Forest Research

Review of literature on biogenic carbon and life cycle assessment of forest bioenergy

Final Task 1 report, DG ENER project, ‘Carbon impacts of biomass consumed in the EU’

May 2014

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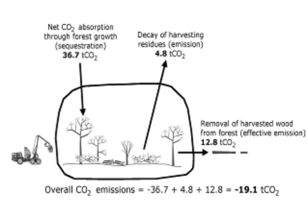

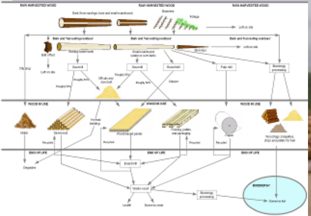

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Forest Research

Biogenic Carbon
and Forest Bioenergy

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Final Task 1 report, DG ENER project,'Carbon impacts of biomass consumed in the EU'

Robert Matthews[1], Laura Sokka[2], Sampo Soimakallio[2], Nigel Mortimer[3], Jeremy Rix[3], Mart-Jan Schelhaas[4], Tom Jenkins[1], Geoff Hogan[1], Ewan Mackie[1], Allison Morris[1] and Tim Randle[1] (2014*) Review of literature on biogenic carbon and life cycle assessment of forest bioenergy.* Final Task 1 report, EU DG ENER project ENER/C1/427, 'Carbon impacts of biomass consumed in the EU'. Forest Research: Farnham.

[1] Forest Research, Alice Holt Lodge, Farnham, UK
[2] VTT Technical Research Centre of Finland, Espoo, Finland
[3] North Energy Associates Limited. Sheffield, UK
[4] Alterra, Wageningen UR, Netherlands

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Executive Summary

1. Introduction

This report has been prepared towards fulfilment of a European Commission project, ENER/C1/427-2012 on 'Carbon impacts of biomass consumed in the EU'. The principal objective of this project, as stated originally in the project tender specification, is to deliver a *qualitative and quantitative* assessment of the direct and indirect greenhouse gas (GHG) emissions associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU under a number of scenarios focussing on the period to 2030, in order to provide objective information on which to base further development of policy on the role of biomass as a source of energy with low associated GHG emissions.

This report addresses Task 1 of the project, which is concerned with a review of scientific literature on the contributions of 'biogenic carbon' to GHG emissions due to the production and use of bioenergy, and how these contributions may be appropriately included in methodologies for calculating GHG emissions. The review is concerned primarily with woody biomass harvested from forests for use as bioenergy, referred to in this report as 'forest bioenergy', because this reflects an important current focus of debate in the scientific literature. The report effectively constitutes the qualitative assessment required as part of the principal objective of this project, and is divided into five sections:

1 Introduction
2 Forests, forest management and wood utilisation
3 Forest biogenic carbon and its management
4 Life cycle assessment: essential concepts and key issues
5 Assessment of literature on GHG emissions of GHG bioenergy.

Detailed supporting information is provided in 11 appendices. This Executive Summary describes the essential content and key messages of the report.

2. Forests, forest management and wood utilisation

In order to set the context for the assessment of GHG emissions due to consumption of forest bioenergy in the EU, Section 2 of this report briefly considers the status of forests in the EU, and more widely, the extent of current and potential future use of forest bioenergy in the EU and the implications for harvesting and utilisation of wood from forests.

Forest bioenergy is typically a co-product of wood material/fibre production

Typically, forest bioenergy is produced as a complementary co-product of wood material/fibre products. It is unusual for forest bioenergy to be the sole product from harvested wood.

Forest bioenergy consumption in the EU has increased and is likely to increase significantly in the period to 2020

The consumption of wood for energy in the EU has been increasing in recent times. The demand for wood in the EU is very likely to increase in the period to 2020 and potentially beyond, with most of this due to a significantly greater increase in the demand for wood for energy.

Forest management will need to change to meet demands for forest bioenergy

In order to fill a gap between future demands for wood and potential supply, it will be necessary to intensify management of EU forests in order to increase removals of primary wood and/or import more wood into the EU and/or mobilise the availability of sources of other woody biomass. This may be achieved through a number of changes to forest management and/or patterns of wood use, which may be more or less likely to actually occur.

Certain harvested wood feedstocks and forest management practices are more likely than others to be involved in the supply of forest bioenergy

In the period to 2020, demand for forest bioenergy seems likely to be met through increased extraction of harvest residues including poor-quality stemwood and trees, the use of sawmill co-products and recovered waste wood. Some small roundwood may be used as a source of bioenergy. It is less likely that forest bioenergy will involve consumption of wood suitable for high value applications, such as sawlogs typically used for the manufacture of sawn timber.

In terms of changes to forest management, a rise in demand for forest bioenergy is already stimulating interest in the extraction of harvest residues and in the introduction of silvicultural thinnings in young stands. In some regions, it is possible that the additional revenue from forest bioenergy is giving incentives for harvesting operations in forests (thinning and/or felling) for co-production, where this would not otherwise occur. Demand for forest bioenergy would need to be very intense for harvesting to be introduced in otherwise unmanaged forest areas, or for forest management to be fundamentally restructured, solely to produce bioenergy. Activities such as enrichment of unproductive forest areas and creation of new forest areas would most likely require very intense demand for forest bioenergy or additional incentives.

Competition for forest biomass for energy use or for paper and board may occur, but there are also existing market trends

The use of sawmill co-products may be based on additional supply associated with increased production of sawn timber, or may involve the diversion of some of the existing supply from the manufacture of wood-based panels. Similarly, some small roundwood used for bioenergy may involve increased co-production with sawn timber, or diversion of supply from the wood-based panel and paper industries. It is difficult to assess the extent to which these activities may occur. Meeting demands for forest bioenergy may involve some direct competition with the wood-based panels and paper industries, or may involve 'picking up' existing supply in situations where demand for wood-based panels and paper is already declining.

Forests are managed for multiple objectives and increased demand for forest bioenergy is very unlikely to change this situation

In the EU and elsewhere, generally forests are managed for many purposes, one of which is to supply forest bioenergy. Production of forest bioenergy is thus most likely to occur as an integrated part of forest management and wood use for a range of objectives. A requirement to produce forest bioenergy seems unlikely to become the principal driver of forest management unless demand for forest bioenergy becomes very intense.

3. Forest biogenic carbon and its management

Section 3 of this report presents an overview of the role of forest carbon stocks as biogenic carbon in contributing to the GHG emissions of forest bioenergy, in particular interactions with forest management and demands for increased bioenergy production.

Sensitivity of GHG emissions due to biogenic carbon

Biogenic carbon can make a very variable contribution to the GHG emissions associated with forest bioenergy. Consequent GHG emissions can vary from negligible levels to very significant levels (similar to or greater than GHG emissions of fossil energy sources). In some specific cases, forest bioenergy use may be associated with net carbon sequestration. Many factors influence GHG emissions of forest bioenergy due to biogenic carbon. These factors have been analysed and their influences are summarised in Figure ES1. GHG emissions are very sensitive to these factors but outcomes are predictable, at least in principle.

Additionality of GHG emissions and reductions

Although perhaps not explicitly stated, there is a general presumption in the discussion presented in this section of a focus on GHG emissions that would occur as a result of changes in the level of consumption of forest bioenergy. Any contribution of biogenic carbon to GHG emissions associated with *existing* consumption of forest bioenergy effectively forms a component of baseline levels of GHG emissions. The critical question is concerned with the effects that a change in the scale of consumption of forest bioenergy would have on baseline levels of GHG emissions, i.e. whether they would increase or decrease. This needs to be clearly understood and allowed for in assessments of contributions of biogenic carbon to GHG emissions of forest bioenergy.

Baseline forest management

As part of the assessment of the effects of changes in levels of consumption of forest bioenergy, it is necessary to include appropriate assumptions about the age distribution of existing forests, deforestation and afforestation into scenarios for future land use and forest management to meet demands for forest bioenergy. It is also necessary to characterise the existing management of relevant forest areas, and the effects of management on the development of forest carbon stocks. Representation of these aspects of forests and their management is required for the construction of a baseline scenario, representing ‘business as usual’ development of the management of forests, against which any policy scenarios may be evaluated. Furthermore, it is necessary to consider the possible influences of changes in demands for forest bioenergy on the age distribution of forests and on future rates of deforestation and afforestation.

Relevance of scale

The concept of scale is relevant to the assessment of GHG emissions associated with the consumption of forest bioenergy in two senses.

Firstly, forest bioenergy systems need to be assessed at an appropriate spatial and temporal scale. The spatial scale needs to reflect the complete terrestrial vegetation system involved in supplying bioenergy. Examples of relevant spatial scales, variously depending on context, include the complete areas of forests supplying a particular consumer with bioenergy, all of the forests situated within a country or group of countries, or all of the forests managed by a commercial company or land owner. The scale of an individual forest stand is generally of less relevance except for very specific, detailed purposes. The temporal scale needs to capture the variable effects of forest bioenergy on GHG emissions over time. GHG emissions calculation methodologies need to address sensitivities of results to interactions between human management of forests and natural processes and in particular the generally contrasting short-term and long-term consequences of forest management interventions.

Secondly, the contribution of biogenic carbon to GHG emissions of forest bioenergy is sensitive to the scale of consumption. For example, a modest increase in consumption might be achieved through marginal adjustments to existing management of forest areas, with limited effects on forest carbon stocks. However, a significant increase in consumption, for example as illustrated by the ‘high wood mobilisation’ scenarios considered in the EUwood study (Mantau *et al.*, 2010) and EFSOS II study (UN-ECE, 2011) would require changes to forest management such as illustrated by scenarios in Table 2.10, Section 2.7. The implications of significant increases in consumption of forest bioenergy in the EU on patterns of forest management and wood utilisation are also assessed in Appendix 11 and also considered in Table ES1. Many of the scenarios identified for changes in forest management would involve significant and variable influences on the development of forest carbon stocks. Consequently, the variable effects of scale of consumption need to be allowed for in assessments of the contribution of biogenic carbon to GHG emissions of forest bioenergy.

Related to the issue of scale, it is important to recognise that transitions in the level of consumption of forest bioenergy, and consequent responses of forest carbon stocks, can involve long timescales. This is particularly true when considering significant increases in consumption of forest bioenergy, which would require major changes to the management of large forest areas over time.

Counterfactuals

For assessments of GHG emissions of forest bioenergy involving changes to the management of forests and/or changes to patterns in the use of harvested wood, it is essential to characterise realistic and justifiable 'counterfactuals'. Often it is relevant to study the change from 'business as usual' in patterns of land use, i.e. forest management, thus making the construction of a 'business as usual' scenario relevant as part of the definition of the counterfactual. For harvested wood products, counterfactuals involve the 'business as usual' patterns for wood use, and also a set of assumptions about what energy sources and materials might be used instead of forest bioenergy and harvested wood products. When defining such counterfactuals, it is important to recognise that the use of wood for material and fibre products, and as a feedstock for chemicals, may become more important than forest bioenergy in the future, as part of the development of a bioeconomy, or an otherwise decarbonised economy.

LULUCF accounting rules

Existing EU and international accounting systems for biogenic carbon in forests and harvested wood, supporting international efforts to limit GHG emissions, serve very specific purposes and are unsuitable for more general application as calculation methods for assessing the GHG emissions associated with forest bioenergy.

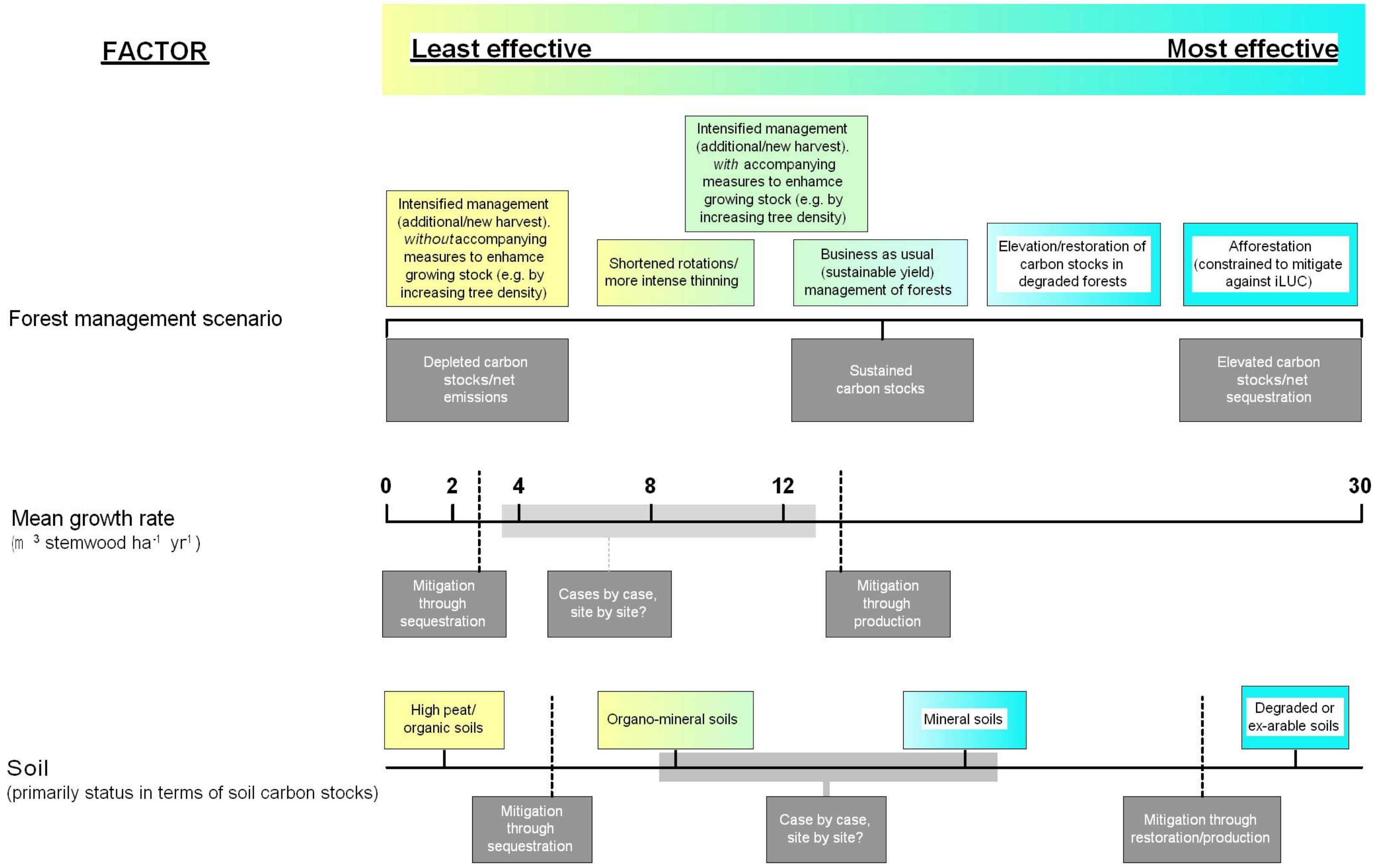

Figure ES1. Illustration of how the GHG emissions associated with the harvesting and use of forest bioenergy may depend on a number of factors.

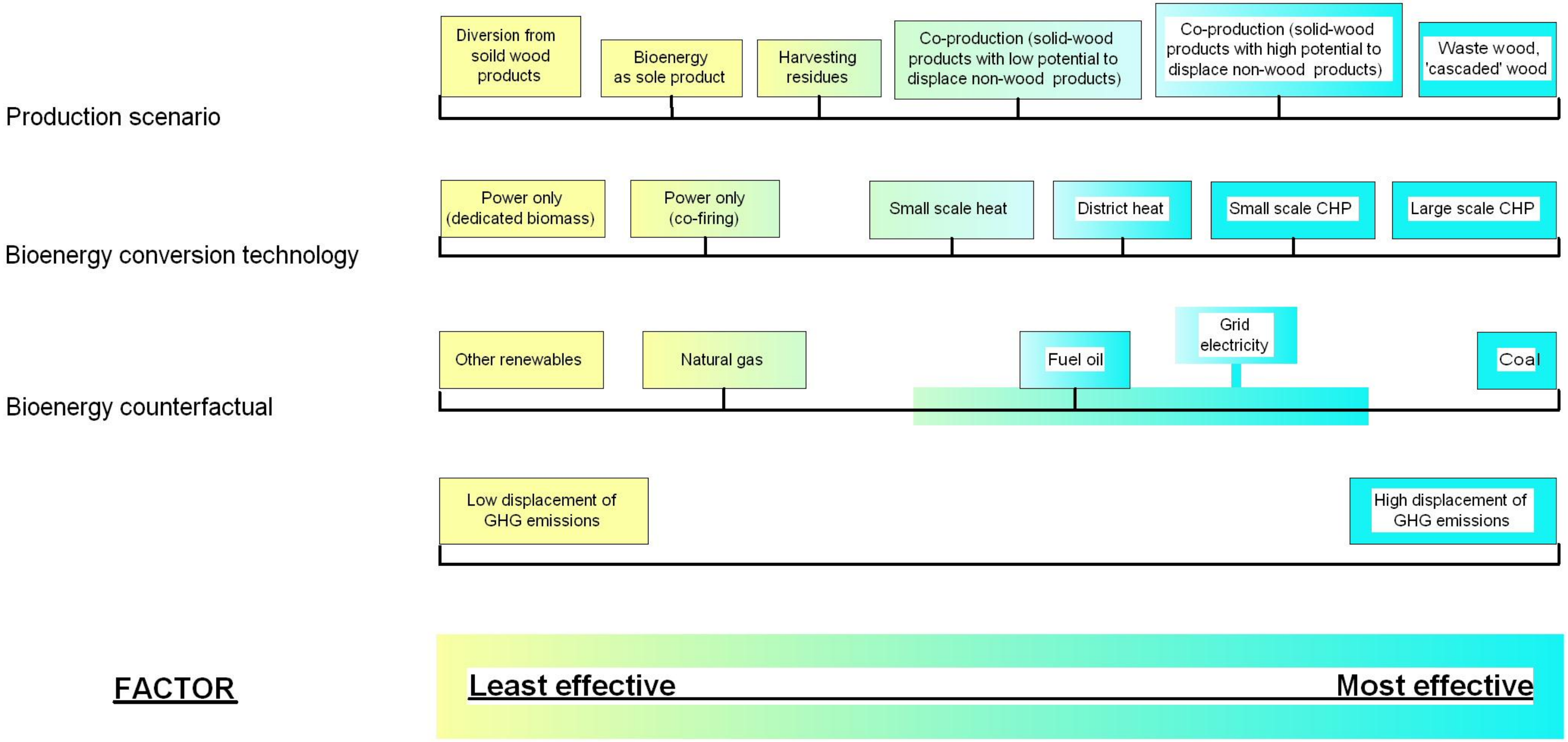

Figure ES1 (continued). Illustration of how the GHG emissions associated with the harvesting and use of forest bioenergy may depend on a number of factors.

4. Life cycle assessment: essential concepts and key issues

Section 4 of this report discusses key concepts and issues concerning LCA methodology, with particular reference to inclusion of biogenic carbon in LCA calculations. Considerable care must be exercised when reviewing and evaluating existing LCA studies, because methodologies may be applied with more or less objective and transparent reasoning.

