08
OK	4	N/A	3	-0.71	-0.73	-0.25	0.04	-0.47	-1.17	-1.69	-3.29
OK	4	N/A	4	-0.71	-0.62	-0.25	0.04	-0.47	-1.17	-1.57	-3.17
OK	6	N/A	2	-0.96	-0.76	-0.38	0.06	-0.68	-1.94	-2.10	-4.65
OK	6	N/A	3	-0.96	-1.07	-0.38	0.06	-0.68	-1.94	-2.41	-4.96
OK	6	N/A	4	-0.96	-1.03	-0.38	0.06	-0.68	-1.94	-2.37	-4.92
BI	4	N/A	2	-0.51	0.14	-0.24	0.05	-0.60	-1.15	-0.61	-2.31
BI	4	N/A	3	-0.51	0.07	-0.24	0.05	-0.60	-1.15	-0.68	-2.37
BI	4	N/A	4	-0.51	0.26	-0.24	0.05	-0.60	-1.15	-0.49	-2.18

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	N/A	2	-1.23	0.01	-0.35	0.08	-0.97	-1.91	-1.57	-4.37
BI	6	N/A	3	-1.23	-0.08	-0.35	0.08	-0.97	-1.91	-1.66	-4.46
BI	6	N/A	4	-1.23	0.09	-0.35	0.08	-0.97	-1.91	-1.48	-4.29
BI	8	N/A	2	-1.70	-0.69	-0.57	0.10	-1.14	-3.05	-2.96	-7.05
BI	8	N/A	3	-1.70	-0.95	-0.57	0.10	-1.14	-3.05	-3.23	-7.32
BI	8	N/A	4	-1.70	-0.91	-0.57	0.10	-1.14	-3.05	-3.19	-7.28
BI	10	N/A	2	-1.96	-1.08	-0.74	0.13	-1.43	-3.98	-3.78	-9.06
BI	10	N/A	3	-1.96	-1.44	-0.74	0.13	-1.43	-3.98	-4.14	-9.42
BI	10	N/A	4	-1.96	-1.48	-0.74	0.13	-1.43	-3.98	-4.18	-9.46
PO	2	N/A	3	-0.21	1.11	-0.09	0.03	-0.22	-0.41	0.81	0.21
PO	2	N/A	4	-0.21	1.43	-0.09	0.03	-0.22	-0.41	1.14	0.54
PO	4	N/A	2	-0.42	0.64	-0.17	0.05	-0.44	-0.82	0.05	-1.16
PO	4	N/A	3	-0.42	0.72	-0.17	0.05	-0.44	-0.82	0.13	-1.09
PO	4	N/A	4	-0.42	1.00	-0.17	0.05	-0.44	-0.82	0.40	-0.81
PO	6	N/A	2	-0.99	0.47	-0.25	0.08	-0.72	-1.36	-0.76	-2.77
PO	6	N/A	3	-0.99	0.52	-0.25	0.08	-0.72	-1.36	-0.72	-2.73
PO	6	N/A	4	-0.99	0.77	-0.25	0.08	-0.72	-1.36	-0.47	-2.48
PO	8	N/A	2	-1.37	0.18	-0.41	0.10	-0.85	-2.18	-1.60	-4.53
PO	8	N/A	3	-1.37	0.15	-0.41	0.10	-0.85	-2.18	-1.63	-4.56
PO	8	N/A	4	-1.37	0.36	-0.41	0.10	-0.85	-2.18	-1.42	-4.35

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	N/A	2	-1.92	-0.36	-0.38	0.08	-0.68	-1.97	-2.66	-5.23
SP	8	N/A	3	-1.92	-0.54	-0.38	0.08	-0.68	-1.97	-2.84	-5.41
SP	8	N/A	4	-1.92	-0.45	-0.38	0.08	-0.68	-1.97	-2.75	-5.32
SP	10	N/A	2	-2.54	-0.78	-0.59	0.11	-0.86	-2.72	-3.91	-7.37
SP	10	N/A	3	-2.54	-1.04	-0.59	0.11	-0.86	-2.72	-4.17	-7.64
SP	10	N/A	4	-2.54	-1.03	-0.59	0.11	-0.86	-2.72	-4.16	-7.63
SS	12	N/A	2	-2.32	-0.71	-0.43	0.12	-0.79	-2.73	-3.47	-6.86
SS	12	N/A	3	-2.32	-0.96	-0.43	0.12	-0.79	-2.73	-3.71	-7.11
SS	12	N/A	4	-2.32	-0.89	-0.43	0.12	-0.79	-2.73	-3.64	-7.04
SS	20	N/A	2	-2.43	-1.50	-0.80	0.21	-1.34	-5.12	-4.73	-10.98
SS	20	N/A	3	-2.43	-1.97	-0.80	0.21	-1.34	-5.12	-5.21	-11.45
SS	20	N/A	4	-2.43	-2.13	-0.80	0.21	-1.34	-5.12	-5.37	-11.61
DF	8	N/A	2	-1.99	-0.42	-0.38	0.08	-0.57	-1.90	-2.79	-5.19
DF	8	N/A	3	-1.99	-0.60	-0.38	0.08	-0.57	-1.90	-2.97	-5.36
DF	8	N/A	4	-1.99	-0.51	-0.38	0.08	-0.57	-1.90	-2.87	-5.27
DF	10	N/A	2	-2.20	-0.77	-0.57	0.10	-0.71	-2.58	-3.54	-6.73
DF	10	N/A	3	-2.20	-1.02	-0.57	0.10	-0.71	-2.58	-3.79	-6.98
DF	10	N/A	4	-2.20	-0.99	-0.57	0.10	-0.71	-2.58	-3.76	-6.95

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	12	N/A	2	-2.53	-1.14	-0.49	0.12	-0.84	-3.17	-4.17	-8.06
DF	12	N/A	3	-2.53	-1.47	-0.49	0.12	-0.84	-3.17	-4.50	-8.39
DF	12	N/A	4	-2.53	-1.53	-0.49	0.12	-0.84	-3.17	-4.56	-8.44

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-9 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to conventional Thin & Fell forestry. 5 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	100	2	-0.01	2.45	0.00	0.01	0.00	0.00	2.44	2.45
BE	2	100	3	-0.01	2.09	0.00	0.01	0.00	0.00	2.08	2.09
BE	2	100	4	-0.01	2.87	0.00	0.01	0.00	0.00	2.87	2.87
BE	6	100	2	-0.02	2.45	0.00	0.01	0.00	0.00	2.43	2.43
BE	6	100	3	-0.02	2.05	0.00	0.01	0.00	0.00	2.03	2.03
BE	6	100	4	-0.02	2.87	0.00	0.01	0.00	0.00	2.85	2.86
OK	2	120	2	-0.02	2.43	0.00	0.01	0.00	0.00	2.42	2.42
OK	2	120	3	-0.02	2.07	0.00	0.01	0.00	0.00	2.05	2.06
OK	2	120	4	-0.02	2.88	0.00	0.01	0.00	0.00	2.86	2.87
OK	4	120	2	-0.04	2.45	0.00	0.01	0.00	0.00	2.41	2.42
OK	4	120	3	-0.04	2.13	0.00	0.01	0.00	0.00	2.09	2.09
OK	4	120	4	-0.04	2.91	0.00	0.01	0.00	0.00	2.87	2.88
OK	6	120	2	-0.13	2.43	0.00	0.01	0.00	0.00	2.30	2.31
OK	6	120	3	-0.13	2.06	0.00	0.01	0.00	0.00	1.93	1.94
OK	6	120	4	-0.13	2.90	0.00	0.01	0.00	0.00	2.77	2.78
BI	4	100	2	-0.08	2.43	0.00	0.01	0.00	0.00	2.35	2.35
BI	4	100	3	-0.08	2.12	0.00	0.01	0.00	0.00	2.04	2.04
BI	4	100	4	-0.08	2.92	0.00	0.01	0.00	0.00	2.83	2.84