LCA is the appropriate methodology for assessing GHG emissions of forest bioenergy

LCA is the appropriate methodology for the assessment of GHG emissions associated with the consumption of forest bioenergy. There can be challenges in representing contributions to GHG emissions due to terrestrial vegetation and its management, but this is true regardless of the methodology employed.

LCA methods and results depend on the goal and scope being addressed

LCA studies can address quite wide ranging goals, scopes and research questions. The specific methodological approaches and detailed calculation methods depend strongly on the specific goal, scope and question being addressed. As a consequence, the results of different LCA studies can vary considerably.

Consequential LCA is used for assessing GHG impacts of changes in bioenergy use

An approach known as consequential LCA, as opposed to an alternative of attributional LCA, should be applied when assessing the impacts on GHG emissions due to increased or decreased forest bioenergy. The purposes, modelling principles and methods of consequential LCA and attributional LCA are fundamentally different and they can produce very different results for GHG emissions. These differences need to be clearly understood.

Consequential LCA requires careful specification of scenarios

The calculation of GHG emissions in consequential LCA typically involves the development of two scenarios, i.e. the scenario of interest (describing how the world may change, e.g. if bioenergy consumption is increased) and a baseline scenario (describing how the world will develop if the changes of interest do not occur). Currently there is some confusion and ongoing debate amongst researchers with regard to the application and definition of a baseline in attributional LCA studies but this debate is not relevant to consequential LCA methods.

5. Assessment of literature on GHG emissions of bioenergy

Section 5 of this report presents the main substance of the review of scientific literature concerned with the assessment of GHG emissions due to the consumption of forest bioenergy.

Careful examination of existing scientific literature suggests a consistent story

To sum up the assessment presented in this section, a superficial consideration of the scientific literature on GHG emissions associated with forest bioenergy would most likely arrive at the impression that the outcomes and conclusions of different publications are highly variable and that the overall picture of forest bioenergy is confused and sometimes contradictory. However, on closer examination, it becomes evident that there is a certain level of fundamental agreement or at least consensus on some basic phenomena.

Biogenic carbon needs to be included in *strategic assessments* of GHG emissions arising from consumption of forest bioenergy

Fundamentally, it is undeniable that the status of forest bioenergy as an energy source with either low or high associated GHG emissions is inextricably linked to the property of wood as a reservoir of biogenic carbon and, crucially, how the source of that biogenic carbon, i.e. the carbon stocks in forests, is managed to produce bioenergy.

It is particularly important to allow for biogenic carbon when making *strategic assessments* of GHG emissions due to policies, plans or decisions involving changes in activities that will lead to increased consumption of forest bioenergy. It is important to clarify that what needs to be demonstrated is the achievement of significant reductions in GHG emissions, as the ‘global consequence’ of any changes to the management of forest areas involved in the supply of forest bioenergy, implying the application of consequential LCA for the purposes of assessment.

GHG emissions of forest bioenergy display systematic variation more than uncertainty

An analysis of published case studies indicates that forest bioenergy sources may involve widely varying outcomes in terms of impacts on GHG emissions. However, it is very important to stress that this variability does not imply that outcomes are uncertain. Rather, much of the variation is systematic and can be related to clearly identifiable factors.

Many factors can influence the GHG emissions of forest bioenergy

The variability in reported results for GHG emissions of forest bioenergy reflects many factors related to the forest bioenergy systems being studied and the methodologies applied in calculations. However, a meta-analysis of published studies would appear to indicate that a major reason why different studies have arrived at different results and conclusions is simply down to the fact that they have looked at different types of forest bioenergy source.

Forest bioenergy systems can vary considerably with respect to a number of factors including:

- Geographical location and spatial scale.
- Characteristics of pre-existing growing stock of forest areas.
- Productive potential of forests.

- Types of forest management intervention involved in producing additional forest bioenergy, e.g. any or all of additional thinning, additional felling, increased extraction of harvest residues, enrichment of growing stock for increased production.
- Whether additional harvesting in forest areas is for forest bioenergy as the sole product or as a co-product alongside material/fibre products.
- The types of feedstocks used for forest bioenergy, e.g. any or all of harvest residues, poor quality trees, small roundwood, stemwood, sawlog co-products, recovered waste wood.
- Energy conversion systems, e.g. small-scale heat, district heat or combined heat and power, power-only, co-firing with coal for power generation, and associated efficiencies of conversion systems.
- Counterfactuals for forest bioenergy sources, e.g. fossil energy sources such as natural gas, oil or coal, and for any material/fibre co-products.
- Counterfactuals for forest management, i.e. how forest areas would have been managed if bioenergy consumption had not been increased, and what this would mean for the development of forest carbon stocks.

The impacts on GHG emissions due to the increased consumption of forest bioenergy depend very strongly on variations in these factors. It follows that forest bioenergy cannot be regarded as an energy source with 'homogenous properties' such as a characteristic value or range for a GHG emissions factor. Rather, such properties need to be assessed for specific types of forest bioenergy sources.

Results for GHG emissions also depend on the methodology applied for assessment

Results reported by published studies for GHG emissions of forest bioenergy also vary because different studies have used different methodologies, often because studies have different goals and address different research questions. For example, most studies apply methods consistent with consequential LCA, with the aim of assessing the impacts of decisions to increase consumption of certain types of forest bioenergy sources. However, a few studies apply attributional LCA as part of the 'operational' assessment of (typically absolute) GHG emissions of specific forest bioenergy sources. These two types of study will, inevitably, arrive at very different results for the GHG emissions of forest bioenergy sources. Clearly, only the former type of study is relevant to the assessment of the potential impacts of policies encouraging the consumption of forest bioenergy. At the same time, it should be stressed that such variations between studies are not necessarily shortcomings or substantive methodological conflicts. Rather, these variations reflect the large range of possible scenarios for forest bioenergy use that can be studied, and the diversity in the specific objectives and questions addressed by different studies.

Increased harvesting typically involves reductions in forest carbon stocks

There is widespread recognition in the research literature that increasing the levels of wood harvesting in existing forest areas will, in most cases, lead to reductions in the overall levels of forest carbon stocks compared with the carbon stocks in the forests under previous levels of harvesting. Where the additional harvesting is used to supply bioenergy as the sole product, then such forest bioenergy will typically involve high associated GHG emissions (i.e. compared with fossil energy sources) for many decades.

Increased biomass production sometimes involves increased forest carbon stocks

There is also recognition that there exist some specific cases where forest management interventions to increase biomass production may involve increased forest carbon stocks. These include situations in which rotations applied to forest stands are extended as part of optimising biomass productivity, or the growing stock of existing degraded or relatively unproductive forests is enriched to enhance productive potential. It is also possible to create new forest areas with the specific purpose of managing them for wood production, provided that forest carbon stocks on the land are increased as part of the conversion of non-forest land to forest stands, and that there are no associated detrimental indirect land-use changes.

GHG emissions of forest bioenergy are very sensitive to assumptions

The outcomes of GHG assessment of forest bioenergy are very sensitive to the counterfactual scenario for land use. The projected development of forest carbon stocks under the counterfactual scenario will depend on the assumed forest management, the potential of the growing stock forming forest areas (tree species, age distribution, climatic conditions, soil quality, nutrient regime etc.), and on the likelihood of natural disturbances.

Similarly, outcomes are very sensitive to the counterfactual scenario for energy systems, which also involve assumptions which may be very uncertain, e.g. because of unforeseen market-mediated effects or future policy developments.

Uncertainties in counterfactual scenarios are inherent due to the fact that the counterfactual scenario is, by definition, a path that charactreristically is not followed. It is thus never possible to verify what would have actually happened. Long time horizons related to forest carbon cycles and lifetimes of energy systems increase the inherent uncertainty. It follows that counterfactual scenarios need to be developed carefully and robustly, and assumptions must be transparent to ensure they are clearly understood when results are interpreted.

GHG emissions of forest bioenergy sources vary over time

The GHG emissions due to the use of forest bioenergy generally vary over time. As a consequence, different results are obtained for GHG emissions when calculated over different periods (or ‘time horizons’), e.g. 1 year, 10 years or 100 years. This complicates the characterisation of forest bioenergy sources, particularly with regard to their potential to contribute to reductions in GHG emissions. There are many examples involving an initial period of increased GHG emissions, compared to the alternative of using fossil energy sources, followed eventually by reductions in GHG emissions. The initial period of increased GHG emissions can vary from less than one year to hundreds of years, depending on the type of forest bioenergy.

There is no obvious scientific basis for selecting a standard time horizon – essentially this is a politically-related decision. The choice of time horizon is thus a critical issue in the assessment of GHG emissions associated with the use of forest bioenergy. In this report (Section 5.2), a target year of 2050 was identified as a policy-relevant time horizon (Allen *et al.*, 2009; Meinshausen *et al.*, 2009).

Forest bioenergy sources likely to contribute to levels of consumption in 2030 vary in risk

A provisional qualitative assessment was made of the likelihood of particular forest bioenergy sources being involved in meeting levels of consumption in 2030. These various forest bioenergy sources varied from 'low risk' to 'very high risk', according to the likelihood of adverse impacts on GHG emissions reductions over the period to 2050, as illustrated in Table ES1[1].

This implies that, potentially, increased consumption of forest bioenergy in the EU could make a highly significant contribution towards achieving reductions in GHG emissions, if 'low risk' and 'moderate risk' sources are used. Conversely, if 'high risk' or 'very high risk' sources are used, increased consumption of forest bioenergy could make a negligible contribution or could seriously frustrate the achievement of GHG emissions reductions.

As part of this qualitative assessment, it is difficult to clarify whether increased consumption of forest bioenergy in the EU is likely to be achieved through 'low risk' and 'moderate risk' scenarios for forest management and bioenergy production, such as increased extraction of harvest residues, or whether a wider range of scenarios with varying risk may be involved. A full systematic analytical assessment is required to determine whether scenarios are more or less likely to actually be involved in meeting increased demands for bioenergy, which is a subject for further research.

Low/high-risk cannot be determined simply in terms of feedstocks

The analysis of scientific literature suggests it is possible to identify 'low risk' and 'high risk' sources of forest bioenergy. However, the same feedstocks can be involved in 'low risk' and 'high risk' scenarios. As a consequence, it is not possible to limit or remove risk of adverse GHG emissions due to consumption of forest bioenergy by favouring particular feedstocks and discouraging the use of others.

In this context, it is also important to recognise that, as part of sustainable forest management and wood utilisation (Sections 2.3 and 2.5):

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[1] It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1, where levels of risk are also defined in Table 5.2.

- Different types and sizes of trees and quantities of wood are harvested at different points in the cycle of forest management. Trees harvested at different ages (and hence of particular dimensions and physical characteristics) will be suitable for different applications and end uses.
- At any one time across a whole forest, a broad mix of trees will be harvested which will be variously suitable for a range of end uses, even though particular types of trees may be harvested from individual stands for specific uses, depending on their stage of development. Collectively, the broad mix of trees harvested from a forest meets a range of demands.
- The wood processing sector is complex, with outputs from the forest providing feedstocks for the manufacture of structural sawn timber, plywood, pallets and fence posts, particleboard and fibreboard, paper and other products including bioenergy.
- The complexity of the wood processing sector can present challenges when attempting to track flows of wood from the forest through to ultimate end use.

For these reasons, there are likely to be very serious obstacles to regulating the consumption of forest bioenergy based on individual consignments of forest bioenergy or based on specific types of forest bioenergy feedstock.

There is reasonable consistency in outcomes for particular bioenergy sources

There is reasonable consistency in the research literature on outcomes for particular forest bioenergy sources with regard to impacts on GHG emissions. The meta-analyses of published studies by the JRC review, Lamers and Junginger (2013) and in this report, list a number of specific examples of forest bioenergy sources, which can be categorised in terms of associated impacts on GHG emissions, as summarised in Table ES1.

Significant initiatives involving increased consumption of forest bioenergy could be subjected to strategic assessment for impacts on GHG emissions

One possible step towards managing risk associated with increased consumption of forest bioenergy could involve commitments by proponents of significant new forest bioenergy projects in the EU to demonstrate that genuine and significant GHG emissions reductions should be achieved, when GHG emissions due to biogenic carbon are considered. This would require *strategic assessment*, as already identified earlier in this discussion as appropriate for assessment of GHG emissions due to policies, plans or decisions involving changes in activities that will lead to increased consumption of forest bioenergy.

It must be stressed that such assessment of new activities involving consumption of forest bioenergy would be undertaken before a decision is taken to proceed with the activities. Such an approach is not suggested for ongoing monitoring of GHG emissions, for example at bioenergy installations to demonstrate compliance with regulations, such as targets for net GHG emissions savings. Further research is needed to assess the implications of the findings of this report for the development of robust methodologies for monitoring of GHG emissions for such regulatory purposes.

Increased use of forest bioenergy might be integrated with carbon stock management

The possibilities could be considered for complementary approaches to support positive management of carbon stocks in forests, or more generally in terrestrial vegetation and soil. Such action would underpin a positive contribution by forest bioenergy to achieving reductions in GHG emissions but would not be explicitly linked to bioenergy consumption. In this context, it should be noted that an existing EU Decision on accounting for GHG emissions in the Land Use, Land-Use Change and Forestry sector effectively provides an appropriate accounting framework at national scale within the EU.

Increased use of forest bioenergy might be integrated with wider measures to support forest carbon stock management

The possibilities could be considered for complementary approaches (i.e. ‘flanking measures’) to support positive management of carbon stocks in forests, or more generally in terrestrial vegetation and soil. In principle, if the extraction of additional biomass in forest areas involves reductions in forest carbon stocks, this could be compensated for by enhancement of vegetation and soil carbon stocks in other parts of the landscape, with the aim of achieving an overall positive impact on carbon stocks at the landscape and/or regional scale. Such action would indirectly support a positive contribution by forest bioenergy to achieving reductions in GHG emissions but would not be explicitly linked to bioenergy consumption. In this context, it should be noted that existing EU Decisions and Regulations on monitoring and accounting for GHG emissions in the Land Use, Land-Use Change and Forestry sector (EU, 2013ab) effectively provide an appropriate accounting framework at national scale within the EU.

The suitability of metrics for GHG emissions depends on the question

Metrics used for assessing the potential of forest bioenergy need to be relevant to the goal, scope and policy or research question being addressed. For example, if there is interest in achieving a significant level of GHG emissions reductions, say 50% to 95%, by a target year such as 2020 or 2050, then results expressed as GHG emissions payback times may be useful for initially sifting out high risk scenarios for forest bioenergy consumption, but are not appropriate for assessing whether target levels of emissions reductions are likely to be met. In this context, a metric such as cumulative reduction in GHG emissions is more appropriate. Furthermore, if there is interest in understanding the effects of various scenarios for forest bioenergy consumption on cumulative radiative (climate) forcing, then a metric should be used which directly expresses such effects.

Table ES1 Classification of forest management/ bioenergy production scenarios in terms of risk

Risk[1]	**Forest management/bioenergy production scenario[2]**	**Comments**
Scenarios potentially relevant to 2020 targets for bioenergy consumption		
'Very high' and 'high'	Co-production of solid wood products and bioenergy through additional thinning and/or felling in forest areas with low potential for displacement of GHG emissions associated with solid wood products[3].	Very sensitive to counterfactuals for forest bioenergy and material/fibre products[3].
	Salvage logging and restoration of forests on rotational management for production of bioenergy only.	
	Diversion of harvested wood from solid wood products to bioenergy, leaving harvesting intensity unchanged.	Very sensitive to counterfactuals for forest bioenergy and solid wood products.
'Moderate'	Salvage logging for co-production of solid wood products and bioenergy followed by restoration of forest areas with moderate harvesting intensity, also for co-production.	
	Extraction of harvest residues[4].	Sensitive to harvesting of stumps, and to fossil energy counterfactual.
	Extraction of pre-commercial thinnings.	Sensitive to fossil energy counterfactual.
'Moderate' to 'low'	Co-production of solid wood products and bioenergy through additional thinning and/or felling in forest areas with high potential to displace GHG emissions associated with solid wood products[5].	Very sensitive to counterfactuals for forest bioenergy and material/fibre products[5].

Notes to Table ES1:

1. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1 and levels of risk are defined in Table 5.2.
2. Scenarios for forest management and bioenergy production have been classified using background shading in the table to indicate their potential relevance to increased consumption of bioenergy in the EU. See Appendix 11 for details.
3. The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals.
4. Moderate risk has been assigned on the assumption that harvesting of stumps would not increase significantly. A high risk would be assigned in the case of stump harvesting.
5. The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals.

Table ES1 (continued) Classification of forest management/ bioenergy production scenarios in terms of risk

Risk[6]	Forest management/bioenergy production scenario[7]	Comments
Additional scenarios potentially relevant to bioenergy consumption above 2020 targets		
'Very high' and 'high'	Additional harvesting of stemwood and 'residual wood' for bioenergy only in forest stands for fire prevention.	
	Additional harvesting of stemwood in forest areas already under management for production, for bioenergy only.	Sensitive to fossil energy counterfactual.
Scenarios unlikely to be involved in increased bioenergy consumption		
'Very high' and 'high'	Harvesting of forest with high carbon stocks and replacement with rotational forest management for production of bioenergy only.	
	Harvesting forests with high carbon stocks for bioenergy only, followed by restoration of forest areas with low productivity plantation for bioenergy only.	
'Moderate'	Harvesting of forest with high carbon stocks and replacement with high-productivity short rotation plantations for production of bioenergy only.	Sensitive to the assumption that short rotation plantations have much faster growth rates than previous forest
'Moderate' to 'low'	Diversion of harvested wood from solid wood products to bioenergy, combined with reduced harvesting intensity.	Requires reduced harvesting intensity to fully compensate for possible impacts of diverting wood
'Low'	Enrichment of growing stock in existing forest areas as part of enhancement of bioenergy production.	Important to avoid negative impacts on soil carbon stocks, where these could occur.
	Creation of new forests for bioenergy only on marginal agricultural land with low initial carbon stock[8].	Sensitive to risks of iLUC.

Notes to Table ES1:

6. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1 and levels of risk are defined in Table 5.2.
7. Scenarios for forest management and bioenergy production have been classified using background shading in the table to indicate their potential relevance to increased consumption of bioenergy in the EU. See Appendix 11 for details.
8. It must be stressed that these activities have been classified as low risk on the assumption that risks of iLUC would be mitigated, e.g. by restricting the activities to marginal/low productivity agricultural land.

1. Introduction

This report has been prepared towards fulfilment of a European Commission project, ENER/C1/427-2012 on 'Carbon impacts of biomass consumed in the EU'. The principal objective of this project, as stated originally in the project tender specification, is to deliver a *qualitative and quantitative assessment* of the direct and indirect greenhouse gas (GHG) emissions[2] associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU under a number of scenarios focussing on the period to 2030, in order to provide objective information on which to base further development of policy on the role of biomass as a source of energy with low associated GHG emissions.

The project comprises five research and technical support tasks:

Task 1: Literature review of biogenic carbon accounting of biomass

Task 2: Scenarios for biomass use in EU

Task 3: Biogenic carbon emissions of biomass used in EU

Task 4: Assessment of indirect emissions from different various sources of solid biomass

Task 5: Ad-hoc technical support.

The effective assessment of the consequences for GHG emissions of bioenergy consumed in the EU also depends on the ability to integrate existing models and relevant modelling capabilities developed by the partners in the project consortium. Therefore, an additional cross-cutting task is explicitly concerned with integration of modelling and calculations.

This report addresses Task 1 of the project.

1.1. Scope of this report

As required under Task 1, this report is concerned with a review of scientific literature on the contributions of 'biogenic carbon' to GHG emissions due to the production and use of bioenergy, and how these contributions may be appropriately included in methodologies for calculating GHG emissions. The report effectively constitutes the *qualitative assessment* required as part of the principal objective of this project.

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[2] The definition of the term 'greenhouse gas emissions' is fundamental to this report. Specific and narrow definitions are needed in some contexts, and these definitions are provided in the glossary to this report (see Appendix 1) and also discussed more fully in Sections 4.4 and 4.5. However, in some contexts, the term may be applied quite broadly, as is the case for much of the content of the early sections of this report.

The review is concerned primarily with woody biomass harvested from forests for use as bioenergy, referred to hereafter in this report as 'forest bioenergy'[3], because this reflects the current focus of debate in the scientific literature. The issues raised in the literature are in fact relevant for all forms of bioenergy, but are of particular importance for forest bioenergy due to its special characteristics, as described in Section 2 of this report. However, implications for bioenergy in a wider sense are briefly considered as part of the conclusions of this review, presented in Section 6 of this report. In particular, conclusions drawn on appropriate methodologies for including contributions to GHG emissions due to biogenic carbon should be generally applicable to all bioenergy sources.

Before embarking on a full critical review of literature on forest biogenic carbon and its significance for the GHG emissions of forest bioenergy, an initial discussion of essential background scientific understanding on this subject is undertaken (Section 1.2). This aims to inform and set the objectives for the review and the approaches adopted in carrying it out. The objectives of the review and the structure for the rest of the report are presented in Section 1.3.

1.2. Essential background

The requirement for a literature review of biogenic carbon accounting of biomass needs to be understood in the context of the potential roles of forest biomass in climate change mitigation, and current scientific understanding of the consequences for GHG emissions of using such biomass as a source of bioenergy. As discussed in Sections 2 and 3, and throughout this report, the biogenic carbon constituted by forest carbon stocks can fulfil several contrasting functions in terms of climate change mitigation:

The carbon stocks in forest biomass, litter and soil represent a natural reservoir of carbon sequestered from the atmosphere.

Forest biomass can be harvested and used as a source of bioenergy which can be used in place of fossil energy sources and/or to make a range of solid wood products (e.g. sawn timber, wood-based panels, card and paper) which also represent a reservoir of sequestered carbon and can be used in place of non-wood materials.

A central concern for this report is to understand how forest management and the use of harvested wood can influence these functions, in particular when synergies between these functions can occur or when risks of antagonism can arise (i.e. when enhancement of one function can be at the expense of the other).

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[3] For the purposes of this project, the term 'forest bioenergy' is defined to mean any biomass extracted from forests that is used to produce energy in the form of heat and power (i.e. not including liquid transport fuels). The biomass may be harvested directly from forests, or may be supplied as a by-product of the manufacture of solid wood products (e.g. offcuts from sawmilling) or may be derived from waste wood sources (e.g. solid wood products disposed of at end of life). This definition is repeated in the glossary in Appendix 1 of this report, along with definitions for many other terms, abbreviations and units.

Forest bioenergy is a potentially very important source of renewable energy (IPCC, 2011). However, the scientific and research literature on the GHG emissions associated with use of forest bioenergy presents a diversity of views and, at times, polarised accounts of the benefits or otherwise of forest bioenergy use as an option for meeting GHG emissions targets.

On one side of the debate, as several recent reports and papers have highlighted, consideration of the intrinsic properties of forest bioenergy would strongly suggest that its use is likely to involve high GHG emissions. This can be illustrated by making simple comparisons of basic physical and chemical properties of wood and fossil energy sources (see Table 1.1). The comparisons made here are based on calorific values[4] and carbon contents reported by Matthews *et al.* (1994) and Matthews (1993). The example calorific values and carbon contents for coal shown in Table 1.1 are 25 MJ kg^{-1} and 0.66 kgC kg^{-1} respectively, whereas example values for air-dry wood (30% moisture content, wet basis) are 12 MJ kg^{-1} and 0.38 kgC kg^{-1}. The carbon content of wood is lower than that of coal, but the calorific value is also markedly lower. If all of the carbon in the wood were to be released to the atmosphere on combustion, burning air-dry wood to produce 1 MJ of energy would release about 31 grams of carbon (equivalent to about 115 grams of CO_2). This result can be compared with an estimate for coal of 26 grams of carbon (equivalent to about 95 grams of CO_2). Example values for fuel oil and natural gas are 20 grams of carbon (73 grams of CO_2) and 14 grams of carbon (53 grams of CO_2) respectively.

It is clear from the results in Table 1.1, and from the preceding paragraph, that forest bioenergy would not be viewed as an energy source with low GHG emissions compared with fossil energy if this were to be assessed simply on the consideration of basic physical and chemical properties of wood.

Superficially, the results in Table 1.1 should be simple and easy to understand. However, already it is essential to be clear about what these results actually represent. The results also raise many questions. It is important to understand that the results in Table 1.1 are based on very direct and simple interpretation of the calorific values and carbon contents of various energy sources. They do not represent the GHG emissions that would actually occur if each type of energy source were to be used, for example, to generate a unit of electrical power. Questions thus arise about the conversion technologies that would be deployed in conjunction with each energy source, and the efficiencies and energy inputs associated with the supply, conversion and delivery chains. Particular questions arise in the case of wood as a source of energy and the calculation of GHG emissions. For example, it is necessary to know how the wood was dried and the energy inputs involved. More fundamentally, as discussed in detail in Section 2 of this report, wood is not a homogenous energy feedstock. Rather, it may be produced from different parts of

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[4] Calorific value may be defined as the quantity of heat produced by the complete combustion of a given amount (i.e. mass) of a substance. Calorific values are typically expressed in units of joules per gram or megajoules per kilogram (MJ kg^{-1}).

trees, which in turn may be harvested at different stages in the management of forest areas. Complexities arise from the requirement to represent land use and land management as an important aspect of bioenergy production and consumption, which is usually less important for other energy sources. For all energy sources and conversion technologies, clearly it is critical to establish a sound methodological basis for calculating associated GHG emissions.

Table 1.1 Illustrative examples of calorific values and carbon contents for wood and fossil energy sources

Energy source	**Net calorific value[2] (MJ kg^{-1})**	**Carbon content[4] (kgC kg^{-1})**	**Implied carbon dioxide emissions on combustion[5,6]**	
			(gC MJ^{-1})	**(gCO$_2$ MJ^{-1})**
Wood (air dry)[3]	12	0.38	31	115
Coal	25	0.66	26	95
Fuel oil	-	-	20	73
Natural gas	-	-	14	53

Notes to Table 1.1:

1 The values in this table have been reported in Matthews *et al.* (1994) and Matthews (1993). It must be stressed that these values are illustrative examples only and that the calorific values and carbon contents of these energy sources can vary.

2 The net calorific value of an energy source is sometimes also referred to as the lower heating value. Net calorific value represents the quantity of heat produced by the complete combustion of a given amount of a substance, allowing for any moisture content, such as in the case of air-dry wood.

3 Air-dry wood is assumed to have moisture content of 30%, wet basis. The net calorific value and carbon content are expressed per air-dry kg.

4 For air-dry wood, the carbon content is expressed in kgC per oven dry kg.

5 Calculated by dividing carbon content by net calorific value and multiplying the result by 1000, assuming (theoretically) that all carbon is released on combustion.

6 Calculated by multiplying the result expressed in units of gC MJ^{-1} by 44/12, assuming (theoretically) that all carbon is released as carbon dioxide on combustion.

A recognition of the role of forests and their management in the supply of forest bioenergy leads naturally to consideration of the other side of the debate concerning the benefits or otherwise of forest bioenergy use as an option for meeting GHG emissions targets. Many papers in the scientific and research literature take a diametrically contrasting view of forest bioenergy, based on the fact that the carbon in wood is ‘biogenic carbon’, rather than ‘fossil carbon’ (or ‘geological carbon’). The carbon in wood can be regarded as biogenic carbon because plants including trees capture CO$_2$ from the atmosphere through photosynthesis, releasing oxygen, also releasing part of the CO$_2$ through respiration, and retaining (‘sequestering’) a reservoir of carbon in organic matter, notably as woody biomass in the case of trees. It is the carbon sequestered in this reservoir of organic matter that may be regarded as ‘biogenic’.

A widely circulated article produced by IEA Bioenergy Task 38 that typifies the presentation of a positive view of forest bioenergy (Matthews and Robertson, 2006) observed that there is a vital difference between energy production from fossil fuels and energy production from biomass. It is argued that burning biomass simply returns to the atmosphere CO_2 that was absorbed as the plants grew. The processes of sequestration of CO_2 and re-release to the atmosphere may take place at different times but, taken as a whole and looking at the net result over time, there should be no net release of CO_2 if a cycle of growth, harvest and regrowth is maintained. This view is reinforced by the inclusion in the Task 38 leaflet of a much-repeated figure, also repeated in this report as Figure 1.1.

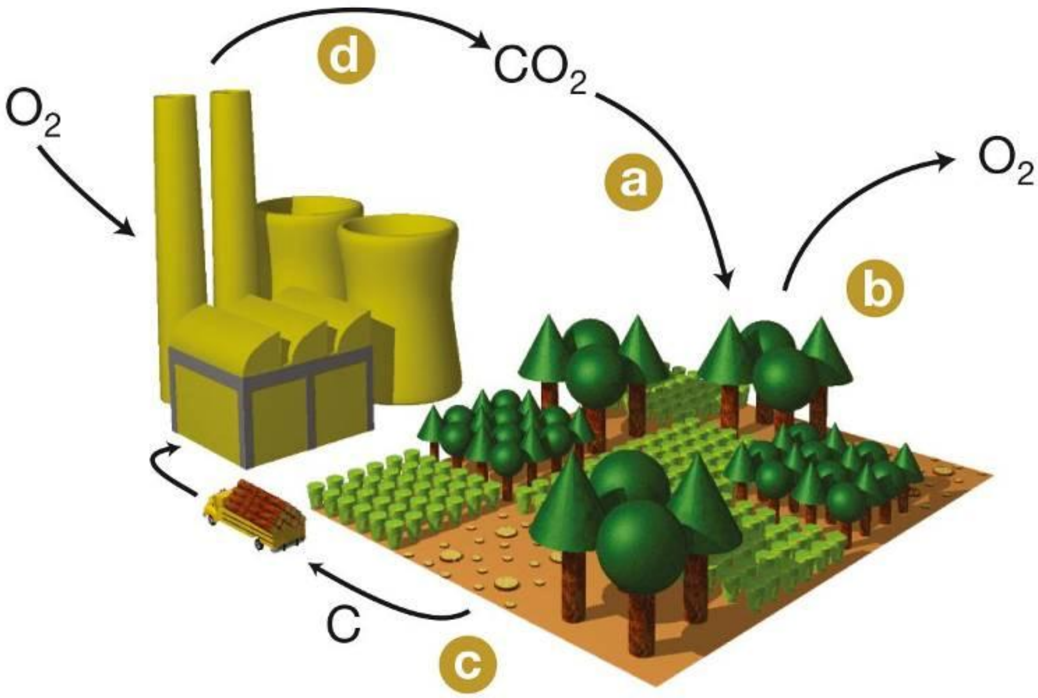

Figure 1.1. The potential 'recycling' of carbon as biomass accumulates in energy crops and forests and is consumed in a power station. (Source: Matthews and Robertson, 2006.)

The discussion presented in Matthews and Robertson (2006) strongly implies that the use of bioenergy presents opportunities to produce energy with low or zero associated net GHG emissions and that there may even be opportunities to sequester additional carbon in the vegetation of crops and forests as part of promoting the production of bioenergy. However, in presenting a generally positive view of bioenergy (including forest bioenergy), it is doubtful that the various contributors to the IEA Bioenergy Task 38 article would have envisaged the unprecedented scale of interest in bioenergy that currently prevails globally and not least in the EU. As outlined in Section 2 of this report, projections of bioenergy consumption in the EU up to 2020 and beyond suggest that biomass production will need to increase significantly. The quantities involved are potentially very challenging and are likely to require significant changes to land management for bioenergy production, as well as large-scale importation of biomass.

In response to the significant upsurge in interest in forest bioenergy as an option for meeting targets for both increased renewable energy generation and reduced levels of GHG emissions, a debate has escalated concerning the effectiveness of forest bioenergy as an energy source with low associated GHG emissions. A growing number of studies in the literature have employed a variety of methodologies for calculating GHG emissions of bioenergy which allow for contributions due to biogenic carbon, and have arrived at widely-varying conclusions.

These developments have lead to an atmosphere of uncertainty and confusion concerning the potential role of forest bioenergy as a source of renewable energy and a means of global climate change mitigation.

Whilst, at times, there may be a lack of clarity, in fact, some of the key factors determining GHG emissions of bioenergy have been understood for some time. For example, Figure 1.2 shows results of theoretical analyses based on forest carbon accounting models presented by Marland and Schlamadinger (1997). These results illustrate the dependency of outcomes in terms GHG emissions over a 100-year time horizon on two factors:

- The rate at which the trees grow (in terms of biomass or carbon accumulation).
- The amount of fossil energy or energy-intensive material that a tonne of biomass can replace (represented by Marland and Schlamadinger as a theoretical ‘multiplier for efficiencies’. (For example, a multiplier of efficiencies of 0.6 implies that the utilisation of 1 kgC of harvested wood can be used to avoid 0.6 kgC of emissions from burning of fossil fuels or consumption of non-wood materials.)

In Figure 1.2, positive results for cumulative GHG emissions indicate a reduction in overall GHG emissions, as a result of harvesting forest biomass and using it in place of fossil energy sources or non-wood materials, also allowing for forest carbon stock changes. Negative results indicate an increase in overall GHG emissions. The three-dimensional representation and two-dimensional contour map in Figure 1.2 display a wide range of outcomes, from very positive (significant reductions in overall GHG emissions), through negligible effects on overall GHG emissions, to very negative (significant increases in overall GHG emissions). Such results reinforce the view that there are critical thresholds in the GHG balances achieved by management of forests for protection of carbon stocks, or for maximum wood production, or for some balance between these extremes.

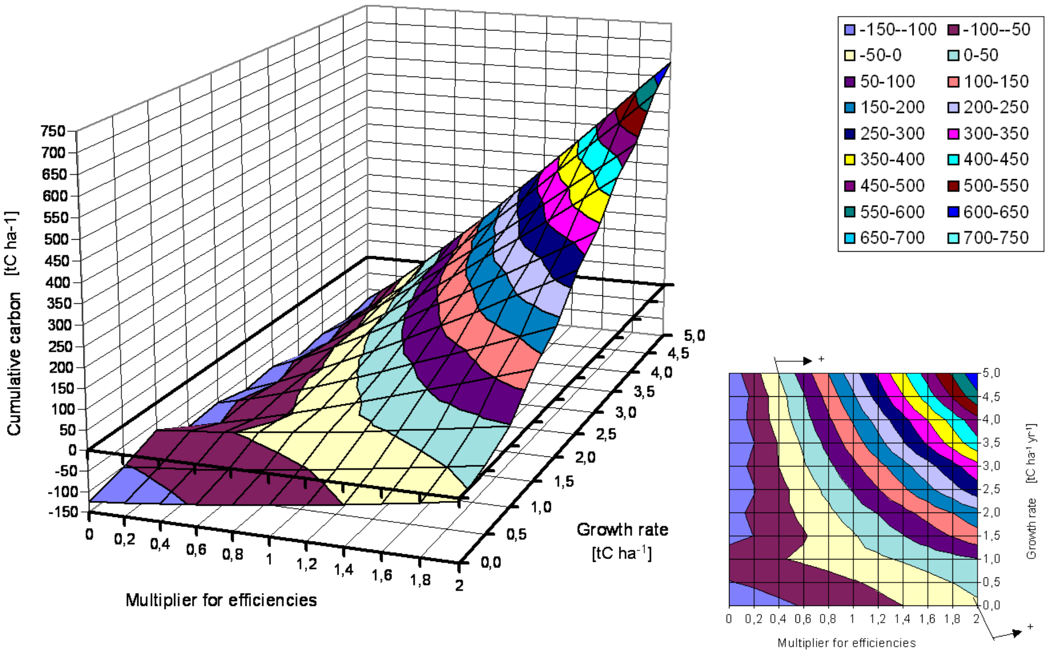

Figure 1.2. Theoretical illustration of the sensitivity of GHG emissions of forest bioenergy to forest growth rate and the 'efficiency' with which wood is utilised. After Marland and Schlamadinger (1997).

Matthews *et al.* (2007) infer from these findings that the potential exists to evaluate options for different situations against such critical thresholds for GHG emissions. However, there is no established and widely-accepted methodology for making such an evaluation. Furthermore, analyses involving many variables, such as the relatively simple example illustrated in Figure 1.2, can be difficult to present clearly and understandably, to enable appropriate insights to be drawn.

Analyses such as illustrated in Figure 1.2 hold out the prospect that apparently contrasting conclusions about the GHG emissions associated with forest bioenergy may be ascribed to and explained in terms of a relatively small number of factors. However, as with the earlier interpretation of Table 1.1, Figure 1.2 raises many questions. For example:

- It is not clear exactly what situation involving the harvesting of biomass from forests is being represented. More specifically, is biomass being harvested as part of ongoing management of forests, or is the biomass being produced through 'additional' harvesting as part of changes to the management of forest areas?
- Is some sort of land use change involved, e.g. introduction of harvesting in previously unmanaged forests areas, or creation of new forest areas on land that was formerly cropland or grassland?

- In terms of the effectiveness of using forest biomass to reduce overall GHG emissions, the 'multiplier for efficiencies' is a theoretical parameter. What range might this parameter take in practice for real bioenergy systems (and the systems they replace), and what factors determine the specific value of the parameter?
- The results in Figure 1.2 are expressed as cumulative values over a 100 year time horizon. How sensitive are the results to the selected time horizon, and to other choices made in defining the methodology for calculations.

It is already evident, therefore, that the interpretation of estimates and analyses of GHG emissions associated with forest bioenergy must be undertaken with great care, with due consideration of the specifics of the forest bioenergy system being studied, and of the detailed approaches adopted in calculations.

1.3. Objectives of Task 1 and report structure

Three key questions arise from the background discussion in Section 1.2, which need to be addressed as part of Task 1 of this project:

1 Is it possible to discern any patterns in the results presented in the existing scientific literature and, in the process, establish whether there are any critical factors determining sensitivity of GHG emissions associated with forest bioenergy? Can such understanding be used to identify lower-risk forest bioenergy pathways in terms of GHG emissions?

2 To what extent are results for GHG emissions estimated for forest bioenergy sensitive to variations in calculation methodologies, and is it possible to understand variability in results in terms of differences in the detailed approaches to calculation adopted in different studies of forest bioenergy?

3 Is it possible to draw insights from the existing scientific literature to identify elements of methodology that would be appropriate for application as part of the assessment to be carried out in this project, including approaches for the reporting and presentation of results?

The approach to Task 1 emphasises systematic approaches to a literature review (i.e. 'summary sheets' for scientific papers including an assessment of 'strengths' and 'weaknesses' of individual studies, and also a formal evaluation against a fixed set of criteria). These approaches are important for this review as tools for understanding the diversity in the scientific literature.