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	100	2	-0.08	2.45	0.00	0.01	0.00	0.00	2.37	2.38
BI	6	100	3	-0.08	2.10	0.00	0.01	0.00	0.00	2.02	2.02
BI	6	100	4	-0.08	2.91	0.00	0.01	0.00	0.00	2.83	2.84
BI	8	100	2	-0.26	2.49	0.00	0.01	0.00	0.00	2.22	2.23
BI	8	100	3	-0.26	2.10	0.00	0.01	0.00	0.00	1.84	1.84
BI	8	100	4	-0.26	2.96	0.00	0.01	0.00	0.00	2.69	2.70
BI	10	100	2	-0.24	2.53	0.00	0.01	0.00	0.00	2.29	2.29
BI	10	100	3	-0.24	2.18	0.00	0.01	0.00	0.00	1.93	1.94
BI	10	100	4	-0.24	3.01	0.00	0.01	0.00	0.00	2.77	2.78
PO	2	50	3	-0.03	2.21	0.00	0.01	0.00	0.00	2.18	2.19
PO	2	50	4	-0.03	2.95	0.00	0.01	0.00	0.00	2.92	2.93
PO	4	50	2	-0.06	2.50	0.00	0.01	0.00	0.00	2.44	2.45
PO	4	50	3	-0.06	2.18	0.00	0.01	0.00	0.00	2.12	2.12
PO	4	50	4	-0.06	2.97	0.00	0.01	0.00	0.00	2.91	2.91
PO	6	50	2	-0.06	2.65	0.00	0.01	0.00	0.00	2.58	2.59
PO	6	50	3	-0.06	2.31	0.00	0.01	0.00	0.00	2.25	2.26
PO	6	50	4	-0.06	3.15	0.00	0.01	0.00	0.00	3.09	3.09
PO	8	50	2	-0.20	2.78	0.00	0.01	0.00	0.00	2.58	2.59
PO	8	50	3	-0.20	2.44	0.00	0.01	0.00	0.00	2.24	2.24
PO	8	50	4	-0.20	3.26	0.00	0.01	0.00	0.00	3.05	3.06

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	70	2	-0.06	2.43	0.00	0.01	0.00	0.00	2.37	2.37
SP	8	70	3	-0.06	2.05	0.00	0.01	0.00	0.00	1.98	1.99
SP	8	70	4	-0.06	2.88	0.00	0.01	0.00	0.00	2.81	2.82
SP	10	70	2	-0.18	2.47	0.00	0.01	0.00	0.00	2.29	2.29
SP	10	70	3	-0.18	2.06	0.00	0.01	0.00	0.00	1.88	1.89
SP	10	70	4	-0.18	2.89	0.00	0.01	0.00	0.00	2.71	2.71
SS	12	50	2	-0.15	2.43	0.00	0.01	0.00	0.00	2.27	2.28
SS	12	50	3	-0.15	2.06	0.00	0.01	0.00	0.00	1.91	1.92
SS	12	50	4	-0.15	2.89	0.00	0.01	0.00	0.00	2.74	2.74
SS	20	50	2	-0.09	2.44	0.00	0.01	0.00	0.00	2.36	2.36
SS	20	50	3	-0.09	2.10	0.00	0.01	0.00	0.00	2.02	2.02
SS	20	50	4	-0.09	2.87	0.00	0.01	0.00	0.00	2.78	2.79
DF	8	70	2	-0.01	2.45	0.00	0.01	0.00	0.00	2.44	2.44
DF	8	70	3	-0.01	2.05	0.00	0.01	0.00	0.00	2.04	2.05
DF	8	70	4	-0.01	2.93	0.00	0.01	0.00	0.00	2.92	2.93
DF	10	70	2	-0.14	2.43	0.00	0.01	0.00	0.00	2.28	2.29
DF	10	70	3	-0.14	2.06	0.00	0.01	0.00	0.00	1.91	1.92
DF	10	70	4	-0.14	2.91	0.00	0.01	0.00	0.00	2.77	2.77

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	12	70	2	-0.16	2.44	0.00	0.01	0.00	0.00	2.27	2.28
DF	12	70	3	-0.16	2.04	0.00	0.01	0.00	0.00	1.88	1.88
DF	12	70	4	-0.16	2.89	0.00	0.01	0.00	0.00	2.72	2.73

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-10 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to conventional Thin & Fell forestry. 30 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	100	2	-0.63	2.41	0.00	0.01	0.00	0.00	1.79	1.79
BE	2	100	3	-0.63	2.47	0.00	0.01	0.00	0.00	1.84	1.85
BE	2	100	4	-0.63	3.05	0.00	0.01	0.00	0.00	2.42	2.43
BE	6	100	2	-3.15	2.41	-0.22	0.01	-0.10	-0.14	-0.96	-1.18
BE	6	100	3	-3.15	2.53	-0.22	0.01	-0.10	-0.14	-0.84	-1.06
BE	6	100	4	-3.15	3.17	-0.22	0.01	-0.10	-0.14	-0.20	-0.42
OK	2	120	2	-1.31	2.57	0.00	0.01	0.00	0.00	1.26	1.27
OK	2	120	3	-1.31	2.67	0.00	0.01	0.00	0.00	1.36	1.37
OK	2	120	4	-1.31	3.29	0.00	0.01	0.00	0.00	1.99	1.99
OK	4	120	2	-2.62	2.37	0.00	0.01	0.00	0.00	-0.25	-0.24
OK	4	120	3	-2.62	2.44	0.00	0.01	0.00	0.00	-0.17	-0.17
OK	4	120	4	-2.62	3.06	0.00	0.01	0.00	0.00	0.45	0.45
OK	6	120	2	-4.16	2.25	-0.51	0.02	-0.20	-0.26	-2.42	-2.87
OK	6	120	3	-4.16	2.37	-0.51	0.02	-0.20	-0.26	-2.30	-2.74
OK	6	120	4	-4.16	3.03	-0.51	0.02	-0.20	-0.26	-1.64	-2.08
BI	4	100	2	-3.26	2.48	-0.40	0.02	-0.24	-0.32	-1.18	-1.72
BI	4	100	3	-3.26	2.63	-0.40	0.02	-0.24	-0.32	-1.03	-1.58
BI	4	100	4	-3.26	3.27	-0.40	0.02	-0.24	-0.32	-0.39	-0.93