In order to explore and answer the above three research questions thoroughly, the results of the systematic assessment are complemented by (and ultimately synthesised through) critical discussion of the essential issues regarding forest bioenergy, associated GHG emissions, methods for their calculation, and the role of forest carbon stocks and forest management.

Accordingly, in order to set the context for the assessment of GHG emissions due to consumption of forest bioenergy in the EU, Section 2 briefly considers the status of forests in the EU, and more widely, the extent of current and potential future use of forest bioenergy in the EU and the implications for harvesting and utilisation of wood from forests. Section 3 presents an overview of the role of forest carbon stocks as biogenic carbon in contributing to the GHG emissions of forest bioenergy, in particular interactions with forest management and demands for increased bioenergy production. This is followed in Section 4 by a complementary discussion of key concepts and issues concerning LCA methodology, with particular reference to inclusion of biogenic carbon in LCA calculations.

Recognising that this is not the first time that the subject of forest bioenergy and GHG emissions has been reviewed, Section 5 considers what insights may be gained from other recently published literature reviews and critical discussions, in particular whether common or disparate views can be discerned. Key examples of existing published studies of forest bioenergy and GHG emissions are then evaluated to establish patterns in the results of these studies. Consideration is also given to how these approaches have been applied as part of the assessment of published studies. Section 5, in conjunction with Appendix 3, also looks initially at existing published statements on methodologies, particularly with regard to metrics for reporting and interpreting GHG emissions due to the use of forest bioenergy. Finally, Section 5 presents a set of conclusions on forest bioenergy, the relevance of forest carbon stocks and forest management, associated GHG emissions, and their calculation and presentation.

This report also includes, in Appendix 1, a substantial glossary of terms, abbreviations and units. It is recognised that the literature on forestry, forest products, bioenergy and GHG emissions employs a diverse set of terms and measures which can be highly technical. Often several terms are used to refer to the same phenomenon or quantity. Sometimes terms are ambiguous or confusing and occasionally they are politically charged. Strenuous efforts have been made throughout this project to employ terms, abbreviations and units of measurement clearly and consistently, and to provide definitions for these in the glossary of this report.

2. Background on forests, forest management and wood utilisation

2.1. Purpose

The GHG emissions associated with the production and consumption of forest bioenergy are intimately linked with the ways in which forests are managed, how harvested wood is used, and how these activities may change in the future. The purpose of this section is to explain how forests are managed and how wood, and in particular forest bioenergy, is produced from forests in the EU27 and around the world. The intention is to establish a common understanding of the subject and of relevant concepts underlying other sections in this report. Readers who are familiar with these topics may wish to skip this section and proceed to Section 3.

A comprehensive description of the status of EU27 and global forests and associated wood supply chains is beyond the scope of this report, but this section explores the essential aspects of these subjects.

The key purposes of the ensuing discussion are:
- To review how forests are currently managed.
- To review how forest bioenergy is conventionally produced as part of forest management.
- To assess how changes might occur in forest management and patterns of wood use to meet significantly increased demand for forest bioenergy in the EU.

2.2. Regions of the world

The ensuing discussion reports a number of results related to forests, forest management and wood production for different regions of the world. Many of these results are derived from data reported as part of the 2010 Global Forest Resource Assessment produced by FAO (2010). In general, the countries comprising different regions have been based on the regions defined in FAO (2010) but with some modifications as indicated in Table 2.1. Some regions are more important for this report than others but all are covered for completeness.

The EU27, Other Europe and North America are identified as currently the most important regions, in terms of existing and potential supply of forest bioenergy for consumption in the EU.

Table 2.1 Countries included in regions referred to in this report

Region	Description
EU27[1]	The Member States of the EU27.
Other Europe[1]	European countries not in the EU27, including 'eastern European' countries such as Belarus and Ukraine. Also the Russian Federation, unless shown separately.
North America[2]	Essentially Canada and the USA. Sometimes Canada and the USA are shown separately.
Africa	Countries included in the region as defined in FAO (2010).
Central America and Caribbean[2]	
South America[2]	
Asia	
Oceania	Countries included in the region as defined in FAO (2010), but often essentially referring to Australia and New Zealand.

Notes to Table 2.1:

1 The EU27 and Other Europe may be grouped together as Europe and the Russian Federation.

2 North America and Central America and Caribbean are sometimes grouped together as Central and North America. South America and Central America and Caribbean are sometimes grouped together as Central and South America.

2.3. Forest management: key principles and practices

Before considering the management of forests from the point of view of the production of forest bioenergy, it is appropriate to consider the concept of forest management more generally. Indeed, the deceptively simple term '(forest) management' is potentially highly ambiguous and consequently requires initial clarification.

A forest area can be managed to achieve a number of objectives including:

- Industrial wood production (through thinning and/or partial or complete felling).
- Protection, conservation and/or enhancement of land-based carbon stocks.
- Protection and/or conservation of soil and water resources, including protection against landslides.
- Remediation and restoration of degraded land.
- Protection and/or conservation of species, habitats and/or ecosystems.
- Recreation and amenity.
- Production of non-timber forest products (e.g. fruits, nuts, bark, rubber etc.).
- Provision of food, feed, fuel and materials for local communities, possibly including shelter for livestock.

It is very important to appreciate that it is common practice to manage forest areas to achieve several, and sometimes many, of these objectives at the same time. This is consistent with the principle of 'multipurpose forest management', which has evolved into a key principle of sustainable forest management, and has been a core tenet in the education and training of forest practitioners for some decades. However, there are very limited and exceptional situations where management of forests is directed at achieving a single objective.

A key foundation of sustainable forest management is the principle of 'sustainable yield management', which involves regulating the level of harvesting from forest areas to ensure that the productive capacity of the forest areas (i.e. their capacity for timber volume and biomass growth) is not exceeded. Sustainable forest management, and in particular sustainable yield management, characteristically involves the cyclical management of individual forest stands as illustrated in Figure 2.1.

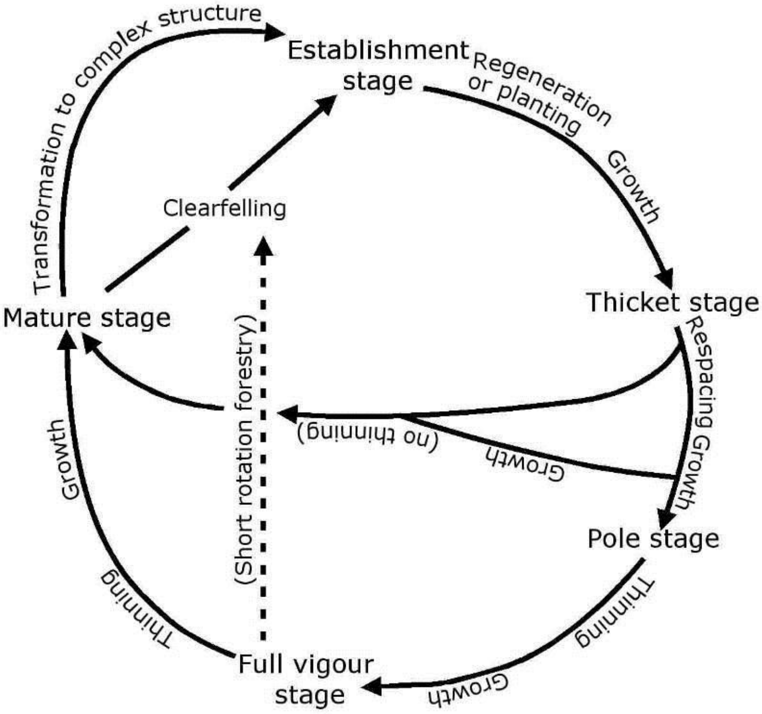

Figure 2.1. Illustration of possible stages in the cyclical management of an individual forest stand (see also Figure 2.2).

Typically, an individual stand is managed through a series of stages involving a balance between tree establishment, growth and harvesting, which can be characterised as (Figure 2.2):

- The 'Tree establishment stage' (Figure 2.2a), in which a new generation of young trees is planted or their natural regeneration is supported or encouraged.
- The 'Thicket stage' (Figure 2.2b), in which a new generation of young trees has become established to form a densely covered area of interlocking tree crowns. At this stage, some of the trees may be removed to give the remaining trees more room to develop (a process known as 'respacing').

- The 'Pole stage' (Figure 2.2c), in which the canopy of still relatively young trees has completely closed, branches and foliage lower down the trees have died, leading to the formation of distinct and relatively straight stemwood below the canopy of the trees. At this stage and during subsequent growth, some of the trees (generally smaller and/or less well formed trees) may be felled to give the remaining trees more room to develop (a process known as 'thinning').
- The 'Full-vigour stage' (Figure 2.2d), in which trees grow from youth to maturity. Generally, this is also the period in which the current annual growth rate of the stand of trees (also referred to as the current annual increment of stem volume, or CAI, see Appendix 2) is close to its maximum. Further thinning operations may be carried out during this stage.
- The 'Mature stage' (Figures 2.2e and 2.2f), in which trees have passed the period of maximum CAI and the dimensions of individual trees can be quite large (e.g. the heights of trees may be 20 m or more and diameters of individual trees may be 20 cm or considerably greater). This is also the growth stage during which maximum mean annual (volume) increment (also known maximum MAI or MAI_{max}[5]) is reached (see Appendix 2). From the mature stage, the management of a stand of trees may develop in one of several directions. At one extreme, the stand may be clear felled (Figure 2.2e) whilst, at the other, it may be retained and protected, in some situations eventually becoming a biologically mature and effectively unmanaged forest. Between these extremes, various patterns of partial felling or thinning may be applied, particularly with the aim of encouraging the regeneration of younger trees, perhaps as an understorey to the existing stand and with the ultimate aim of creating or maintaining a complex stand with trees of mixed age and/or species (Figure 2.2f).

Figure 2.2 also illustrates how a stand of trees can produce a diverse range of types of harvested wood over a cycle of management, but with a strong tendency for specific types of wood to be produced at different points in the cycle, reflecting the stages in the development of the trees forming the stand.

When considering such cyclical management of individual forest stands it is very important to recognise that:

- Different types and sizes of trees and quantities of wood are harvested at different points in the cycle of management (Figure 2.2). Trees harvested at different ages (and hence of particular dimensions and physical characteristics) will be suitable for different applications and end uses.
- Typically, individual stands forming an entire forest will all be at different points in the cycle of management, leading to a diverse forest structure. This also means that, at any one time across a whole forest, a broad mix of trees will be harvested which will be variously suitable for a range of end uses, even though particular types of trees

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[5] Mean annual volume increment (MAI) is the average rate of cumulative volume production up to a given year. In even-aged stands, MAI is calculated by dividing cumulative volume production by age. See also Appendix 2.

may be harvested from individual stands for specific uses, depending on their stage of development. Collectively, the broad mix of trees harvested from a forest meets a range of demands. Wood fibre of various qualities, including forest bioenergy, is required by the wood processing sector and wider consumers.

These points have critical significance when assessing any impacts due to the harvesting and use of wood for bioenergy. As an important example, there may be situations where small trees are harvested from young stands (for example respacing in the thicket stage and thinning in the pole stage) and used entirely as a source of bioenergy. However, these stands will produce wood primarily for other end uses later in their cycle of management. It must be acknowledged that, if prices were sufficiently attractive, some trees of larger dimensions might be used entirely for bioenergy, thus competing with other industrial uses of the wood. However, across an entire forest, it would be very unusual for all of the harvested wood to be used for bioenergy. Consequently, when considering how wood is harvested to serve a range of end uses, it is necessary to consider appropriate spatial and temporal scales, which in general involves considering whole forests and looking across cycles in the management of stands.

The cycle of forest management as discussed above and illustrated in Figures 2.1 and 2.2 is an idealised representation of sustainable (yield) forest management. That said, it is a quite accurate description of the management of significant areas of forest in the EU27 and in other regions of the globe. In other forest areas under sustainable management, the actual patterns of management may be described as variations on this theme.

As a relatively extreme example, a stand of trees managed with a principal objective of raw wood fibre production might involve trees grown on a relatively short cycle (or rotation). This might consist of an Establishment stage, based on planting and/or regeneration (Figure 2.2a), growing the stand through the Thicket stage (Figure 2.2b) without respacing the trees up to the Pole stage (Figure 2.2c), and then clear felling. Another example may occur in situations where permission is granted by a forest owner to a commercial company to harvest trees in existing forests. In this case, management may involve the thinning, partial felling or clear felling of existing stands in their Mature stage of development (Figure 2.2e). Following the felling of trees, an Establishment stage may take place through natural regeneration, or be actively supported. The young trees are then allowed to grow through the Thicket, Pole and Full-vigour stages, possibly with little or no intervention, until the Mature stage is restored in the stand.

Figure 2.2a-f. Illustration of typical management interventions during stages in the cyclical management of a forest stand. Conifer trees are depicted but the stages also apply to broadleaves.

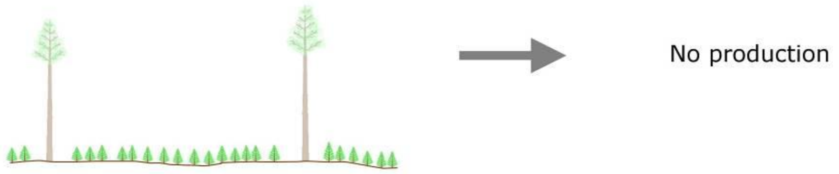

Figure 2.2a. Establishment stage. Young trees are allowed to regenerate or are actively planted to form a new generation of trees. This may occur on land that previously was not forest or on land where trees have previously been clear felled. In some situations, young trees will sprout from the old stumps of previously felled trees (coppicing). In forest stands with complex, mixed age and possibly mixed species composition, establishment may be carried out underneath a canopy of older trees. In addition to possible planting, management interventions may include some form of ground preparation, weed control and protection of trees against grazing animals. During this stage the trees are too young for any wood to be produced.

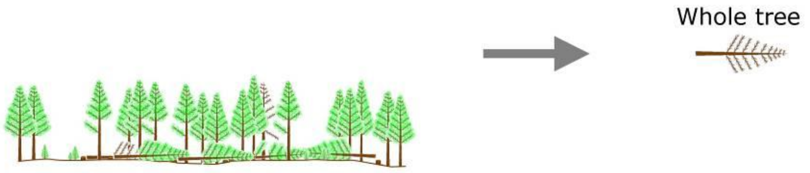

Figure 2.2b. Thicket stage. A new generation of young trees has become established to form a densely covered area of interlocking tree crowns. At this stage, some of the trees may be removed to give the remaining trees more room to develop (a process known as ‘respacing’). The trees that are removed may be left to decay in the forest or they may be harvested. The harvested trees are so small they are of limited use and most likely be chipped and used for fuel.

Figure 2.2a-f (continued). Illustration of typical management interventions during stages in the cyclical management of a forest stand. Conifer trees are depicted but the stages also apply to broadleaves.

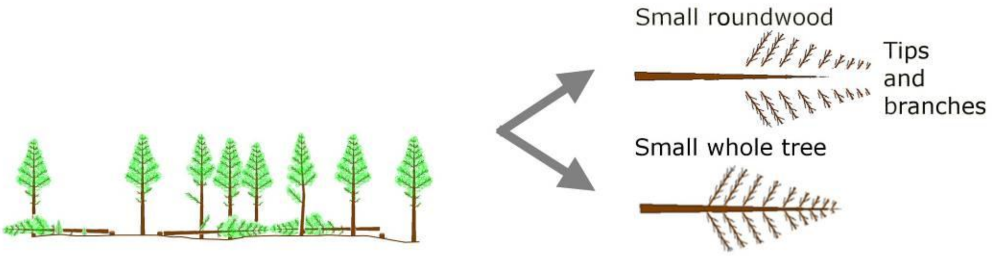

Figure 2.2c. Pole stage. A canopy of still relatively young trees has completely closed, branches and foliage lower down the trees have died, leading to the formation of distinct and relatively straight stemwood below the canopy of the trees. At this stage and during subsequent growth, some of the trees (generally smaller and/or less well formed trees) may be felled to give the remaining trees more room to develop (a process known as 'thinning'). The trees removed as thinnings will normally be harvested. Small trees and trees with very poor stem form (e.g. heavily branched or with severe defects) will be used to supply wood chips for panels (e.g. particleboard) or for bioenergy. Larger, well formed trees will be converted into bars and small roundwood to make fencing, pallets, panels and paper. A fraction of these products may be used as a bioenergy feedstock. Branch wood from the converted trees will most likely be left in the forest but could in theory be removed as harvesting residues. (See also Section 2.5.)

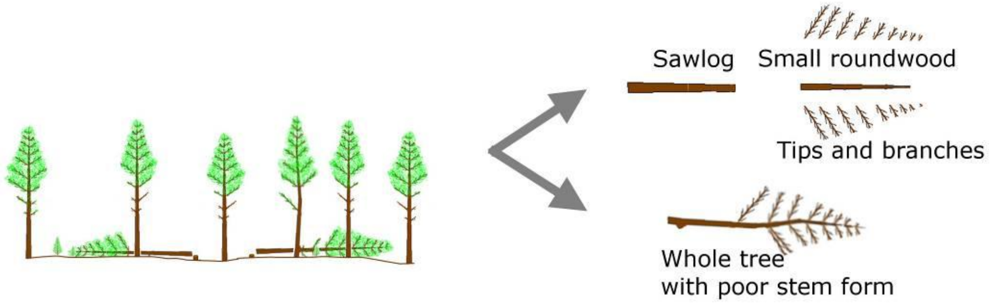

Figure 2.2d. Full-vigour stage. The trees grow from youth to maturity. Generally, this is also the period in which the growth rate of the stand of trees is close to its maximum. Further thinning operations may be carried out during this stage. The trees removed as thinnings will normally be harvested. Trees with very poor stem form (e.g. heavily branched or with severe defects) will be used to supply wood chips for panels (e.g. particleboard) or for bioenergy. Well formed trees will be converted into sawlogs, bars and small roundwood to make sawn timber, fencing, pallets, panels and paper. A fraction of these products may be used as a bioenergy feedstock. Branch wood from the converted trees will most likely be left in the forest but could in theory be removed as harvesting residues. (See also Section 2.5.)

Figure 2.2a-f (continued). Illustration of typical management interventions during stages in the cyclical management of a forest stand. Conifer trees are depicted but the stages also apply to broadleaves.

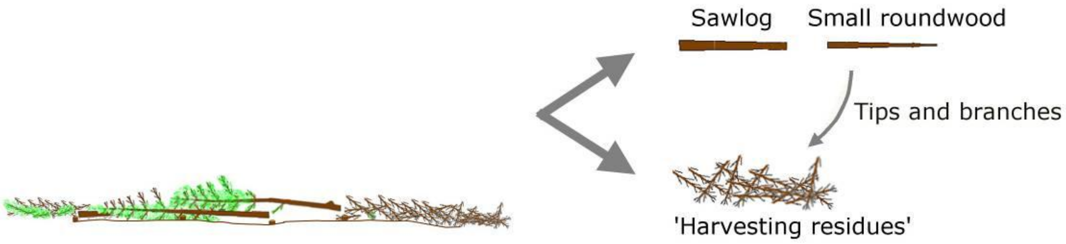

Figure 2.2e. Mature stage (clear felling). Trees have passed the period of maximum growth rate and the dimensions of individual trees can be quite large. From the mature stage, the management of a stand of trees may develop in one of several directions. In this example, the stand is clear felled. The felled trees will be harvested. The trees will be converted into sawlogs, bars and small roundwood to make sawn timber, fencing, pallets, panels and paper. A fraction of these products may be used as a bioenergy feedstock. Branch wood from the converted trees will form part of ‘harvesting residues’, along with other pieces of wood such as stem tips and large but poor quality butt logs. The harvesting residues may be left in the forest, may be burned on site (in preparation for establishing the next stand), or may be harvested and used for bioenergy. (See also Section 2.5.)

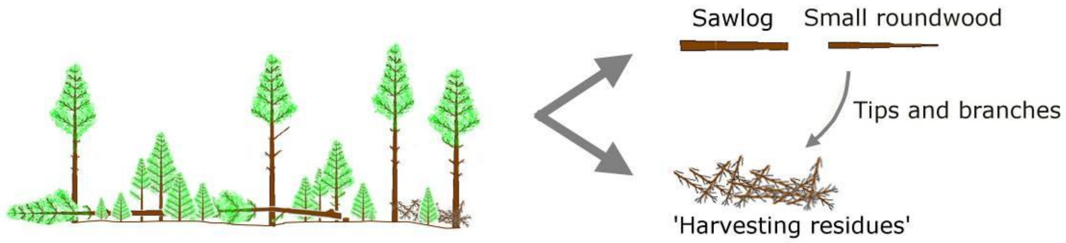

Figure 2.2f. Mature stage (transformation to complex structure). One alternative to clear felling (see Figure 2.2e) involves transforming a mature stand to create a complex structure in terms of tree ages and possibly species. This is achieved through a combination of thinning, regeneration and planting as part of a continuous process. A diverse mixture of trees will be harvested during thinnings and used for a range of products. (See Figures 2.2b-e and also Section 2.5).

2.4. Forest management around the world

EU27 Member States produce forest biomass for energy production from their own forests, and also import it from various regions around the world. For this reason, it is necessary to consider the distribution, rates of growth, ownership and management of forests at both global and European scales. The demand for forest biomass for energy production has implications for the management of forests across the globe, as explored further in Sections 2.6 and 2.7.

2.4.1. EU27 and world forest cover

Forests[6] cover just over 4 Gha, or 31% of the global land area (FAO, 2010; see also Table 2.2 below). A further 8.8% of global land area (just over 1 Gha) is classified as other wooded land[7]. This report focuses on forests, as opposed to other wooded land, as representing the resource of principal relevance to the discussion of forest bioenergy.

With the exception of Oceania, forest area is distributed fairly evenly amongst the major regions of the globe (see Table 2.2). However, forests are distributed unevenly within each major region. For example, in North America, forest areas tend to be concentrated at the margins of the continent (Figure 2.6). In Europe, highest forest cover percentages are generally found in Northern (boreal) Europe (Finland, Sweden, Latvia, Estonia) and mountainous areas (Slovenia, Austria) (Table 2.3, Figure 2.4 and Figure 2.5).

Table 2.2 Distribution of land and forest areas for regions of the globe

Region / sub-region	Land area		Forest area		
	million ha	% of global land area	million ha	% land area	% of global land area
Africa	2974	22.9	674	22.7	5.18
Asia	3091	23.8	593	19.2	4.55
EU27	419	3.2	157	37.5	1.21
Other Europe	1796	13.8	848	47.2	6.52
Central and North America	2135	16.4	705	33.0	5.42
Oceania	849	6.5	191	22.5	1.47
South America	1746	13.4	864	49.5	6.64
World	**13011**	**100.0**	**4033**	**31.0**	**31.00**

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[6] FAO (2010) defines forest as: 'Land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 per cent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use'.

[7] FAO (2010) defines other wooded land as: 'Land not classified as 'Forest', spanning more than 0.5 hectares; with trees higher than 5 metres and a canopy cover of 5-10 per cent, or trees able to reach these thresholds in situ; or with a combined cover of shrubs, bushes and trees above 10 per cent. It does not include land that is predominantly under agricultural or urban land use'.

Table 2.3 Distribution of land and forest areas amongst Member States in the EU27 (Source: FAO, 2010)

EU27 Member State	Land area		Forest area		
	1000 ha	% of EU27 land area	1000 ha	% of land area	% of EU27 land area
Austria	8245	2.0	3887	47.1	0.93
Belgium	3028	0.7	678	22.4	0.16
Bulgaria	10864	2.6	3927	36.1	0.94
Cyprus	924	0.2	173	18.7	0.04
Czech Republic	7726	1.8	2657	34.4	0.63
Denmark	4243	1.0	544	12.8	0.13
Estonia	4239	1.0	2217	52.3	0.53
Finland	30409	7.3	22157	72.9	5.29
France	55010	13.1	15954	29.0	3.81
Germany	34877	8.3	11076	31.8	2.65
Greece	12890	3.1	3903	30.3	0.93
Hungary	8961	2.1	2029	22.6	0.48
Ireland	6888	1.6	739	10.7	0.18
Italy	29411	7.0	9149	31.1	2.19
Latvia	6229	1.5	3354	53.8	0.80
Lithuania	6268	1.5	2160	34.5	0.52
Luxembourg	259	0.1	87	33.6	0.02
Malta	32	0.0	<1	0.9	0.00
Netherlands	3388	0.8	365	10.8	0.09
Poland	30633	7.3	9337	30.5	2.23
Portugal	9068	2.2	3456	38.1	0.83
Romania	22998	5.5	6573	28.6	1.57
Slovakia	4810	1.1	1933	40.2	0.46
Slovenia	2014	0.5	1253	62.2	0.30
Spain	49919	11.9	18173	36.4	4.34
Sweden	41033	9.8	28203	68.7	6.74
United Kingdom	24250	5.8	2881	11.9	0.69
All EU27	**418616**	**100.0**	**156865**	**37.5**	**37.47**

However, whilst Table 2.3 indicates where forest resources in the EU27 are mainly located, it does not follow that forests (and indeed forest industries) are of low importance for other Member States. For example, percentage forest cover in the UK is about 15% (Forestry Commission, 2013) and the area of UK forests represents about 2% of the EU27 forest area, but even this relatively modest resource supports an important forestry sector and significant wood processing infrastructure. It is also important to appreciate the heterogeneity of forests in different Member States, for example, although Finland and Spain have similar areas of forest, their characteristics are very contrasting (see for example Section 3.3).

Forest areas in Europe and North America have a rather similar species composition, with the proportions of conifer and broadleaf forests at roughly 60% and 40% respectively. The distribution of conifer and broadleaf forests across Europe and North America exhibits a general trend towards conifer forest areas in the North and West and broadleaf forest areas in the South and East, but this is subject to considerable variability. In Asia, Africa and South America, broadleaf forests are more dominant, although there are small but important areas of conifer forest, notably those created as industrial plantations.

2.4.2. Growth rates of EU27 and world forests

The rate of growth of forests is obviously a key factor in determining the quantities of wood (including forest biomass) that can be sustainably supplied from forests.

The frequently used forestry term ‘yield’ refers generally to the level of timber or biomass harvested or produced from an individual stand of trees, or from an area of forest formed of many stands. As briefly outlined in Section 2.3, the concept of ‘sustainable yield management’ underpins sustainable forest management, and involves regulating the level of harvesting from forest areas to ensure that the productive capacity of the forest areas (i.e. their capacity for timber volume and biomass growth) is not exceeded. Although systematic and comprehensive data on potential growth rates of forests for countries and regions are not generally available, Forest Research has collated and reviewed sources of information on the potential productivity of forests, focussing primarily on Europe, Russia and North America, but where possible more widely (see for example Christie and Lines, 1979). Much of this information came from an examination of published regional and national yield tables, which give an indication of the expected base growth rates of the existing forest growing stock. It should be noted that these yield tables generally do not take account of any increases in growth rates that might be achieved through the use of fertilisation, a better matching of tree species to site, a change of tree species, tree breeding, genetic modification, etc.

The potential growth rate of a forest stand can be expressed as maximum mean annual increment ($\mathrm{MAI}_{\mathrm{max}}$, see Appendix 2). The ‘mean growth rate’ of forests (expressed as mean $\mathrm{MAI}_{\mathrm{max}}$) is estimated at about 6, 4, and 6 $\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$ respectively for the major regions of the EU27, Other Europe and North America. (Note that the estimate of mean growth rate for Other Europe excluding Russia is about 5 $\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$.) Growth rates observed in tropical regions of Africa, Asia, South and Central America and Oceania can be much higher, typically 14 to 20 m^3 ha^{-1} yr^{-1} and 30 m^3 ha^{-1} yr^{-1}, or greater in the most favourable warm and moist areas (Evans and Turnbull, 2004). For historical reasons, the mean growth rates observed in some parts of the world are lower than might potentially be achieved. Forests in some regions are often located on less fertile land at the margins of agriculture, in the uplands, or on other land where climatic and edaphic factors may limit the rate of tree growth.

Within the major regions of the EU27, Russia with other Europe and North America, growth rates of forests exhibit broad trends, tending to be higher towards the West, particularly near oceans, and lower further East and particularly further North. To a large extent, these trends reflect the preference of trees for warm, moist growing conditions and also to some extent the distribution of conifer and broadleaf forests. In the EU27, the mean growth rates of forests in different Member States show such variations (Figure 2.3). The growth rates of individual stands of trees exhibit considerable variation around mean values, mostly depending on their stage of development (Figures 2.2a-f).

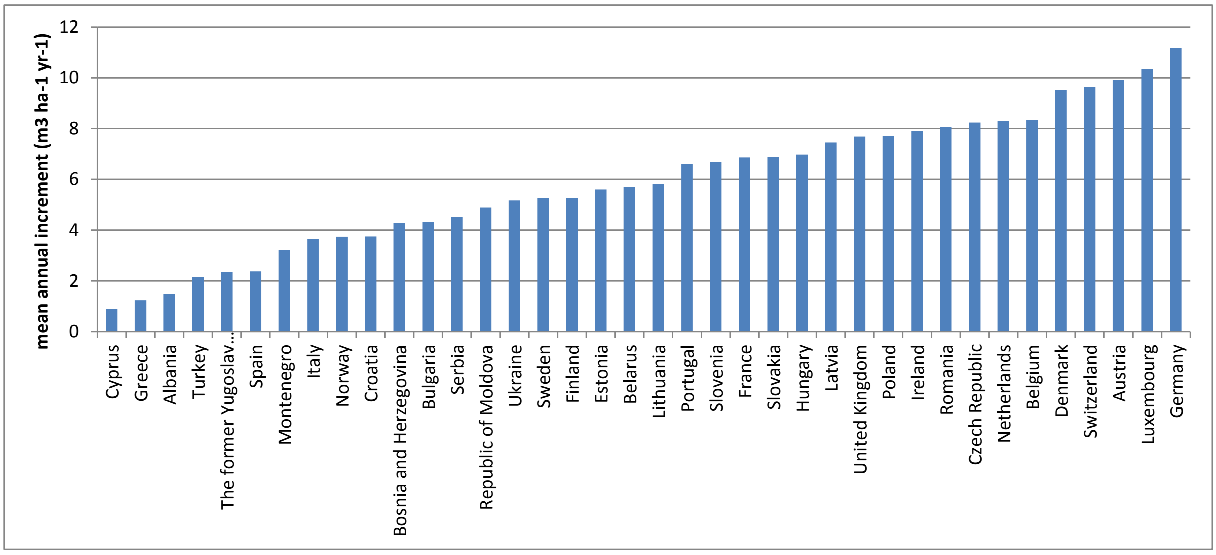

Figure 2.3. Mean annual increment per country in Europe as simulated by the EFISCEN model for the period 2010-2015 (UN-ECE, 2011).

In the major regions of the EU27, Other Europe and North America, in general (but with exceptions), conifer tree species have higher stem volume growth rates than broadleaf tree species. In general, broadleaved trees have more mass per unit of volume and more branchwood per unit of stemwood compared with conifer trees. Therefore, if growth rate is expressed in terms of total tree biomass (oven-dry tonnes, odt) rather than stem volume, growth rates of conifers and broadleaves are more comparable.

Simplistic calculations can be made based on total forest areas and estimated mean growth rates for individual countries to suggest very rough estimates for the theoretical maximum potential for biomass production from forests. For example, an estimate of about 0.4 Godt yr^{-1} is obtained for the EU27, 0.05 Godt yr^{-1} for Other Europe (excluding the Russian Federation), 1.6 Godt yr^{-1} for the Russian Federation and 1.8 Godt yr^{-1} for North America. However, it must be stressed that for a range of reasons, such maximum potentials could never be realised or even approached in practice. Such estimates nevertheless suggest extreme upper limits for forest biomass production which serve as a 'reality check' when constructing scenarios for biomass production and consumption, such as considered in Task 2 of this project.

2.4.3. Ownership and management of EU27 and world forests

The characterisation of the management of forests in different regions of the world is difficult because available data are not comprehensive and the categorisation of forests is subjective and often ambiguous. However, some insights about forest management may be drawn from statistics reported as part of FAO (2010).

FAO (2010) reports information on 'Forest Designation', which indicates the primary function or management objective assigned to areas of forest, examples being 'Production' and 'Protection of soil and water'. Unfortunately, this information is missing for many countries and areas. Moreover, the primary function designated for a forest area may not be a sufficient indicator of forest management for reasons already explained in Section 2.3. For these reasons, it may be more appropriate to make inferences about the management of forest areas in different regions of the world based on their ownership and broad classification (i.e. into categories such as 'primary forest' and 'planted forest').

Forest ownership can be an important factor in how forests are managed. A usual distinction is in public and private ownership. However, the terms public and private ownership have different interpretations in different regions of the globe. Table 2.4 summarises how these terms may be interpreted and, in particular, the implications for management of forests in different countries and regions. It must be stressed that these descriptions are somewhat speculative and provide 'caricatures' of forest management in different regions.

Globally, about 80% of forest area (3.2 Gha) is in public ownership[8] with most of the rest in private ownership[9] (about 18% or 0.7 Gha) (Table 2.5). Public ownership varies considerably between regions, ranging from about 40% in EU27 and USA to around 95% in Other Europe, Canada and Africa. Also within regions there is considerable variation in ownership (Figures 2.4 to 2.6).

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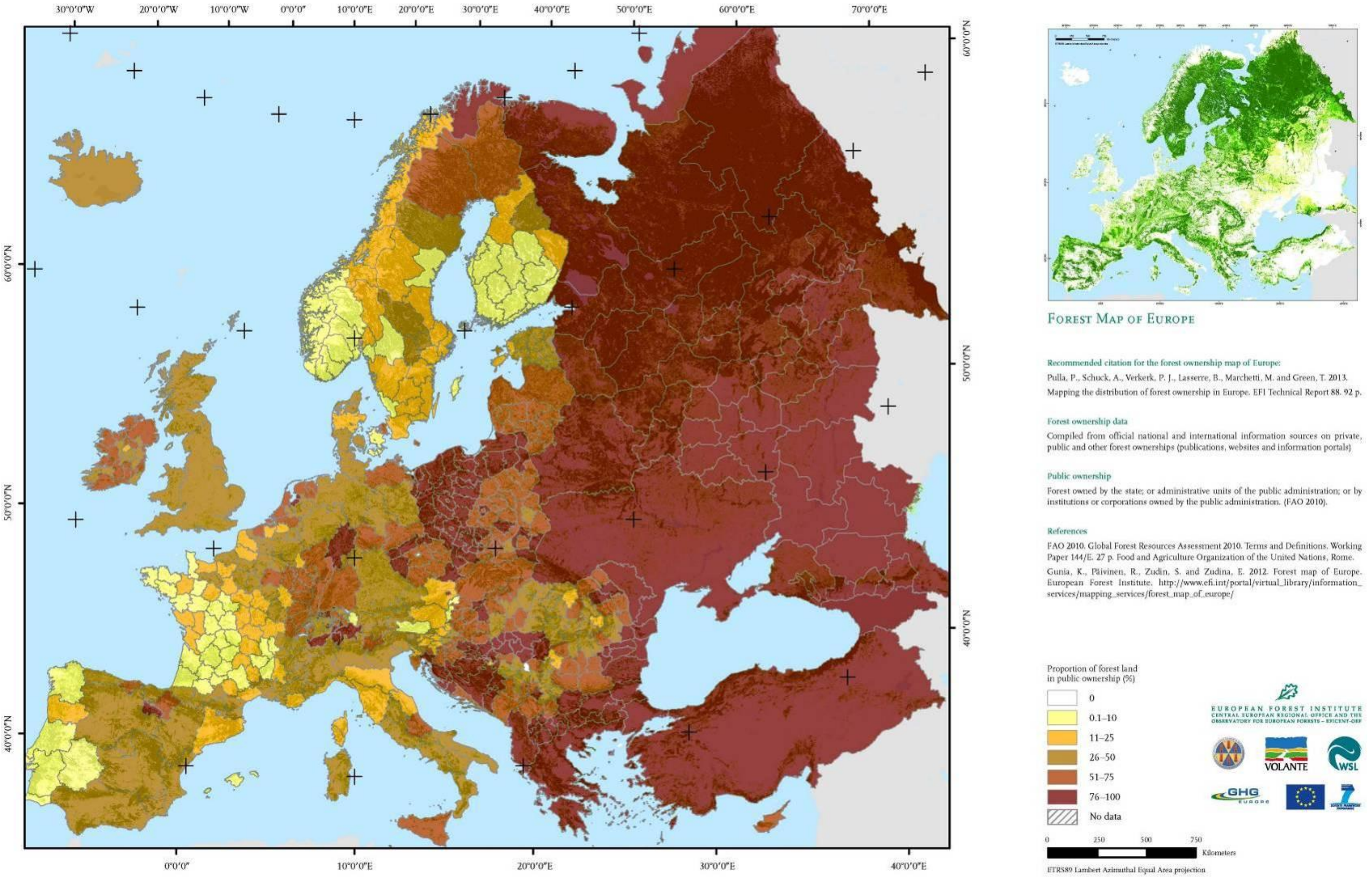
[8] FAO (2010) defines 'public ownership' as referring to 'forest owned by the State; or administrative units of the Public Administration or by institutions or corporations owned by the Public Administration'.

[9] FAO (2010) defines 'private ownership' as referring to 'forests owned by individuals, families, communities, private-operatives, corporations and other business entities, private religious and educational institutions, pension or investment funds, NGOs, nature conservation associations and other private institutions'.

Table 2.4 Summary description of forest management in public and private ownership in different regions of the globe

Country/ region	Forest areas in public ownership	Forest areas in private ownership
EU27	Generally implies forest areas that are state-owned and managed by state-run management organisations. As such, these forest areas may be subjected to a variety of forest management practices most likely consistent with multipurpose forestry and 'management cycles' as described in Section 2.3. Some areas will consist of natural reserves and national parks.	Generally implies forest areas that are privately owned (and which may be quite small), owned by individuals and families, which might be managed by a local co-operative of owners or by a private management corporation, or may not be managed at all.
Other Europe	As EU27, but there are also areas in state-ownership where permissions may be granted for private forestry companies to carry out harvesting as thinning or partial/complete clear felling. Harvesting activities in such forests are regulated.	As EU27. Small contribution to global total.
Russian Federation	As Europe.	No forest in private ownership in the Russian Federation.
USA	As Europe.	Mainly like EU27, but also a significant minority of forests owned and managed by large private corporations.
Canada	As Europe.	As USA. Small contribution to global total.
Oceania	Primarily, implies areas in state-ownership where permissions may be granted for private forestry companies to carry out harvesting as thinning or partial/complete clear felling. Harvesting activities in such forests are regulated.	Diverse (see Rest of Europe and Asia/South America).
Asia and South America	As Oceania but, in some regions, regulation may be challenging due to the extent of the resource needing to be regulated.	Generally implies forest areas owned by multinationals (in particular forest areas formed of industrial plantations). Some areas owned by communities for local use, some areas owned by NGOs and conservation organisations primarily for conservation.
Africa		As Asia/South America. Small contribution to global total.