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	100	2	-5.03	2.28	-0.77	0.04	-0.51	-0.69	-3.53	-4.69
BI	6	100	3	-5.03	2.42	-0.77	0.04	-0.51	-0.69	-3.38	-4.54
BI	6	100	4	-5.03	3.10	-0.77	0.04	-0.51	-0.69	-2.70	-3.86
BI	8	100	2	-6.61	1.89	-1.21	0.06	-0.84	-1.20	-5.93	-7.92
BI	8	100	3	-6.61	2.02	-1.21	0.06	-0.84	-1.20	-5.81	-7.80
BI	8	100	4	-6.61	2.68	-1.21	0.06	-0.84	-1.20	-5.15	-7.14
BI	10	100	2	-8.06	1.63	-1.66	0.07	-1.16	-1.65	-8.09	-10.83
BI	10	100	3	-8.06	1.75	-1.66	0.07	-1.16	-1.65	-7.97	-10.71
BI	10	100	4	-8.06	2.41	-1.66	0.07	-1.16	-1.65	-7.32	-10.06
PO	2	50	2	-1.28	3.21	-0.14	0.01	-0.09	-0.11	1.78	1.60
PO	2	50	3	-1.28	3.48	-0.14	0.01	-0.09	-0.11	2.06	1.87
PO	2	50	4	-1.28	4.21	-0.14	0.01	-0.09	-0.11	2.78	2.59
PO	4	50	2	-2.57	3.01	-0.29	0.02	-0.18	-0.23	0.16	-0.23
PO	4	50	3	-2.57	3.25	-0.29	0.02	-0.18	-0.23	0.39	0.01
PO	4	50	4	-2.57	3.97	-0.29	0.02	-0.18	-0.23	1.11	0.73
PO	6	50	2	-3.98	2.84	-0.55	0.04	-0.37	-0.49	-1.69	-2.52
PO	6	50	3	-3.98	3.09	-0.55	0.04	-0.37	-0.49	-1.44	-2.27
PO	6	50	4	-3.98	3.80	-0.55	0.04	-0.37	-0.49	-0.73	-1.55
PO	8	50	2	-5.25	2.57	-0.86	0.05	-0.62	-0.85	-3.53	-4.95
PO	8	50	3	-5.25	2.81	-0.86	0.05	-0.62	-0.85	-3.30	-4.72

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
PO	8	50	4	-5.25	3.52	-0.86	0.05	-0.62	-0.85	-2.59	-4.01
SP	8	70	2	-3.79	2.30	-0.44	0.02	-0.15	-0.18	-1.93	-2.24
SP	8	70	3	-3.79	2.40	-0.44	0.02	-0.15	-0.18	-1.83	-2.14
SP	8	70	4	-3.79	3.05	-0.44	0.02	-0.15	-0.18	-1.18	-1.49
SP	10	70	2	-4.78	2.07	-0.71	0.04	-0.41	-0.53	-3.43	-4.33
SP	10	70	3	-4.78	2.17	-0.71	0.04	-0.41	-0.53	-3.32	-4.23
SP	10	70	4	-4.78	2.80	-0.71	0.04	-0.41	-0.53	-2.69	-3.60
SS	12	50	2	-5.64	2.00	-0.76	0.05	-0.43	-0.69	-4.39	-5.47
SS	12	50	3	-5.64	2.09	-0.76	0.05	-0.43	-0.69	-4.31	-5.39
SS	12	50	4	-5.64	2.71	-0.76	0.05	-0.43	-0.69	-3.69	-4.77
SS	20	50	2	-10.95	1.16	-1.90	0.10	-1.06	-1.87	-11.70	-14.53
SS	20	50	3	-10.95	1.20	-1.90	0.10	-1.06	-1.87	-11.65	-14.48
SS	20	50	4	-10.95	1.82	-1.90	0.10	-1.06	-1.87	-11.04	-13.86
DF	8	70	2	-4.05	2.11	-0.40	0.02	-0.15	-0.23	-2.33	-2.69
DF	8	70	3	-4.05	2.18	-0.40	0.02	-0.15	-0.23	-2.27	-2.63
DF	8	70	4	-4.05	2.80	-0.40	0.02	-0.15	-0.23	-1.65	-2.00
DF	10	70	2	-5.12	1.95	-0.78	0.04	-0.36	-0.57	-3.94	-4.84
DF	10	70	3	-5.12	2.04	-0.78	0.04	-0.36	-0.57	-3.86	-4.76

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	10	70	4	-5.12	2.68	-0.78	0.04	-0.36	-0.57	-3.22	-4.11
DF	12	70	2	-6.88	1.72	-0.94	0.05	-0.45	-0.72	-6.09	-7.22
DF	12	70	3	-6.88	1.81	-0.94	0.05	-0.45	-0.72	-6.01	-7.14
DF	12	70	4	-6.88	2.45	-0.94	0.05	-0.45	-0.72	-5.37	-6.50

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-11 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to conventional Thin & Fell forestry. 80 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	100	2	-1.76	1.47	-0.27	0.02	-0.22	-0.34	-0.56	-1.10
BE	2	100	3	-1.76	1.61	-0.27	0.02	-0.22	-0.34	-0.42	-0.95
BE	2	100	4	-1.76	2.07	-0.27	0.02	-0.22	-0.34	0.04	-0.50
BE	6	100	2	-5.29	-0.14	-0.92	0.05	-0.72	-1.17	-6.35	-8.20
BE	6	100	3	-5.29	-0.23	-0.92	0.05	-0.72	-1.17	-6.44	-8.29
BE	6	100	4	-5.29	0.14	-0.92	0.05	-0.72	-1.17	-6.07	-7.92
OK	2	120	2	-1.90	1.37	-0.26	0.02	-0.21	-0.32	-0.79	-1.30
OK	2	120	3	-1.90	1.50	-0.26	0.02	-0.21	-0.32	-0.65	-1.16
OK	2	120	4	-1.90	1.95	-0.26	0.02	-0.21	-0.32	-0.21	-0.71
OK	4	120	2	-3.79	0.47	-0.52	0.03	-0.43	-0.63	-3.84	-4.87
OK	4	120	3	-3.79	0.48	-0.52	0.03	-0.43	-0.63	-3.83	-4.86
OK	4	120	4	-3.79	0.87	-0.52	0.03	-0.43	-0.63	-3.44	-4.47
OK	6	120	2	-5.22	-0.28	-0.92	0.05	-0.71	-1.19	-6.42	-8.27
OK	6	120	3	-5.22	-0.39	-0.92	0.05	-0.71	-1.19	-6.53	-8.38
OK	6	120	4	-5.22	-0.04	-0.92	0.05	-0.71	-1.19	-6.18	-8.03
BI	4	100	2	-3.11	0.52	-0.32	0.03	-0.37	-0.54	-2.90	-3.78
BI	4	100	3	-3.11	0.54	-0.32	0.03	-0.37	-0.54	-2.89	-3.77
BI	4	100	4	-3.11	0.91	-0.32	0.03	-0.37	-0.54	-2.51	-3.39

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	100	2	-4.27	-0.01	-0.47	0.04	-0.57	-0.87	-4.75	-6.15
BI	6	100	3	-4.27	-0.09	-0.47	0.04	-0.57	-0.87	-4.83	-6.23
BI	6	100	4	-4.27	0.26	-0.47	0.04	-0.57	-0.87	-4.48	-5.88
BI	8	100	2	-5.39	-0.99	-0.58	0.06	-0.71	-1.40	-6.96	-9.01
BI	8	100	3	-5.39	-1.25	-0.58	0.06	-0.71	-1.40	-7.21	-9.27
BI	8	100	4	-5.39	-0.99	-0.58	0.06	-0.71	-1.40	-6.95	-9.01
BI	10	100	2	-6.45	-1.48	-0.69	0.07	-0.89	-1.81	-8.63	-11.26
BI	10	100	3	-6.45	-1.80	-0.69	0.07	-0.89	-1.81	-8.94	-11.58
BI	10	100	4	-6.45	-1.58	-0.69	0.07	-0.89	-1.81	-8.72	-11.35
PO	2	50	2	-0.62	1.89	-0.25	0.03	-0.27	-0.38	1.02	0.41
PO	2	50	3	-0.62	2.08	-0.25	0.03	-0.27	-0.38	1.21	0.60
PO	2	50	4	-0.62	2.55	-0.25	0.03	-0.27	-0.38	1.68	1.07
PO	4	50	2	-1.25	1.62	-0.49	0.05	-0.53	-0.75	-0.13	-1.36
PO	4	50	3	-1.25	1.76	-0.49	0.05	-0.53	-0.75	0.01	-1.22
PO	4	50	4	-1.25	2.20	-0.49	0.05	-0.53	-0.75	0.46	-0.78
PO	6	50	2	-1.90	1.39	-0.69	0.07	-0.80	-1.25	-1.20	-3.17
PO	6	50	3	-1.90	1.50	-0.69	0.07	-0.80	-1.25	-1.09	-3.05
PO	6	50	4	-1.90	1.93	-0.69	0.07	-0.80	-1.25	-0.66	-2.62
PO	8	50	2	-2.50	1.12	-0.73	0.10	-0.97	-1.97	-2.10	-4.95
PO	8	50	3	-2.50	1.21	-0.73	0.10	-0.97	-1.97	-2.02	-4.87