Recommended citation for the forest ownership map of Europe:

Pulla, P., Schuck, A., Verkerk, P. J., Lasserre, B., Marchetti, M. and Green, T. 2013. Mapping the distribution of forest ownership in Europe. EFI Technical Report 88. 92 p.

Forest ownership data

Compiled from official national and international information sources on private, public and other forest ownerships (publications, websites and information portals)

Public ownership

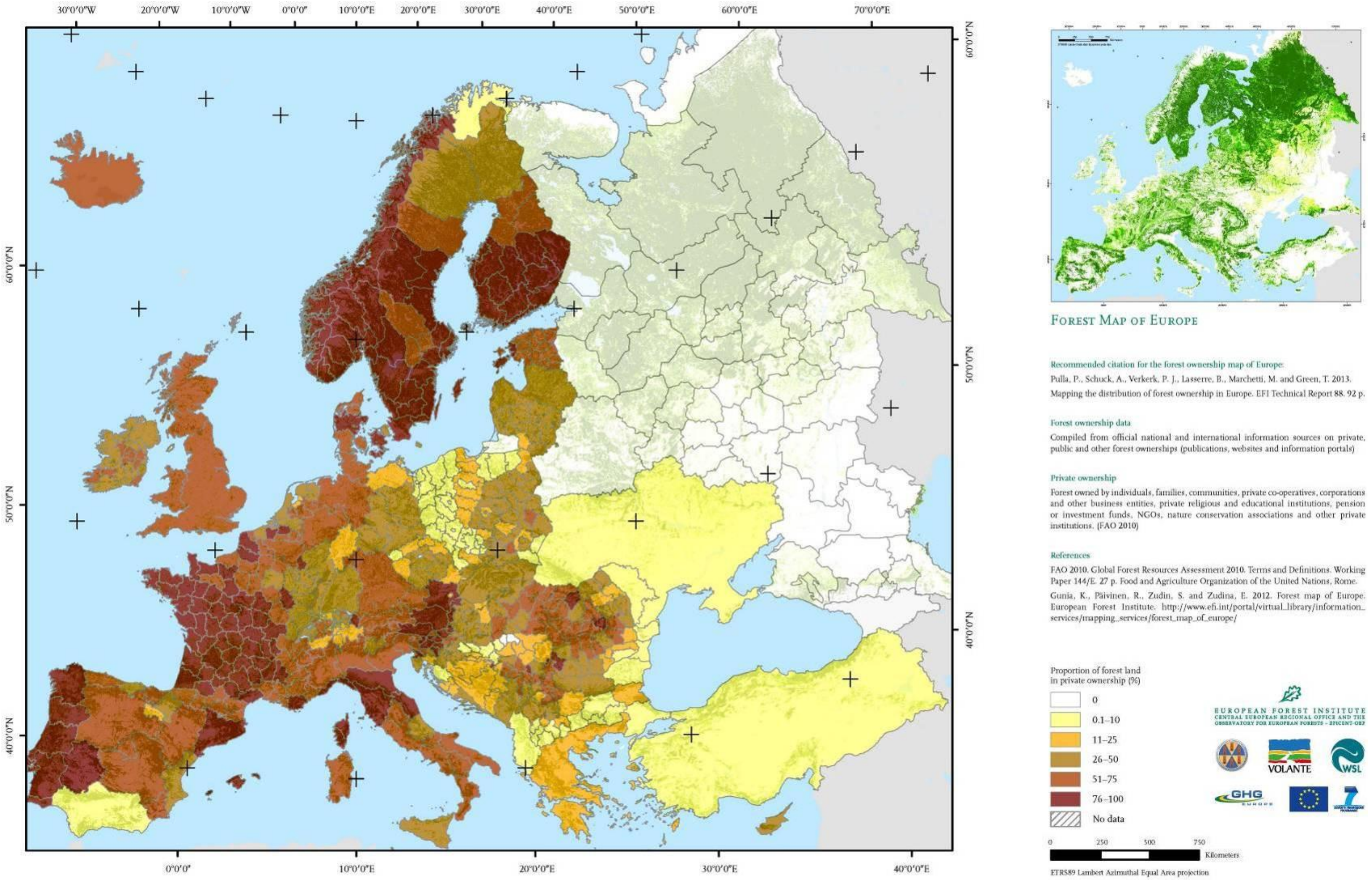
Forest owned by the state; or administrative units of the public administration; or by institutions or corporations owned by the public administration. (FAO 2010).

References

FAO 2010. Global Forest Resources Assessment 2010. Terms and Definitions. Working Paper 144/E. 27 p. Food and Agriculture Organization of the United Nations, Rome.

Gunia, K., Päivinen, R., Zudin, S. and Zudina, E. 2012. Forest map of Europe. European Forest Institute. http://www.efi.int/portal/virtual_library/information_services/mapping_services/forest_map_of_europe/

Figure 2.4. Map showing the spatial distribution of forests in public ownership in Europe. (Source: Pulla *et al.*, 2013.)



FOREST MAP OF EUROPE

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Private ownership

Forest owned by individuals, families, communities, private co-operatives, corporations and other business entities, private religious and educational institutions, pension or investment funds, NGOs, nature conservation associations and other private institutions. (FAO 2010)

References

FAO 2010. Global Forest Resources Assessment 2010. Terms and Definitions. Working Paper 144/E. 27 p. Food and Agriculture Organization of the United Nations, Rome.

Gunia, K., Päivinen, R., Zudin, S. and Zudina, E. 2012. Forest map of Europe. European Forest Institute. http://www.efi.int/portal/virtual_library/information_services/mapping_services/forest_map_of_europe/

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Figure 2.5. Map showing the spatial distribution of forests in private ownership in Europe. (Source: Pulla *et al.*, 2013.)

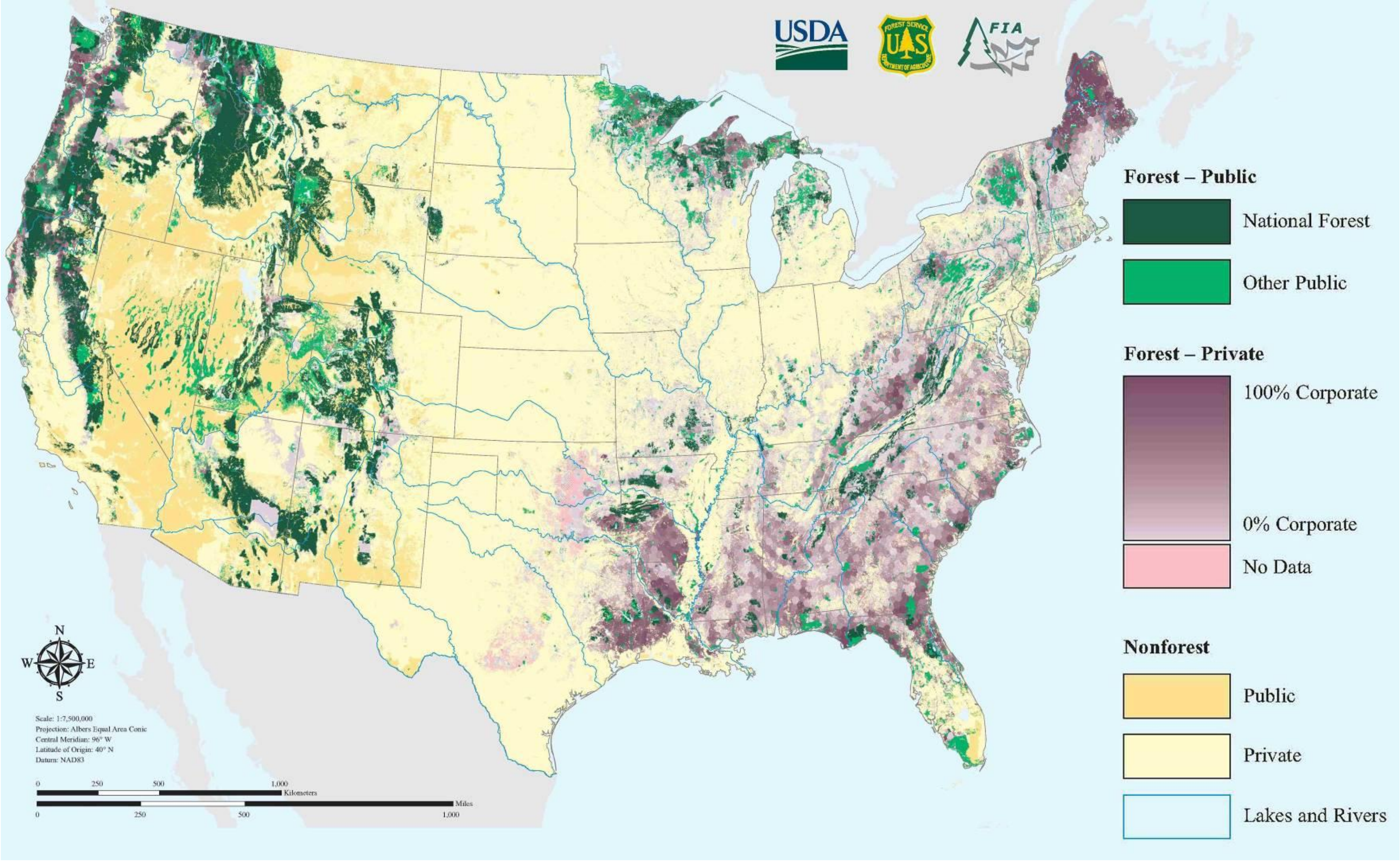

Figure 2.6. Map showing spatial distribution of forests in the conterminous States of the USA. Ownership of forest areas is also indicated. (Adapted from Nelson *et al.*, 2011.)

Table 2.5 Ownership of forests in major regions of the globe (from FAO, 2010)

Country/region	Percentage forest area by ownership within country/region		
	Public	**Private**	**Other**
EU27	40.4	58.4	1.2
Other Europe (including Russia)	98.6	1.4	0.0
Canada	92.0	8.0	0.0
USA	43.0	57.0	0.0
Central America and Caribbean	58.8	39.7	1.5
South America	75.1	21.5	3.4
Asia	80.8	19.1	0.1
Oceania	62.0	37.3	0.8
Africa	94.7	3.7	1.5
Total	80	18	2

Note: percentages for a country may not sum to 100 due to rounding.

FAO (2010) classifies forest areas using the categories of planted forest[10], other naturally regenerated forest[11] and primary forest[12], as summarised in Table 2.6. These are particularly subjective and ambiguous terms which, more generally, are not favoured for use in this report. It is also important to note that reporting of data according to this classification is incomplete. For example, FAO (2010) includes a note explaining that zero area of primary forest reported for a country may be due to a lack of information on the area of primary forest. Hence, considerable caution is required when interpreting statistics referring to this classification, particularly if attempting to draw inferences about how forests are being managed. On this basis, data reported by FAO (2010) suggest that at least 36% of the global forest area is within the category of primary forest. Thus potentially, up to 64% (57% naturally regenerated forest plus 7% planted forest) of the global forest area may be under active forest management. As already stressed, it is difficult to determine precisely what this means for the extent and types of forest management. Thus, this is likely to be an upper limit for the area being managed globally for wood production.

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[10] FAO (2010) defines ‘planted forest’ as ‘forest predominantly composed of trees established through planting and/or deliberate seeding’.

[11] FAO (2010) defines ‘other naturally regenerated forest’ as ‘naturally regenerated forest where there are clearly visible indications of human activities’.

[12] FAO (2010) defines ‘primary forest’ as ‘naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed’.

Table 2.6 Characterisation of forests in major regions of the globe

Country/region	Percentage forest area by characteristic within country/region		
	Planted	Regenerated	Primary
EU27	27.8	69.2	3.0
Other Europe	3.2	66.5	30.4
Canada	2.9	43.8	53.3
USA	8.3	66.9	24.8
Central America and Caribbean	4.9	51.4	43.7
South America	1.7	22.0	76.3
Asia	20.8	60.7	18.6
Oceania	2.1	79.3	18.6
Africa	3.1	87.4	9.6

Note: percentages for a country may not sum to 100 due to rounding.

Table 2.7 Estimated percentage area of forest within regions under management for wood production

Region	Percentage area	Comments
EU27	60	Varies between 10 and 90 for individual Member States
Other Europe	35	Lower in the Russian Federation in percentage terms
North America	35	Higher in the USA than Canada in percentage terms
Oceania	Between 2 and 20	Higher in New Zealand than Australia in percentage terms

Within any country or region, areas of planted forest will be amongst those most likely to be managed for wood production; this may also be the case for areas of other naturally regenerated forest, whilst being least likely for areas of primary forest. Management for wood production is also likely to be associated with forest areas that have relatively high growth rates, since these areas will be more favourable in economic terms. As a consequence, forest areas in the far north of Canada, Fennoscandia and the Russian Federation are particularly unlikely to be managed for industrial wood production. Table 2.7 gives the estimated percentages of forest area under management for wood production in four regions.

The relatively high percentage of planted forests in the EU27 may be noted, which most likely reflects significant afforestation activities in several Member States during the previous century (see Section 3.3). The high percentage of planted forests in Asia is largely due to China, where there has been a recent programme of afforestation. The limitations in the reporting of primary forest area have already been stressed above. However, it may be noted that the percentage area of primary forest in the EU27 is very small, in contrast to other regions and countries notably South America, Canada, Asia and Other Europe. It is very important to recognise that primary forest (e.g. as defined in FAO, 2010) should not be assumed to always be in an undisturbed state with high associated growing stock. For example, the FAO definition of primary forest suggests forest areas apparently unaffected by human activities and with 'ecological processes not significantly disturbed' (FAO, 2010), but these ecological processes may include significant natural disturbance processes such as storms, fires and attacks by insects or diseases. It follows that the growing stock of primary forest areas can be very variable between and within regions, depending on the interplay between tree growth and natural disturbance processes.

Beyond the preceding qualitative discussion, it is difficult to make definitive statements about forest management practices in different regions of the world, and generally there is a lack of systematic data on this subject. Areas of forest likely to be involved in management for wood production will include the vast majority of plantations and a variable proportion of natural/semi-natural forest areas. Various factors will determine whether forests are managed for production including wood properties of trees, growth rate, accessibility and proximity to processing facilities or centres of population, and most obviously the level of demand for wood.

In the EU27, forest management involving wood production should adhere closely to the broad principles described in Section 2.3. This is also true for forest management in other regions of the world, but some important distinctions should be noted. Notably, in Other Europe, the Russian Federation and North America, there can be greater emphasis on more extensive management practices involving harvesting. These practices include, for example, periodic harvests in natural and semi-natural forests involving complete clear felling or the removal of a significant proportion of the trees forming a forest area, in some cases concentrating on removal of the highest quality trees. After harvesting, forest areas are allowed to regenerate. The process of regeneration may be unassisted, or may be supported by the retention of seed trees as part of harvesting operations, or possibly planting of new trees. The 'rotation' in such forest areas is effectively determined by the time taken for trees to regenerate following harvesting, to the point where further harvesting becomes economically attractive.

2.5. How wood is produced and used

As outlined in Section 2.3, at any one time across a whole forest, a broad mix of trees will be harvested which will be variously suitable for a range of end uses (although it is extremely uncommon for whole stands of trees to be felled and all of the harvested wood to be used for bioenergy). Generally, whole trees are used for bioenergy only when they are very small and otherwise would be 'felled to waste'; when they are of small diameter, or when they are of large diameter and also of poor stem form (and so unsuitable for producing high grade sawn timber). However, potential for competition for 'lower-grade' wood material between the bioenergy sector and the particleboard and pallet sectors needs to be recognised.

The wood processing sector is complex, with outputs from the forest providing feedstocks for the manufacture of structural sawn timber, plywood, pallets and fence posts, particleboard and fibreboard, paper and other products including bioenergy. Whilst it is common for bioenergy feedstocks to be derived from co-production of higher value timber products, it is very unlikely that wood will be diverted from the manufacture of high value wood products to supply forest bioenergy. Nevertheless, there are risks that co-products could be diverted from the manufacture of particleboard, fibreboard and paper to meet growing demand for bioenergy feedstocks. These subjects will be addressed within the current sub-section.

The main factors determining the suitability of raw harvested wood for specific uses are size (i.e. diameter and length of stemwood or branches) and straightness. Figure 2.7 illustrates examples of raw harvested wood and describes how these typically would be processed for specific end uses.

A glossary of technical terms is included in Appendix 1 of this report, but certain terms are so essential to understanding the ensuing analysis and discussion, that it is necessary to direct the reader to these at the outset. These essential terms are listed in Box 2.1, below, and full definitions are presented in Appendix 1.

Figure 2.7 illustrates the potential complexity of the wood processing sector, notably how raw wood products such as sawlogs and small roundwood are prioritised for manufacture of certain finished products (such as sawn timber products, pallets and paper). The figure also shows how raw products can form feedstocks for one or more co-products, often involving exchanges in woody material amongst different sub-sectors of the wood processing industries. As a key example, typically sawlogs are processed in a sawmill to manufacture a principal product of sawn timber, in the process generating co-products of sawlog offcuts and sawdust. These co-products may be used as feedstocks in a boardmill for the manufacture of wood-based panels, or may be processed at the sawmill, boardmill or elsewhere to supply as wood chips or wood pellets for burning as bioenergy. Some of the material may be utilised as animal bedding. Wood processing mills may also use some harvested wood as bioenergy to provide heat and possibly power for the mill itself, e.g. for processing stages or for offices.

Box 2.1 Essential terms used to refer to types of felled and/or harvested wood

The following technical terms are essential to understanding the analysis and discussion in the remainder of the report. The reader is referred to the definitions, which are presented in the glossary (Appendix 1).

Harvesting residues (or felling or forest residues)
Industrial roundwood
Primary wood
Recycled wood
Removals
Roundwood
Sawlogs
Secondary wood
Small roundwood
Stemwood or 'main stem'
Waste wood
Woodfuel (as a commodity)
Woodfuel (as a reported statistic)

It should be evident from the illustration in Figure 2.7 that the wood from harvested trees is rarely used to make a single product, such as solely to manufacture wood based panels, paper or wood pellets for bioenergy. However, as explained in Section 2.3, there may be exceptions, such as small trees or trees with very deformed stems which may be used entirely for products such as wood based panels or possibly bioenergy. Different elements from the harvested trees typically comprise a diverse assortment in terms of sizes and properties (such as stem form), which are suitable for different end uses. As discussed in Section 2.7, this is reflected in the prices attracted by different types of tree (e.g. broadleaf or conifer) and tree components (i.e. sawlogs, small roundwood and branchwood).

Bioenergy is typically produced from low value feedstocks including (see Figures 2.2 and 2.7):

- small and poorly formed trees
- harvesting residues
- some co-products of sawmills and boardmills and
- secondary wood from products disposed of at end of life.

As discussed briefly in Section 2.7, currently, forest bioenergy does not appear to be price-competitive with the feedstock markets for finished solid wood products such as sawn timber, wood based panels or paper products. However, it is more difficult to determine whether forest bioenergy is in competition for sources of wood conventionally used as feedstock for the wood-based panel industries.

The complexity of the wood processing sector can present challenges when attempting to track flows of wood from the forest through to ultimate end use. This may be important, for example, if there is a requirement to characterise in detail the types of feedstock contributing towards supplies of forest bioenergy. Furthermore, changes in demands for different types of wood product, such as a marked increase in demand for forest bioenergy, may influence flows of wood through the forest and wood processing sectors. The task of determining such potential changes must be undertaken carefully, taking into account possible interactions between demands for different types of wood. However, it remains the case that certain raw wood products and co-products have properties that are optimal for the manufacture of certain specific finished wood products. These properties are likely to remain critical in determining how raw wood is prioritised for consumption within the forest and wood processing sectors.

A further layer of complexity is added when considering trade in raw wood, semi-finished and finished wood products between Member States of the EU27, and between the EU27 and other regions of the world. Despite the potential complexity of the task, in principle it is possible to characterise flows of wood in and out of the EU27 and between EU27 Member States, as was presented in the EUwood report of Mantau *et al.* (2010). The study of Mantau *et al.* (2010) was referred to and extended in the European Forest Sector Outlook Study II (EFSOS II), 2010-2030 (UN-ECE, 2011). In practice, such exercises have rarely been undertaken and examples of how such an analysis might be undertaken and reported at Member State level are shown in Figures 2.8 and 2.9. The main flows of imported and home-grown (including exported) wood and various co-products within the forest and wood processing sectors of Great Britain are illustrated in Figure 2.9. The patterns of wood utilisation depicted in the figure are in broad agreement with the idealised patterns portrayed in Figure 2.7. The significant contribution made by imported wood (in the case of Great Britain) is also evident in Figure 2.9. Such analyses are very useful for identifying the original sources and types of wood feedstocks involved in the supply of different categories of wood product (including bioenergy), but it is perhaps pertinent that this particular example is based on a study dating from the mid 1990s, which has not been updated more recently.

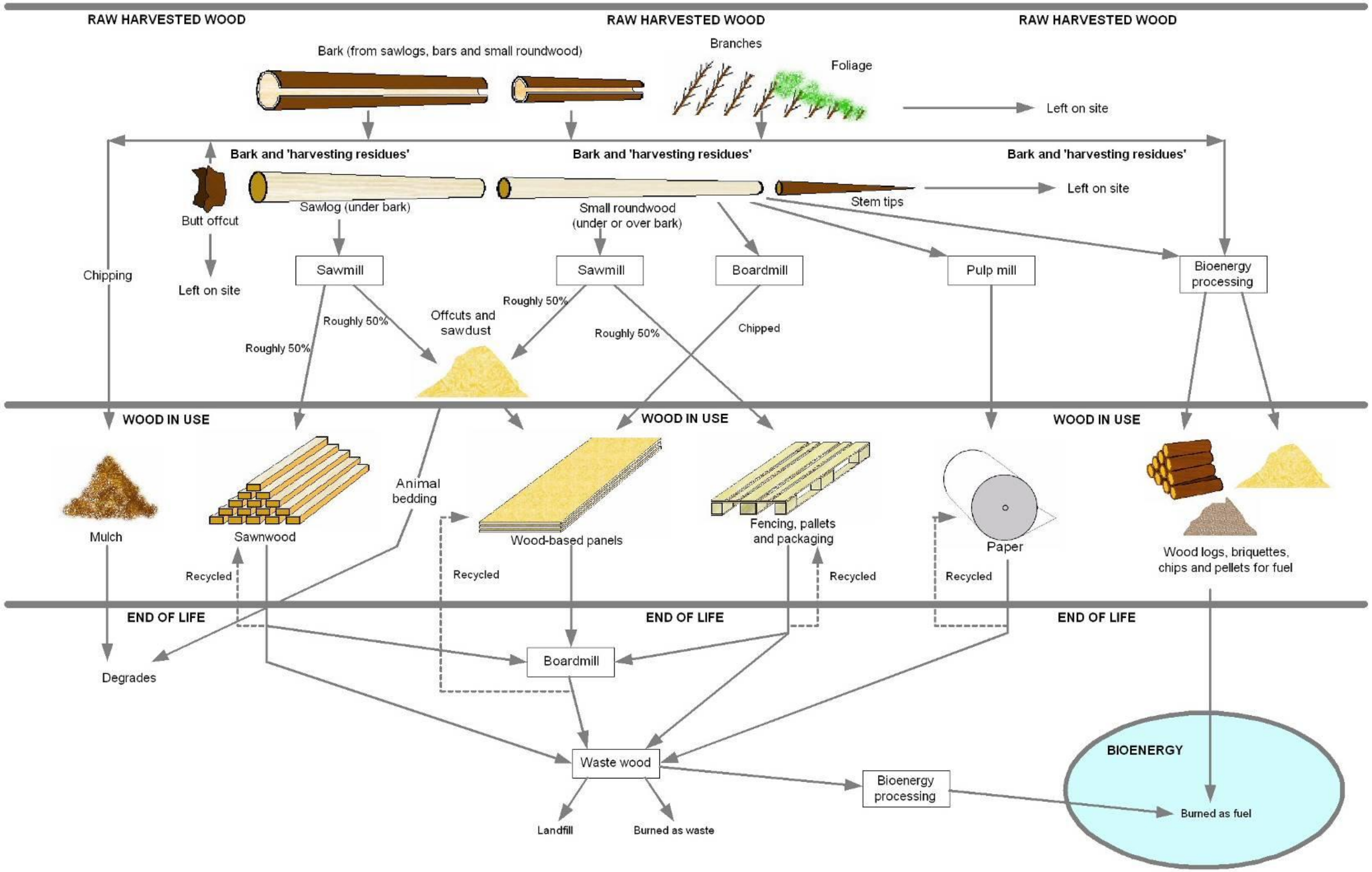

Figure 2.7. Simplified illustration of how different types of raw wood products are processed into finished wood products and potentially recycled at ‘end of life’.

Figure 2.8 summarises the results of an analysis of the countries of origin for a range of solid wood products imported into the UK in 2010. The country/region of origin of wood material is influenced by the type of wood product, for example (and most obviously) whether the country produces the particular product. The source of wood material will also vary annually due to changes in the markets, and relative and absolute values for each wood product type. Figure 2.8 shows the percentage of types of wood product imported in 2010 by the country of origin. For example, in 2010, more than 60% of the total softwood sawnwood imported into the UK came from just three countries, which happen to be EU27 Member States, i.e. Sweden (43%), Latvia (14%) and Finland (12%). Imports of softwood sawnwood, particleboard, fibreboard, paper and paperboard in 2010 came mainly from within the EU27. Imports of sawn hardwood, plywood and wood pulp in 2010 came mainly from outside the EU27.

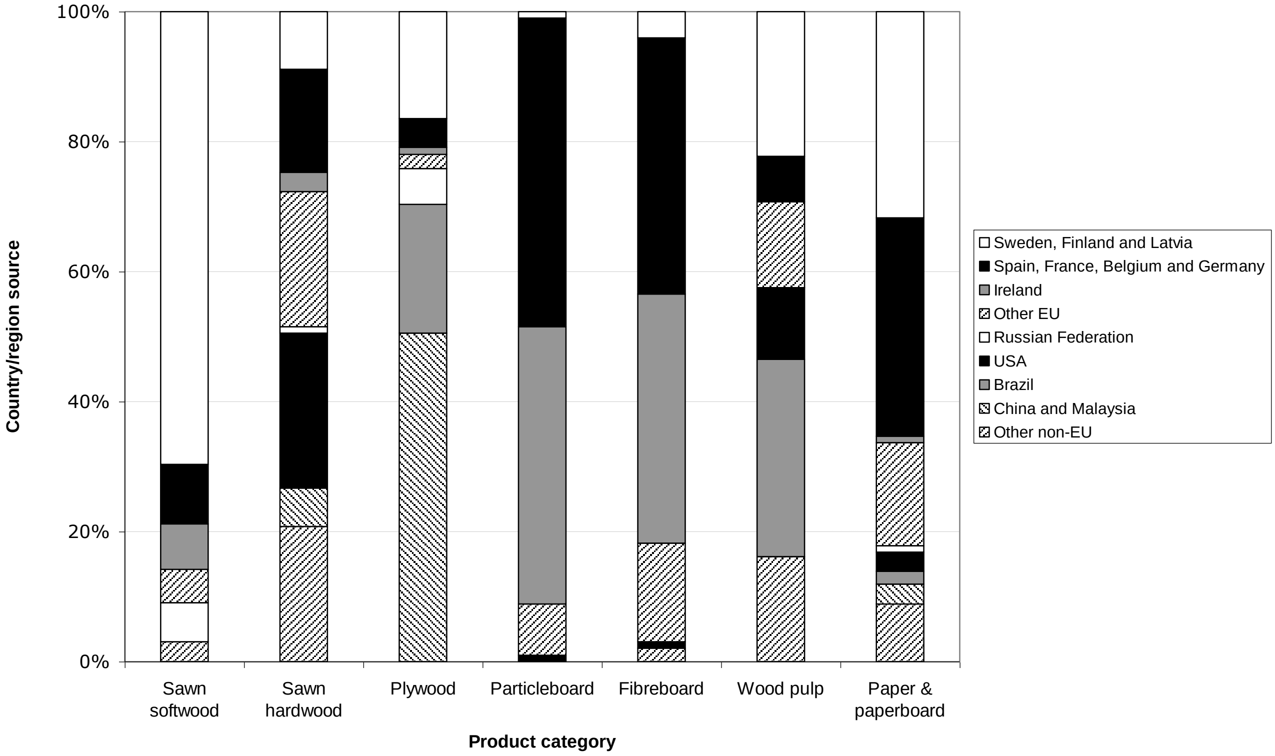

Figure 2.8. Bar chart showing the country of origin, by percentage of total imports, of types of wood product into the UK in 2010. Based on Forestry Commission (2011).

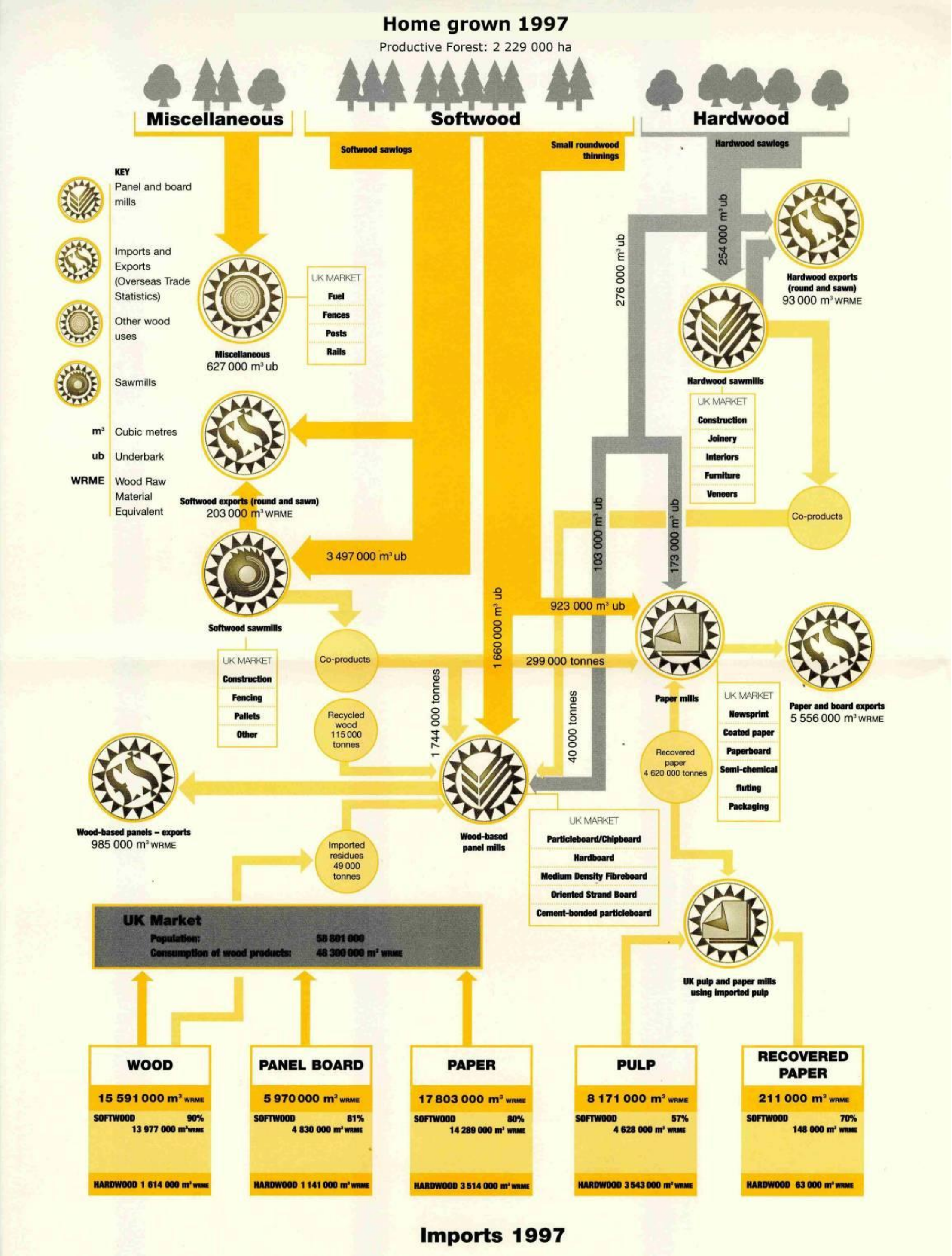

Figure 2.9. Illustration of the principal flows of wood in the British/UK forest and wood processing sectors for the year 1997. (Source: FICGB, 1998.)

Whilst statistics such as presented in Figures 2.8 and 2.9 serve as an illustration of wood flows within an EU27 Member State, including the contributions due to home-grown and imported wood, the patterns for other Member States will be very variable. Unfortunately, data on wood consumption are not available for all Member States or the EU27 as a whole at the level of detail in Figures 2.8 and 2.9. It is also notable that information on sources of forest bioenergy is missing from the results in Figures 2.8 and 2.9. This subject is considered further in Sections 2.6 and 2.7.

The potential complexity of flows of wood may complicate the LCA calculations needed for the assessment of GHG emissions associated with forest bioenergy. This point is explored further in Section 4 of this report.

2.6. Current and potential future production and consumption of forest bioenergy

So far, the discussion in this section has discussed aspects of forests, forest management and wood utilisation and, where appropriate, noted relevance to the assessment of GHG emissions due to the production and use of forest bioenergy. It is now appropriate to address directly the subject of forest bioenergy production and consumption. There are no comprehensive data sources on which to base such a discussion, but several reports and data sets are available which help to gain a picture of the existing and potential future use of bioenergy, globally and in the EU27. The main relevant sources are:

- An analysis undertaken by the GB Forestry Commission of FAO statistics on ‘wood removals’ (i.e. wood harvesting) for regions of the world over the period from 1990 to 2010 (Forestry Commission, 2012).
- A synthesis of data from National Renewable Energy Action Plans (NREAPs) published by EU27 Member States in response to the EU Renewable Energy Directive (Beurskens *et al.*, 2011).
- The final report of the EC EUwood Project (Mantau *et al.*, 2010).
- Information on import and export prices of wood products collected and reported by the UN-ECE (www.unece.org/forests/output/prices.html).
- The UN-ECE European Forest Sector Outlook Study II (EFSOS II) 2010-2030 (UN-ECE, 2011).
- Statistics on woodfuel trade in the UK collected and reported by UK HM Revenue and Customs, accessed through the UKTradeInfo website (www.uktradeinfo.com).
- Statistics on woodfuel consumption in the UK in 2011 reported by Ofgem (2012).
- An EU/global-scale economic analysis of the potential contribution of forest biomass to the EU target for utilisation of renewable energy sources and its implications for the EU forest industries (Moiseyev *et al.*, 2011).
- The Joint Wood Energy Enquiry by the UN-ECE (http://www.unece.org/forests/jwee.html).

Forest bioenergy is commonly referred to as ‘woodfuel’ in these reports and data sets, and a number of categories of woodfuel can be identified, as described in Box 2.2.

Box 2.2 Major categories of woodfuel and their uses

Logs: Almost unprocessed raw harvested wood, possibly small stemwood, parts of large stemwood, often parts of branches, with or without bark. Most frequently used for domestic heating, some for food smoking.

Briquettes: Wood chips, sawdust, and waste and scrap wood, possibly bark, compressed at high temperature to form a homogenised mass of wood with uniform dimensions. Most frequently used for domestic heating, some for food smoking.

Chips: Solid wood, with or without bark, comminuted to make small to moderate size pieces of wood. Often wood chips are made to specified dimensions. Used for a range of applications including (relatively) small-scale power generation, domestic and small-scale commercial heating, food smoking. Wood chips may also be used for non-fuel uses, notably animal bedding.

Pellets: Wood which has been ground to sawdust and then compressed to form pellets of a size, shape and consistency. Used in large quantities for large-scale power generation, including co-firing with coal, also used for domestic and commercial heating systems, particularly automated systems.

Based on an analysis of statistics compiled by the FAO, a report produced by the GB Forestry Commission has summarised ‘wood removals’ from forests for regions of the world over the period 1990 to 2010, to meet demands for industrial roundwood and woodfuel (Forestry Commission, 2012). Total removals for the EU27 and for the globe are shown in Table 2.8. At the global scale, removals to meet demands for woodfuel slightly exceed those for industrial roundwood, accounting for around 53% of total removals. It is difficult to discern a trend in removals for industrial roundwood when compared with fluctuations in values for different years. However, there is a suggestion that removals for woodfuel have been rising gradually since 1995. The Forestry Commission report notes that ‘around three quarters of woodfuel removals took place in Asia and Africa’, and that, ‘globally, removals of woodfuel increased by 1% between 2009 and 2010’. This small percentage rise very approximately represents an increase in annual removals of around of 11 million cubic metres over bark. It should also be noted that the high proportion of woodfuel removals in Asia and Africa is generally associated with local domestic use for heating and cooking.

Table 2.8 also shows wood removals in the EU27 for woodfuel and industrial roundwood for the period 1990 to 2010, based on the report by the GB Forestry Commission (2012). Compared with the global scale, removals for woodfuel represent a smaller share of total removals (17% to 20% over the period). However, removals for woodfuel appear to have risen noticeably since 1995, amounting to about 75 million cubic metres in 1995 and 96 million cubic metres in 2010. A similar trend cannot be discerned for the share of removals of woodfuel in the EU27 compared with total removals. This share seems to remain stable over the period 1990 to 2005, taking a value of 17% or 18%, but then rises to 20% in 2010. It may be relevant to note that small-scale harvesting of wood to provide supplies of woodfuel for local domestic consumption may be poorly represented in statistics for wood removals in some regions, not least the EU27. In some situations, this could involve quite significant quantities of wood and associated forest harvesting activities. It is unclear whether the apparent rise in removals for woodfuel in the EU27 is real or reflects improved monitoring and reporting.