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
PO	8	50	4	-2.50	1.61	-0.73	0.10	-0.97	-1.97	-1.61	-4.46
SP	8	70	2	-1.27	-0.08	-2.33	0.11	-0.94	-2.77	-3.68	-7.28
SP	8	70	3	-1.27	-0.18	-2.33	0.11	-0.94	-2.77	-3.78	-7.38
SP	8	70	4	-1.27	0.12	-2.33	0.11	-0.94	-2.77	-3.48	-7.08
SP	10	70	2	-1.57	-0.49	-2.76	0.14	-1.12	-3.65	-4.83	-9.46
SP	10	70	3	-1.57	-0.66	-2.76	0.14	-1.12	-3.65	-5.00	-9.63
SP	10	70	4	-1.57	-0.41	-2.76	0.14	-1.12	-3.65	-4.74	-9.38
SS	12	50	2	-2.87	0.55	-0.95	0.12	-0.96	-2.66	-3.27	-6.77
SS	12	50	3	-2.87	0.49	-0.95	0.12	-0.96	-2.66	-3.33	-6.83
SS	12	50	4	-2.87	0.83	-0.95	0.12	-0.96	-2.66	-2.99	-6.49
SS	20	50	2	-5.35	-0.46	-1.56	0.22	-1.61	-5.09	-7.37	-13.85
SS	20	50	3	-5.35	-0.67	-1.56	0.22	-1.61	-5.09	-7.58	-14.06
SS	20	50	4	-5.35	-0.41	-1.56	0.22	-1.61	-5.09	-7.32	-13.81
DF	8	70	2	-1.04	-0.18	-2.17	0.11	-0.78	-2.69	-3.39	-6.76
DF	8	70	3	-1.04	-0.31	-2.17	0.11	-0.78	-2.69	-3.51	-6.88
DF	8	70	4	-1.04	-0.02	-2.17	0.11	-0.78	-2.69	-3.22	-6.59
DF	10	70	2	-1.30	-0.60	-2.71	0.13	-0.92	-3.46	-4.61	-8.85
DF	10	70	3	-1.30	-0.78	-2.71	0.13	-0.92	-3.46	-4.80	-9.04

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	10	70	4	-1.30	-0.53	-2.71	0.13	-0.92	-3.46	-4.55	-8.79
DF	12	70	2	-1.51	-0.99	-3.01	0.15	-1.07	-4.19	-5.51	-10.62
DF	12	70	3	-1.51	-1.24	-3.01	0.15	-1.07	-4.19	-5.76	-10.87
DF	12	70	4	-1.51	-1.04	-3.01	0.15	-1.07	-4.19	-5.56	-10.67

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-12 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to conventional Thin & Fell forestry. 200 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	100	2	-0.38	0.63	-0.47	0.04	-0.44	-1.00	-0.21	-1.62
BE	2	100	3	-0.38	0.73	-0.47	0.04	-0.44	-1.00	-0.11	-1.52
BE	2	100	4	-0.38	1.04	-0.47	0.04	-0.44	-1.00	0.20	-1.21
BE	6	100	2	-1.09	-0.62	-1.41	0.10	-1.22	-3.21	-3.12	-7.45
BE	6	100	3	-1.09	-0.81	-1.41	0.10	-1.22	-3.21	-3.31	-7.64
BE	6	100	4	-1.09	-0.64	-1.41	0.10	-1.22	-3.21	-3.15	-7.48
OK	2	120	2	-0.78	0.66	-0.14	0.03	-0.32	-0.68	-0.26	-1.22
OK	2	120	3	-0.78	0.75	-0.14	0.03	-0.32	-0.68	-0.17	-1.14
OK	2	120	4	-0.78	1.04	-0.14	0.03	-0.32	-0.68	0.12	-0.84
OK	4	120	2	-1.57	0.03	-0.28	0.05	-0.63	-1.36	-1.82	-3.75
OK	4	120	3	-1.57	-0.03	-0.28	0.05	-0.63	-1.36	-1.88	-3.82
OK	4	120	4	-1.57	0.17	-0.28	0.05	-0.63	-1.36	-1.68	-3.62
OK	6	120	2	-2.16	-0.45	-0.48	0.07	-0.90	-2.18	-3.09	-6.09
OK	6	120	3	-2.16	-0.65	-0.48	0.07	-0.90	-2.18	-3.29	-6.29
OK	6	120	4	-2.16	-0.52	-0.48	0.07	-0.90	-2.18	-3.15	-6.16
BI	4	100	2	-0.58	0.04	-0.54	0.05	-0.65	-1.31	-1.09	-3.01
BI	4	100	3	-0.58	0.00	-0.54	0.05	-0.65	-1.31	-1.13	-3.04
BI	4	100	4	-0.58	0.20	-0.54	0.05	-0.65	-1.31	-0.93	-2.84
BI	6	100	2	-0.80	-0.33	-0.78	0.07	-0.88	-1.99	-1.91	-4.71

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	100	3	-0.80	-0.47	-0.78	0.07	-0.88	-1.99	-2.04	-4.84
BI	6	100	4	-0.80	-0.31	-0.78	0.07	-0.88	-1.99	-1.88	-4.68
BI	8	100	2	-1.01	-0.97	-1.00	0.09	-1.05	-2.85	-2.97	-6.78
BI	8	100	3	-1.01	-1.26	-1.00	0.09	-1.05	-2.85	-3.27	-7.08
BI	8	100	4	-1.01	-1.23	-1.00	0.09	-1.05	-2.85	-3.23	-7.04
BI	10	100	2	-1.20	-1.31	-1.20	0.11	-1.28	-3.53	-3.71	-8.40
BI	10	100	3	-1.20	-1.68	-1.20	0.11	-1.28	-3.53	-4.08	-8.77
BI	10	100	4	-1.20	-1.70	-1.20	0.11	-1.28	-3.53	-4.10	-8.80
PO	2	50	3	-0.22	1.20	-0.19	0.04	-0.37	-0.54	0.80	-0.07
PO	2	50	4	-0.22	1.54	-0.19	0.04	-0.37	-0.54	1.13	0.27
PO	4	50	2	-0.43	0.77	-0.38	0.07	-0.75	-1.07	-0.04	-1.79
PO	4	50	3	-0.43	0.90	-0.38	0.07	-0.75	-1.07	0.08	-1.66
PO	4	50	4	-0.43	1.20	-0.38	0.07	-0.75	-1.07	0.39	-1.36
PO	6	50	2	-0.62	0.57	-0.55	0.10	-1.05	-1.70	-0.59	-3.25
PO	6	50	3	-0.62	0.66	-0.55	0.10	-1.05	-1.70	-0.51	-3.16
PO	6	50	4	-0.62	0.93	-0.55	0.10	-1.05	-1.70	-0.23	-2.89
PO	8	50	2	-0.80	0.37	-0.75	0.12	-1.19	-2.65	-1.18	-4.89
PO	8	50	3	-0.80	0.41	-0.75	0.12	-1.19	-2.65	-1.14	-4.85
PO	8	50	4	-0.80	0.65	-0.75	0.12	-1.19	-2.65	-0.90	-4.61
SP	8	70	2	-1.86	0.03	-0.42	0.10	-0.92	-2.52	-2.26	-5.60
SP	8	70	3	-1.86	-0.04	-0.42	0.10	-0.92	-2.52	-2.32	-5.66

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	70	4	-1.86	0.14	-0.42	0.10	-0.92	-2.52	-2.14	-5.48
SP	10	70	2	-2.26	-0.27	-0.61	0.13	-1.11	-3.42	-3.14	-7.54
SP	10	70	3	-2.26	-0.40	-0.61	0.13	-1.11	-3.42	-3.28	-7.68
SP	10	70	4	-2.26	-0.28	-0.61	0.13	-1.11	-3.42	-3.15	-7.55
SS	12	50	2	-1.16	-0.07	-1.17	0.17	-1.27	-3.85	-2.40	-7.34
SS	12	50	3	-1.16	-0.16	-1.17	0.17	-1.27	-3.85	-2.48	-7.43
SS	12	50	4	-1.16	0.02	-1.17	0.17	-1.27	-3.85	-2.31	-7.25
SS	20	50	2	-1.90	-0.91	-2.02	0.29	-1.94	-7.02	-4.82	-13.50
SS	20	50	3	-1.90	-1.19	-2.02	0.29	-1.94	-7.02	-5.10	-13.78
SS	20	50	4	-1.90	-1.16	-2.02	0.29	-1.94	-7.02	-5.08	-13.75
DF	8	70	2	-1.78	-0.07	-0.38	0.10	-0.77	-2.45	-2.23	-5.35
DF	8	70	3	-1.78	-0.16	-0.38	0.10	-0.77	-2.45	-2.32	-5.44
DF	8	70	4	-1.78	0.00	-0.38	0.10	-0.77	-2.45	-2.16	-5.28
DF	10	70	2	-2.12	-0.36	-0.55	0.13	-0.93	-3.21	-3.04	-7.06
DF	10	70	3	-2.12	-0.52	-0.55	0.13	-0.93	-3.21	-3.20	-7.21
DF	10	70	4	-2.12	-0.42	-0.55	0.13	-0.93	-3.21	-3.09	-7.11
DF	12	70	2	-2.51	-0.65	-0.62	0.15	-1.08	-3.92	-3.78	-8.63
DF	12	70	3	-2.51	-0.87	-0.62	0.15	-1.08	-3.92	-4.00	-8.85
DF	12	70	4	-2.51	-0.83	-0.62	0.15	-1.08	-3.92	-3.96	-8.81

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-13 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Short Rotation Forestry (SRF). 5 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	25	2	-0.01	2.45	0.00	0.01	0.00	0.00	2.44	2.45
BE	2	25	3	-0.01	2.09	0.00	0.01	0.00	0.00	2.08	2.09
BE	2	25	4	-0.01	2.87	0.00	0.01	0.00	0.00	2.87	2.87
BE	6	25	2	-0.02	2.45	0.00	0.01	0.00	0.00	2.43	2.43
BE	6	25	3	-0.02	2.05	0.00	0.01	0.00	0.00	2.03	2.03
BE	6	25	4	-0.02	2.87	0.00	0.01	0.00	0.00	2.85	2.86
OK	2	25	2	-0.02	2.43	0.00	0.01	0.00	0.00	2.42	2.42
OK	2	25	3	-0.02	2.07	0.00	0.01	0.00	0.00	2.05	2.06
OK	2	25	4	-0.02	2.88	0.00	0.01	0.00	0.00	2.86	2.87
OK	4	25	2	-0.04	2.45	0.00	0.01	0.00	0.00	2.41	2.42
OK	4	25	3	-0.04	2.13	0.00	0.01	0.00	0.00	2.09	2.09
OK	4	25	4	-0.04	2.91	0.00	0.01	0.00	0.00	2.87	2.88
OK	6	25	2	-0.13	2.43	0.00	0.01	0.00	0.00	2.30	2.31
OK	6	25	3	-0.13	2.06	0.00	0.01	0.00	0.00	1.93	1.94
OK	6	25	4	-0.13	2.90	0.00	0.01	0.00	0.00	2.77	2.78
BI	4	25	2	-0.08	2.43	0.00	0.01	0.00	0.00	2.35	2.35
BI	4	25	3	-0.08	2.12	0.00	0.01	0.00	0.00	2.04	2.04
BI	4	25	4	-0.08	2.92	0.00	0.01	0.00	0.00	2.83	2.84
BI	6	25	2	-0.08	2.45	0.00	0.01	0.00	0.00	2.37	2.38

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	25	3	-0.08	2.10	0.00	0.01	0.00	0.00	2.02	2.02
BI	6	25	4	-0.08	2.91	0.00	0.01	0.00	0.00	2.83	2.84
BI	8	25	2	-0.26	2.49	0.00	0.01	0.00	0.00	2.22	2.23
BI	8	25	3	-0.26	2.10	0.00	0.01	0.00	0.00	1.84	1.84
BI	8	25	4	-0.26	2.96	0.00	0.01	0.00	0.00	2.69	2.70
BI	10	25	2	-0.24	2.53	0.00	0.01	0.00	0.00	2.29	2.29
BI	10	25	3	-0.24	2.18	0.00	0.01	0.00	0.00	1.93	1.94
BI	10	25	4	-0.24	3.01	0.00	0.01	0.00	0.00	2.77	2.78
PO	2	25	3	-0.03	2.21	0.00	0.01	0.00	0.00	2.18	2.19
PO	2	25	4	-0.03	2.95	0.00	0.01	0.00	0.00	2.92	2.93
PO	4	25	2	-0.06	2.50	0.00	0.01	0.00	0.00	2.44	2.45
PO	4	25	3	-0.06	2.18	0.00	0.01	0.00	0.00	2.12	2.12
PO	4	25	4	-0.06	2.97	0.00	0.01	0.00	0.00	2.91	2.91
PO	6	25	2	-0.06	2.65	0.00	0.01	0.00	0.00	2.58	2.59
PO	6	25	3	-0.06	2.31	0.00	0.01	0.00	0.00	2.25	2.26
PO	6	25	4	-0.06	3.15	0.00	0.01	0.00	0.00	3.09	3.09
PO	8	25	2	-0.20	2.78	0.00	0.01	0.00	0.00	2.58	2.59
PO	8	25	3	-0.20	2.44	0.00	0.01	0.00	0.00	2.24	2.24
PO	8	25	4	-0.20	3.26	0.00	0.01	0.00	0.00	3.05	3.06
SP	8	25	2	-0.06	2.43	0.00	0.01	0.00	0.00	2.37	2.37
SP	8	25	3	-0.06	2.05	0.00	0.01	0.00	0.00	1.98	1.99

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	25	4	-0.06	2.88	0.00	0.01	0.00	0.00	2.81	2.82
SP	10	25	2	-0.18	2.47	0.00	0.01	0.00	0.00	2.29	2.29
SP	10	25	3	-0.18	2.06	0.00	0.01	0.00	0.00	1.88	1.89
SP	10	25	4	-0.18	2.89	0.00	0.01	0.00	0.00	2.71	2.71
SS	12	25	2	-0.15	2.43	0.00	0.01	0.00	0.00	2.27	2.28
SS	12	25	3	-0.15	2.06	0.00	0.01	0.00	0.00	1.91	1.92
SS	12	25	4	-0.15	2.89	0.00	0.01	0.00	0.00	2.74	2.74
SS	20	25	2	-0.09	2.44	0.00	0.01	0.00	0.00	2.36	2.36
SS	20	25	3	-0.09	2.10	0.00	0.01	0.00	0.00	2.02	2.02
SS	20	25	4	-0.09	2.87	0.00	0.01	0.00	0.00	2.78	2.79
DF	8	25	2	-0.01	2.45	0.00	0.01	0.00	0.00	2.44	2.44
DF	8	25	3	-0.01	2.05	0.00	0.01	0.00	0.00	2.04	2.05
DF	8	25	4	-0.01	2.93	0.00	0.01	0.00	0.00	2.92	2.93
DF	10	25	2	-0.14	2.43	0.00	0.01	0.00	0.00	2.28	2.29
DF	10	25	3	-0.14	2.06	0.00	0.01	0.00	0.00	1.91	1.92
DF	10	25	4	-0.14	2.91	0.00	0.01	0.00	0.00	2.77	2.77
DF	12	25	2	-0.16	2.44	0.00	0.01	0.00	0.00	2.27	2.28
DF	12	25	3	-0.16	2.04	0.00	0.01	0.00	0.00	1.88	1.88
DF	12	25	4	-0.16	2.89	0.00	0.01	0.00	0.00	2.72	2.73

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-14 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Short Rotation Forestry (SRF). 30 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	25	2	-0.07	1.51	0.00	0.02	-0.18	0.00	1.44	1.28
BE	2	25	3	-0.07	1.48	0.00	0.02	-0.18	0.00	1.42	1.26
BE	2	25	4	-0.07	1.99	0.00	0.02	-0.18	0.00	1.92	1.76
BE	6	25	2	-0.36	1.76	0.00	0.04	-0.96	0.00	1.40	0.47
BE	6	25	3	-0.36	1.81	0.00	0.04	-0.96	0.00	1.45	0.52
BE	6	25	4	-0.36	2.38	0.00	0.04	-0.96	0.00	2.02	1.10
OK	2	25	2	-0.14	1.70	0.00	0.02	-0.37	0.00	1.56	1.22
OK	2	25	3	-0.14	1.71	0.00	0.02	-0.37	0.00	1.57	1.23
OK	2	25	4	-0.14	2.28	0.00	0.02	-0.37	0.00	2.14	1.79
OK	4	25	2	-0.28	1.62	0.00	0.03	-0.74	0.00	1.34	0.63
OK	4	25	3	-0.28	1.62	0.00	0.03	-0.74	0.00	1.34	0.63
OK	4	25	4	-0.28	2.16	0.00	0.03	-0.74	0.00	1.88	1.18
OK	6	25	2	-0.67	1.71	0.00	0.06	-1.71	0.00	1.03	-0.63
OK	6	25	3	-0.67	1.76	0.00	0.06	-1.71	0.00	1.08	-0.58
OK	6	25	4	-0.67	2.36	0.00	0.06	-1.71	0.00	1.69	0.03
BI	4	25	2	-0.53	1.82	0.00	0.05	-1.28	0.00	1.29	0.06
BI	4	25	3	-0.53	1.89	0.00	0.05	-1.28	0.00	1.37	0.14
BI	4	25	4	-0.53	2.48	0.00	0.05	-1.28	0.00	1.96	0.73
BI	6	25	2	-1.00	1.73	0.00	0.08	-2.42	0.00	0.73	-1.61

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	25	3	-1.00	1.81	0.00	0.08	-2.42	0.00	0.82	-1.53
BI	6	25	4	-1.00	2.42	0.00	0.08	-2.42	0.00	1.42	-0.92
BI	8	25	2	-1.52	1.38	0.00	0.11	-3.55	0.00	-0.14	-3.59
BI	8	25	3	-1.52	1.43	0.00	0.11	-3.55	0.00	-0.09	-3.54
BI	8	25	4	-1.52	2.03	0.00	0.11	-3.55	0.00	0.51	-2.94
BI	10	25	2	-2.01	1.13	0.00	0.13	-4.66	0.00	-0.88	-5.40
BI	10	25	3	-2.01	1.16	0.00	0.13	-4.66	0.00	-0.84	-5.37
BI	10	25	4	-2.01	1.74	0.00	0.13	-4.66	0.00	-0.26	-4.79
PO	2	25	2	-0.24	2.34	0.00	0.03	-0.47	0.00	2.10	1.67
PO	2	25	3	-0.24	2.53	0.00	0.03	-0.47	0.00	2.29	1.86
PO	2	25	4	-0.24	3.19	0.00	0.03	-0.47	0.00	2.95	2.51
PO	4	25	2	-0.48	2.24	0.00	0.05	-0.93	0.00	1.76	0.87
PO	4	25	3	-0.48	2.40	0.00	0.05	-0.93	0.00	1.92	1.03
PO	4	25	4	-0.48	3.05	0.00	0.05	-0.93	0.00	2.57	1.68
PO	6	25	2	-0.91	2.16	0.00	0.07	-1.77	0.00	1.25	-0.44
PO	6	25	3	-0.91	2.34	0.00	0.07	-1.77	0.00	1.43	-0.27
PO	6	25	4	-0.91	3.00	0.00	0.07	-1.77	0.00	2.09	0.39
PO	8	25	2	-1.38	1.93	0.00	0.10	-2.60	0.00	0.55	-1.95
PO	8	25	3	-1.38	2.09	0.00	0.10	-2.60	0.00	0.71	-1.79
PO	8	25	4	-1.38	2.73	0.00	0.10	-2.60	0.00	1.35	-1.15

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	25	2	-0.53	1.67	0.00	0.06	-1.36	0.00	1.14	-0.16
SP	8	25	3	-0.53	1.69	0.00	0.06	-1.36	0.00	1.17	-0.14
SP	8	25	4	-0.53	2.28	0.00	0.06	-1.36	0.00	1.76	0.45
SP	10	25	2	-0.84	1.53	0.00	0.08	-2.11	0.00	0.69	-1.34
SP	10	25	3	-0.84	1.56	0.00	0.08	-2.11	0.00	0.72	-1.31
SP	10	25	4	-0.84	2.14	0.00	0.08	-2.11	0.00	1.30	-0.73
SS	12	25	2	-1.16	1.44	0.00	0.09	-2.03	0.00	0.28	-1.66
SS	12	25	3	-1.16	1.46	0.00	0.09	-2.03	0.00	0.30	-1.64
SS	12	25	4	-1.16	2.02	0.00	0.09	-2.03	0.00	0.86	-1.08
SS	20	25	2	-2.69	0.76	0.00	0.19	-4.69	0.00	-1.93	-6.44
SS	20	25	3	-2.69	0.74	0.00	0.19	-4.69	0.00	-1.95	-6.46
SS	20	25	4	-2.69	1.29	0.00	0.19	-4.69	0.00	-1.40	-5.90
DF	8	25	2	-0.45	1.51	0.00	0.06	-1.31	0.00	1.06	-0.19
DF	8	25	3	-0.45	1.50	0.00	0.06	-1.31	0.00	1.05	-0.20
DF	8	25	4	-0.45	2.07	0.00	0.06	-1.31	0.00	1.62	0.37
DF	10	25	2	-0.75	1.48	0.00	0.08	-2.08	0.00	0.72	-1.28
DF	10	25	3	-0.75	1.50	0.00	0.08	-2.08	0.00	0.75	-1.26
DF	10	25	4	-0.75	2.08	0.00	0.08	-2.08	0.00	1.33	-0.67
DF	12	25	2	-1.04	1.31	0.00	0.11	-2.89	0.00	0.27	-2.52
DF	12	25	3	-1.04	1.33	0.00	0.11	-2.89	0.00	0.28	-2.50

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	12	25	4	-1.04	1.90	0.00	0.11	-2.89	0.00	0.86	-1.93

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-15 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Short Rotation Forestry (SRF). 80 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	25	2	-0.04	0.96	0.00	0.02	-0.20	0.00	0.92	0.74
BE	2	25	3	-0.04	0.95	0.00	0.02	-0.20	0.00	0.91	0.73
BE	2	25	4	-0.04	1.31	0.00	0.02	-0.20	0.00	1.26	1.08
BE	6	25	2	-0.23	1.11	0.00	0.04	-1.08	0.00	0.89	-0.15
BE	6	25	3	-0.23	1.15	0.00	0.04	-1.08	0.00	0.93	-0.11
BE	6	25	4	-0.23	1.54	0.00	0.04	-1.08	0.00	1.31	0.27
OK	2	25	2	-0.09	1.09	0.00	0.03	-0.42	0.00	1.00	0.61
OK	2	25	3	-0.09	1.11	0.00	0.03	-0.42	0.00	1.02	0.63
OK	2	25	4	-0.09	1.49	0.00	0.03	-0.42	0.00	1.40	1.01
OK	4	25	2	-0.17	1.02	0.00	0.04	-0.83	0.00	0.84	0.05
OK	4	25	3	-0.17	1.03	0.00	0.04	-0.83	0.00	0.85	0.06
OK	4	25	4	-0.17	1.40	0.00	0.04	-0.83	0.00	1.22	0.43
OK	6	25	2	-0.42	1.06	0.00	0.06	-1.93	0.00	0.64	-1.23
OK	6	25	3	-0.42	1.10	0.00	0.06	-1.93	0.00	0.68	-1.19
OK	6	25	4	-0.42	1.48	0.00	0.06	-1.93	0.00	1.07	-0.80
BI	4	25	2	-0.33	1.15	0.00	0.05	-1.44	0.00	0.82	-0.56
BI	4	25	3	-0.33	1.21	0.00	0.05	-1.44	0.00	0.88	-0.51
BI	4	25	4	-0.33	1.59	0.00	0.05	-1.44	0.00	1.27	-0.12
BI	6	25	2	-0.62	1.06	0.00	0.09	-2.72	0.00	0.44	-2.20
BI	6	25	3	-0.62	1.12	0.00	0.09	-2.72	0.00	0.50	-2.14

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	25	4	-0.62	1.51	0.00	0.09	-2.72	0.00	0.89	-1.75
BI	8	25	2	-0.94	0.77	0.00	0.12	-4.00	0.00	-0.17	-4.05
BI	8	25	3	-0.94	0.77	0.00	0.12	-4.00	0.00	-0.17	-4.05
BI	8	25	4	-0.94	1.15	0.00	0.12	-4.00	0.00	0.21	-3.67
BI	10	25	2	-1.25	0.56	0.00	0.15	-5.24	0.00	-0.69	-5.78
BI	10	25	3	-1.25	0.54	0.00	0.15	-5.24	0.00	-0.71	-5.80
BI	10	25	4	-1.25	0.90	0.00	0.15	-5.24	0.00	-0.35	-5.44
PO	2	25	2	-0.15	1.57	0.00	0.03	-0.53	0.00	1.42	0.93
PO	2	25	3	-0.15	1.72	0.00	0.03	-0.53	0.00	1.57	1.08
PO	2	25	4	-0.15	2.16	0.00	0.03	-0.53	0.00	2.01	1.52
PO	4	25	2	-0.30	1.48	0.00	0.05	-1.05	0.00	1.18	0.18
PO	4	25	3	-0.30	1.61	0.00	0.05	-1.05	0.00	1.31	0.31
PO	4	25	4	-0.30	2.05	0.00	0.05	-1.05	0.00	1.75	0.75
PO	6	25	2	-0.57	1.39	0.00	0.08	-1.99	0.00	0.82	-1.09
PO	6	25	3	-0.57	1.52	0.00	0.08	-1.99	0.00	0.95	-0.96
PO	6	25	4	-0.57	1.96	0.00	0.08	-1.99	0.00	1.39	-0.52
PO	8	25	2	-0.86	1.18	0.00	0.11	-2.92	0.00	0.32	-2.49
PO	8	25	3	-0.86	1.28	0.00	0.11	-2.92	0.00	0.42	-2.39
PO	8	25	4	-0.86	1.70	0.00	0.11	-2.92	0.00	0.84	-1.97
SP	8	25	2	-0.33	1.03	0.00	0.06	-1.53	0.00	0.71	-0.76
SP	8	25	3	-0.33	1.06	0.00	0.06	-1.53	0.00	0.73	-0.73

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	25	4	-0.33	1.44	0.00	0.06	-1.53	0.00	1.11	-0.36
SP	10	25	2	-0.52	0.91	0.00	0.09	-2.37	0.00	0.39	-1.89
SP	10	25	3	-0.52	0.93	0.00	0.09	-2.37	0.00	0.41	-1.88
SP	10	25	4	-0.52	1.30	0.00	0.09	-2.37	0.00	0.78	-1.51
SS	12	25	2	-0.72	0.83	0.00	0.10	-2.28	0.00	0.11	-2.08
SS	12	25	3	-0.72	0.82	0.00	0.10	-2.28	0.00	0.10	-2.08
SS	12	25	4	-0.72	1.18	0.00	0.10	-2.28	0.00	0.46	-1.72
SS	20	25	2	-1.68	0.22	0.00	0.21	-5.28	0.00	-1.45	-6.52
SS	20	25	3	-1.68	0.14	0.00	0.21	-5.28	0.00	-1.54	-6.61
SS	20	25	4	-1.68	0.46	0.00	0.21	-5.28	0.00	-1.22	-6.29
DF	8	25	2	-0.28	0.92	0.00	0.06	-1.47	0.00	0.64	-0.77
DF	8	25	3	-0.28	0.93	0.00	0.06	-1.47	0.00	0.65	-0.77
DF	8	25	4	-0.28	1.29	0.00	0.06	-1.47	0.00	1.01	-0.40
DF	10	25	2	-0.46	0.88	0.00	0.09	-2.34	0.00	0.42	-1.84
DF	10	25	3	-0.46	0.89	0.00	0.09	-2.34	0.00	0.43	-1.83
DF	10	25	4	-0.46	1.26	0.00	0.09	-2.34	0.00	0.80	-1.46
DF	12	25	2	-0.64	0.74	0.00	0.12	-3.25	0.00	0.09	-3.04
DF	12	25	3	-0.64	0.73	0.00	0.12	-3.25	0.00	0.08	-3.05
DF	12	25	4	-0.64	1.09	0.00	0.12	-3.25	0.00	0.44	-2.69

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

Table A2-16 Calculated change in carbon stocks and GHG emissions associated with change in land us from grassland to Short Rotation Forestry (SRF). 200 year time horizon

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BE	2	25	2	-0.02	0.57	0.00	0.02	-0.22	0.00	0.55	0.35
BE	2	25	3	-0.02	0.60	0.00	0.02	-0.22	0.00	0.58	0.38
BE	2	25	4	-0.02	0.85	0.00	0.02	-0.22	0.00	0.83	0.63
BE	6	25	2	-0.12	0.69	0.00	0.04	-1.16	0.00	0.57	-0.55
BE	6	25	3	-0.12	0.75	0.00	0.04	-1.16	0.00	0.63	-0.48
BE	6	25	4	-0.12	1.02	0.00	0.04	-1.16	0.00	0.90	-0.21
OK	2	25	2	-0.05	0.66	0.00	0.03	-0.44	0.00	0.62	0.20
OK	2	25	3	-0.05	0.72	0.00	0.03	-0.44	0.00	0.67	0.26
OK	2	25	4	-0.05	0.98	0.00	0.03	-0.44	0.00	0.94	0.52
OK	4	25	2	-0.09	0.61	0.00	0.04	-0.89	0.00	0.52	-0.33
OK	4	25	3	-0.09	0.66	0.00	0.04	-0.89	0.00	0.56	-0.28
OK	4	25	4	-0.09	0.92	0.00	0.04	-0.89	0.00	0.82	-0.02
OK	6	25	2	-0.22	0.65	0.00	0.07	-2.06	0.00	0.43	-1.57
OK	6	25	3	-0.22	0.71	0.00	0.07	-2.06	0.00	0.49	-1.50
OK	6	25	4	-0.22	0.98	0.00	0.07	-2.06	0.00	0.76	-1.23
BI	4	25	2	-0.17	0.71	0.00	0.06	-1.53	0.00	0.54	-0.94
BI	4	25	3	-0.17	0.79	0.00	0.06	-1.53	0.00	0.62	-0.86
BI	4	25	4	-0.17	1.07	0.00	0.06	-1.53	0.00	0.90	-0.58

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
BI	6	25	2	-0.33	0.65	0.00	0.09	-2.90	0.00	0.32	-2.49
BI	6	25	3	-0.33	0.72	0.00	0.09	-2.90	0.00	0.39	-2.42
BI	6	25	4	-0.33	1.01	0.00	0.09	-2.90	0.00	0.68	-2.14
BI	8	25	2	-0.50	0.45	0.00	0.13	-4.27	0.00	-0.05	-4.19
BI	8	25	3	-0.50	0.47	0.00	0.13	-4.27	0.00	-0.03	-4.17
BI	8	25	4	-0.50	0.73	0.00	0.13	-4.27	0.00	0.23	-3.91
BI	10	25	2	-0.66	0.29	0.00	0.16	-5.59	0.00	-0.37	-5.79
BI	10	25	3	-0.66	0.29	0.00	0.16	-5.59	0.00	-0.37	-5.80
BI	10	25	4	-0.66	0.54	0.00	0.16	-5.59	0.00	-0.13	-5.55
PO	2	25	3	-0.08	1.17	0.00	0.04	-0.56	0.00	1.09	0.57
PO	2	25	4	-0.08	1.50	0.00	0.04	-0.56	0.00	1.42	0.89
PO	4	25	2	-0.16	0.95	0.00	0.05	-1.12	0.00	0.79	-0.28
PO	4	25	3	-0.16	1.09	0.00	0.05	-1.12	0.00	0.94	-0.13
PO	4	25	4	-0.16	1.41	0.00	0.05	-1.12	0.00	1.25	0.19
PO	6	25	2	-0.30	0.88	0.00	0.09	-2.12	0.00	0.58	-1.46
PO	6	25	3	-0.30	1.01	0.00	0.09	-2.12	0.00	0.71	-1.32
PO	6	25	4	-0.30	1.33	0.00	0.09	-2.12	0.00	1.03	-1.00
PO	8	25	2	-0.45	0.73	0.00	0.12	-3.12	0.00	0.28	-2.72
PO	8	25	3	-0.45	0.83	0.00	0.12	-3.12	0.00	0.38	-2.62
PO	8	25	4	-0.45	1.14	0.00	0.12	-3.12	0.00	0.68	-2.32

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
SP	8	25	2	-0.18	0.63	0.00	0.07	-1.63	0.00	0.45	-1.11
SP	8	25	3	-0.18	0.68	0.00	0.07	-1.63	0.00	0.50	-1.06
SP	8	25	4	-0.18	0.95	0.00	0.07	-1.63	0.00	0.77	-0.80
SP	10	25	2	-0.29	0.55	0.00	0.09	-2.53	0.00	0.26	-2.18
SP	10	25	3	-0.29	0.59	0.00	0.09	-2.53	0.00	0.30	-2.14
SP	10	25	4	-0.29	0.84	0.00	0.09	-2.53	0.00	0.55	-1.88
SS	12	25	2	-0.40	0.49	0.00	0.11	-2.44	0.00	0.09	-2.24
SS	12	25	3	-0.40	0.51	0.00	0.11	-2.44	0.00	0.11	-2.22
SS	12	25	4	-0.40	0.75	0.00	0.11	-2.44	0.00	0.35	-1.98
SS	20	25	2	-0.95	0.08	0.00	0.23	-5.63	0.00	-0.86	-6.27
SS	20	25	3	-0.95	0.01	0.00	0.23	-5.63	0.00	-0.93	-6.34
SS	20	25	4	-0.95	0.21	0.00	0.23	-5.63	0.00	-0.73	-6.14
DF	8	25	2	-0.17	0.56	0.00	0.07	-1.57	0.00	0.39	-1.12
DF	8	25	3	-0.17	0.59	0.00	0.07	-1.57	0.00	0.42	-1.09
DF	8	25	4	-0.17	0.84	0.00	0.07	-1.57	0.00	0.67	-0.84
DF	10	25	2	-0.27	0.53	0.00	0.10	-2.50	0.00	0.26	-2.14
DF	10	25	3	-0.27	0.56	0.00	0.10	-2.50	0.00	0.29	-2.11
DF	10	25	4	-0.27	0.81	0.00	0.10	-2.50	0.00	0.54	-1.86

Species *(see key)*	Yield class	Rotation	Soil class	Change in carbon stock in trees + deadwood and litter over time horizon	Change in carbon stock in soil over time horizon	Change in carbon stock in harvested wood products over time horizon	GHG emissions from forest operations	GHG emissions mitigated in energy sector over time horizon	GHG emissions mitigated in construction sector over time horizon	Total change in carbon stock over time horizon	Total change in carbon stock + total mitigated GHG emissions over time horizon
		Years		tCO_2/ha/yr	tCO_2/ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2-eq./ha/yr	tCO_2/ha/yr	tCO_2-eq./ha/yr
DF	12	25	2	-0.38	0.44	0.00	0.13	-3.47	0.00	0.06	-3.29
DF	12	25	3	-0.38	0.45	0.00	0.13	-3.47	0.00	0.07	-3.27
DF	12	25	4	-0.38	0.69	0.00	0.13	-3.47	0.00	0.31	-3.03

***Key**: BE = Beech; BI =Silver birch and birch; DF =Douglas fir; OK =Oak; PO = Aspen and black poplar; SP = Scots pine; SS = Sitka spruce*

A3.References for Annex-4

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