Subject to the qualifying remarks in the preceding discussion, the results in Table 2.8 provides some very tentative evidence that consumption of wood for fuel appears to have increased in recent times but, although consumption of woodfuel takes place mainly in Asia and Africa, consumption within the EU27 appears to be growing, and also to be contributing to a small extent to recent increases at the global scale.

It is important to note that a simplistic interpretation of the share of removals for woodfuel in the EU27, compared with total removals (up to 20%), might lead to the conclusion that use of wood for energy in the EU27 remains minor compared to the use of wood to make materials for construction, paper and packaging (i.e. industrial roundwood). However, as Mantau *et al.* (2010) have stressed, it is important to appreciate the complex patterns in the utilisation of wood, involving the supply of feedstock from a range of sources and the re-use of wood materials at end of life (see Sections 2.3 and 2.5 of this report).

Mantau *et al.* (2010) identify two major categories of wood supply, 'forest woody biomass' and 'other woody biomass':

1. Forest woody biomass essentially consists of primary wood from forests, i.e. wood derived directly from forest harvesting which has not already been used previously, plus woody biomass from harvest residues and stump removal.
2. Other woody biomass represents wood from a range of sources, including secondary wood (i.e. recycled wood and waste wood) and 'arboricultural arisings' (i.e. wood derived from non-forest trees such as on farmland, in parkland, as part of hedges and in urban areas).

The results in Table 2.8 reflect the harvesting of primary wood to meet demands for materials and energy, but both primary wood and other woody biomass sources are utilised to meet these demands. Generally speaking, in the context of the EU27, the tendency has been for most primary wood to be used for materials and woodfuel demands to be met largely by sources of other woody biomass. Consequently, the results for woodfuel in Table 2.8 (which only reflect consumption of primary wood) significantly underestimate total consumption of wood for energy. A further complication arises because primary wood used for materials can re-enter the wood supply at the end of the life of the primary product. For example, primary wood may be used initially to make sawn timber for construction; when this reaches the end of its service life the waste wood may be used to manufacture particleboard, or may be used for fuel, alternatively when the particleboard product reaches the end of its service life, the wood may then be used for fuel. This means that sources of other wood include a significant component of recycled primary wood, effectively but legitimately double-counting some of the original supply of primary wood. These points need to be appreciated when interpreting information on potential wood supply and demands.

Table 2.8 Wood removals[1] in the EU27 and globally over the period 1990 to 2010

Region	**Wood removals (million m^3 over bark)**				**Woodfuel share**
	Year	**Industrial roundwood**	**Woodfuel**	**Total primary wood**	
EU27	1990	357	76	433	17%
	1995	330	75	405	18%
	2000	383	78	461	17%
	2005	416	85	501	17%
	2010	380	96	476	20%
Global	1990	1 775	2 050	3 825	54%
	1995	1 709	2 025	3 734	54%
	2000	1 832	2 040	3 871	53%
	2005	1 954	2 081	4 035	52%
	2010	1 737	2 111	3 848	55%

Notes to Table 2.8:

1 Wood removals are to meet demands for woodfuel and industrial roundwood. These results have been adjusted from underbark values reported in Forestry Commission (2012), for application in subsequent analysis.

As already noted, the results in Table 2.8 reflect the harvesting of primary wood to meet demands for materials and energy. Mantau *et al.* (2010) have estimated the potential supply from sources of other woody biomass for the year 2010, and have also made projections of the potential supply from this source in 2020 and 2030. In Figure 2.10, the reported removals of primary wood in the EU27 for the period 1990 to 2010 (already presented in Table 2.8) are shown in combination with the estimates from Mantau *et al.* (2010) of potential supply from other woody biomass sources for 2010 and 2020.

Mantau *et al.* (2010) also made projections of potential for supply of primary wood from EU27 forests in 2020 and 2030. In their report, Mantau *et al.* (2010) considered both wood from forests and wood from trees outside the forest as being important sources of primary woody biomass within the EU 27. However, for the purposes of the current study, primary wood is assumed to equate to removals from forests as shown in Table 2.8 and Figure 2.10. In addition in Figure 2.10, removals for the years from 2010 to 2020 have been extrapolated by assuming the same level as reported for the year 2010. This assumption is reasonably consistent with the pattern of removals observed between 1990 and 2010, although there is a slight increase over this period. The assumption is supported by simulations made with the CARBINE model of future potential for wood production from EU27 forests under a 'business as usual' scenario, i.e. a scenario in which forest management is assumed to continue as currently practised across the EU, which suggest that levels of production should remain fairly stable in coming decades unless the management applied to forest areas is changed. The results in Figure 2.10 are expressed in millions of cubic metres under bark.

Combining the result in Figure 2.10 for reported total removals of primary wood in 2010 with potential supply of other woody biomass gives a total potential wood supply from all EU27 sources of nearly 800 million cubic metres, rising to just over 845 million cubic metres in 2020.

The estimates of demand for wood materials in 2010 and 2020 were taken directly from Mantau *et al.* (2010). The report of Mantau *et al.* also gives an estimate of the demand for woodfuel (energy), however the authors note that their estimates (particularly of future demands) could be confirmed in the future through consideration of information reported in National Renewable Energy Action Plans (NREAPs) published by EU Member States in response to the EU Renewable Energy Directive.

In order to estimate the trend in potential future demands for woodfuel in the EU27, an analysis was carried out on NREAP data reported by Beurskens *et al.* (2011), specifically on energy derived from solid biomass reported in Tables 120 and 134. The results of this analysis were then reconciled with the estimate for woodfuel demand for 2010 as reported by Mantau *et al.* (2010) by making a simple percentage adjustment to arrive at the estimates for woodfuel demand shown in Figure 2.10. It is important to stress that these results are based on a series of speculative assumptions and that they must therefore be regarded as strictly preliminary, however, the levels suggested in 2020 turn out to be consistent with those estimated independently by Mantau *et al.* (2010) and the figures published in the EFSOS II report (UN-ECE, 2011). The estimated total demand for woody biomass (for materials and for energy) is shown in Figure 2.10.

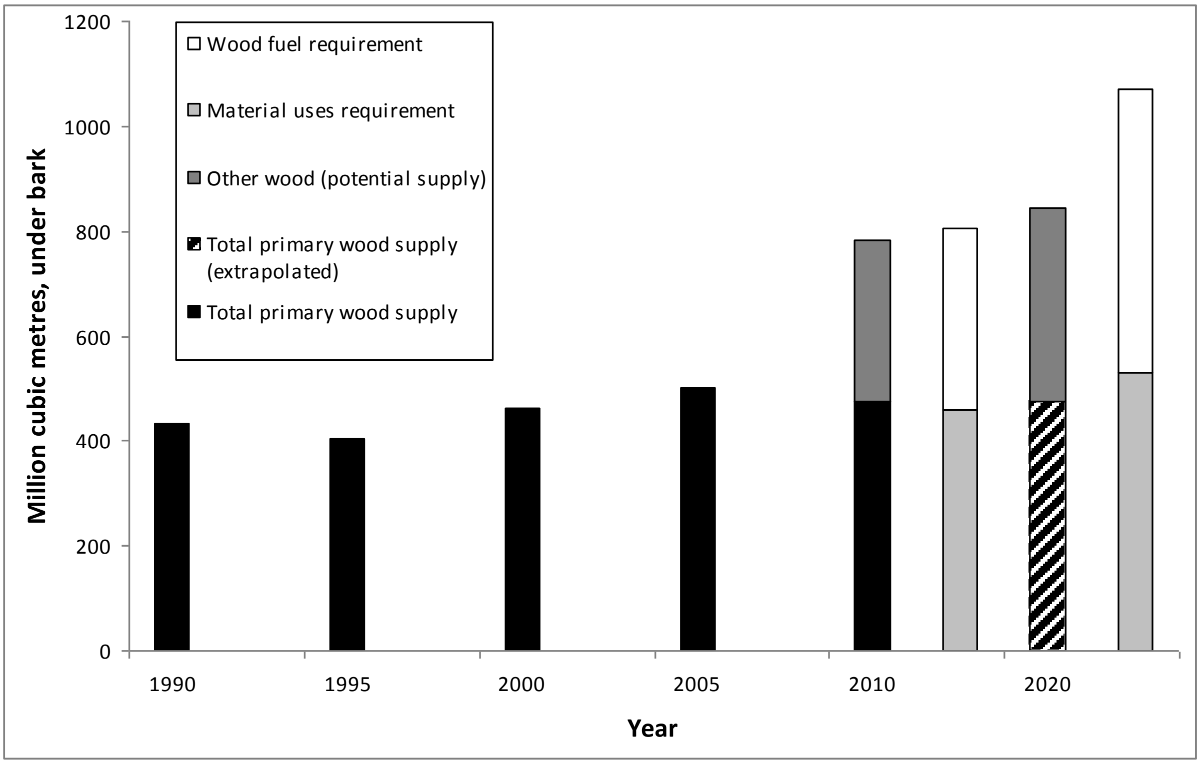

Figure 2.10. Recent and projected removals of primary wood from EU27 forests in comparison with demand.

A number of important observations can be drawn from the results in Figure 2.10:

1. If the estimate of Mantau *et al.* (2010) for the demand for woodfuel in 2010 is accurate, then it is significantly greater than the level of removals of primary wood from EU27 forests being used directly for woodfuel, suggesting that the bulk of the existing demand is met from sources of other woody biomass.
2. As a corollary, the bulk of removals of primary wood from EU27 forests appears to be meeting demands for wood materials (i.e. construction wood, paper and packaging), although some of this demand is met from sources of other woody biomass.
3. The demand for wood materials is projected to rise from about 460 million cubic metres in 2010 to 530 million cubic metres in 2020 (an increase of 1.5% per year).
4. In 2010 the demand for woodfuel (about 345 million cubic metres) amounted to about three quarters of the demand for wood materials, however, this demand is projected to rise significantly over the period to 2020 (5.7% per year) such that the demand for woodfuel exceeds that for materials by about 2020. (Mantau *et al.* report a similar result but with woodfuel exceeding materials by 2017.)

5 The total demand for wood (for both materials and energy) matches the total supply due to removals of primary wood from EU27 forests and other woody biomass sources in 2010 but is projected to outstrip supply in the period 2010 to 2020 (assuming forests are managed according to a 'business as usual' scenario).

Three clear conclusions can be drawn from these observations and from the results presented in Figure 2.10 and Table 2.8:

1 The consumption of wood for energy in the EU27 has been increasing in recent times.
2 The demand for wood in the EU27 is very likely to increase in the period to 2020, with most of this due to a significantly greater increase in the demand for wood for energy.
3 In order to fill a gap between future demands for wood and potential supply, it will be necessary to intensify management of EU27 forests in order to increase removals of primary wood and/or import more wood into the EU27 and/or mobilise the availability of sources of other woody biomass. (This is the essential conclusion of the report of Mantau *et al.*, published in 2010, and reinforced in Section 5.4 of the EFSOS II report, UN-ECE, 2011.)

In fact, significant quantities of woodfuel are already being traded in the EU27, including significant imports from non-EU countries in some cases. Systematic information on trade in woodfuel is not easily available, because many consignments of wood are below the monetary threshold for full or even partial reporting. An internal study by Forest Research for the GB Forestry Commission has analysed available data on imports of woodfuel to the UK, including an indication of the main countries of origin, as shown in Table 2.9. It should be noted that Table 2.9 does not include importation of pulpwood (small roundwood), some of which is used as fuel (in solid or chipped form), or is chipped to make animal bedding. Imports of wood pellets and coniferous wood chips make up the vast bulk of imports, with the remainder (less than 1%) appearing to be for specialist applications, and for 'topping up' domestic woodfuel supplies.

Whilst the quantities of imported woodfuel shown in Table 2.9 are certainly significant, it is important to place them in perspective. The estimates shown are for the UK and a rather different picture would be observed for the EU (i.e. a much greater proportion of domestic woodfuel consumption rather than reliance on imports). It should also be noted that wood consumption for fibre/materials in the UK amounts to approximately 50 million cubic metres per year (see Figure 2.9), which very approximately equates to 20 million oven dry tonnes. This should be compared to the estimate for imported woodfuel in Table 2.9 of approximately 1.6 million tonnes, the bulk of which will be oven dry.

Table 2.9 Estimates of woodfuel imported into the UK for the year 2012

(Main source: HMRC, 2012, following analysis and interpretation by Hogan, 2013)

Woodfuel product category[1]	Main uses[1]	Quantity[2] (kilotonnes)			Main sources
		EU origin	Non-EU origin	Total	
Wood pellets	Power generation Domestic heating (very small compared with power generation)	123	1 364	1 487	Non-EU: Canada (57%), USA (32%) and South Africa (2%) EU: Latvia (7%), Portugal (1%), Germany (< 1%)
Coniferous wood chips	Power generation	91	0.07	91	Republic of Ireland (75%), most likely imported to Northern Ireland; The Netherlands[3]
Non-coniferous wood chips	Domestic cooking and food smoking	1.3	0.08	1.3	Mainly EU
Kiln dried wood logs	Domestic heating and to a lesser extent cooking	6.8	1.6	8.4	Latvia; The Netherlands[3]
Sawdust	Wood briquettes (also animal bedding and litter as non woodfuel uses)	0.88	0.55	1.4	Mainly EU
Waste and scrap wood	As for sawdust, also food smoking	6.7	0.79	7.5	

Notes to Table 2.9:

1 See Box 2.2.

2 Quantities expressed in kilotonnes mass including any moisture content.

3 The Netherlands is likely to be an intermediary rather than the original source, possibly for all material.

As clearly shown in Table 2.9, in 2012 in the UK, wood pellets for power generation accounted for nearly 93% of imported woodfuel by mass (probably more if all quantities of woodfuel were expressed in oven dry tonnes), with nearly 90% originating from Canada and the USA, and more than half the total supply coming from Canada. Most of the remainder of imported woodfuel appears to consist of relatively local trade in coniferous wood chips between the Republic of Ireland and Northern Ireland, also mainly for power generation.

Systematic data on increased consumption of forest bioenergy at EU scale are not easily available. However, reference may be made to the findings of the EUwood study (Mantau *et al.*, 2010) and the EFSOS II study (UN-ECE, 2011), which both conclude that very high efforts would be required to mobilise wood resources in the EU in order to meet 2020 targets for bioenergy consumption and projected levels of consumption in 2030, *if all the additional wood supply were to be met from within the EU forest sector.* The EFSOS II study also indicated that increased demand for bioenergy in the EU would involve a rise in imported wood and increased prices for wood raw materials, suggesting some pressure on potential for wood supply.

2.7. Potential impact of increased consumption of forest bioenergy

It is very difficult to assess the implications of a significant increase in demand for forest bioenergy in the EU on forest management and wood feedstock consumption for energy, within the EU and based on imports. Global and regional economic models may give an indication of gross flows of wood between Member States and from outside the EU. However, these types of model are less suited to assessing effects on forest management, because operational constraints and wider silvicultural objectives will play a very important role in determining the response of the forest sector, alongside gross requirements for forest bioenergy. Generally there will be trade-offs between different forest management objectives, not all of which can be adequately represented by costs and revenues.

Additional wood resource can be ‘mobilised’ by increasing the intensity of harvesting or increasing forest biomass extraction in forests by one means or another. In some situations, introducing such management in forest areas would aim to meet a range of objectives (improved forest quality, habitat creation, wood production, rural development and economic diversification). It is also important to recognise that there is a range of forest management activities that can be classed as ‘intensification’ of management or harvesting including:

- Increased biomass (more trees) removed during thinning.
- Adjustment of rotations applied to the felling of trees or stands closer to a productive optimum.
- Introduction of harvesting in forest areas previously not under management for production.

- Increased extraction of biomass in harvesting operations (e.g. harvesting of so-called 'harvest residues' when previously this was not carried out).
- Increased density of tree planting/regeneration following harvesting, to enhance early productive potential.
- Fertilization of poor sites, or drainage of wet sites stimulating the increment.
- Restocking forest areas with better growing/more productive trees.
- Forest area expansion, allowing increased harvesting in the existing forest or new forest areas.
- Enrichment of areas of forest 'scrub' to 'high forest' with greater productive potential.

These forest management activities have variable impacts on forest carbon stocks; generally involving reductions but also, in the case of the last four or five examples, potentially involving increases. Each of the above examples can also be characterised in terms of more detailed cases. For example, the introduction of harvesting in forest areas not previously subjected to forest management can involve harvesting of 'biologically mature' and previously undisturbed forest, which may or may not have high carbon stocks, depending on the type of forest ecosystem. It may also involve the introduction of management in forest areas that were created in recent decades with the original intention of increasing wood production, but which subsequently fell into neglect due to lack of market or policy incentives. (This is a situation that may be relevant for some EU Member States that have carried out afforestation in recent decades.)

The range of possible management activities listed above, all of which could be associated with the expression, 'intensification of forest management', illustrates how confusion might arise in debates about the influence of forest management for bioenergy production on forest carbon stocks and resultant GHG emissions. This emphasises the importance of clear use of terms and wordings in any discussions of such issues.

Alongside changes to forest management in the EU and other regions, the supply of forest bioenergy may be increased by utilising recovered waste wood and by diverting harvested wood and recycled wood from use/reuse for the manufacture of wood fibre products. It follows that there are many ways in which increased demand for forest bioenergy might be met through changes to forest management and changes in patterns of wood feedstock consumption. A systematic analysis of scenarios for meeting increased demands for forest bioenergy is beyond the scope of this report but is explored further in Task 2 of this project. A provisional qualitative assessment of possible changes to forest management and patterns of wood use is shown in Table 2.10. The various activities are listed in the table according to a subjective descending order, in terms of the likelihood of their occurrence, depending on the level of demand for forest bioenergy. An indication is also given of what would happen, in terms of forest management or use of wood feedstock, if the change in activity did not take place (i.e. activity not required to meet increased demand for forest bioenergy).

According to the provisional qualitative assessment in Table 2.10, certain changes to forest management or uses of wood feedstock would occur, depending on the level of demand for forest bioenergy. Certain activities are already occurring (e.g. local harvesting of wood to provide small-scale domestic heat and internal consumption of sawmill co-products for heat and power generation in sawmills and boardmills). A rise in demand for forest bioenergy is already stimulating interest in the extraction of harvest residues and in the introduction of silvicultural thinnings in young stands. In some regions, it is possible that the additional revenue from forest bioenergy, adding value to the revenue derived from material/fibre products, is giving incentives for harvesting operations in forests (thinning and/or felling), where this would not otherwise occur. However, there is a lack of systematic information about any such developments in the forest sector. Demand for forest bioenergy would need to be very intense for harvesting to be introduced in otherwise unmanaged forest areas, or for forest management to be fundamentally restructured (e.g. significant shortening of rotations), solely to produce bioenergy. Activities such as enrichment of unproductive forest areas and creation of new forest areas would most likely require very intense demand for forest bioenergy or additional incentives.

A number of the activities included in Table 2.10 involve the possible diversion of existing wood feedstock, currently supplying requirements for material/fibre products, for use as bioenergy instead. The possibility that such shifts in patterns of wood use could occur is undeniable but is difficult to assess. Major changes to existing patterns of wood use would most likely require intense demand for forest bioenergy with the consequence that forest bioenergy becomes price-competitive with wood material/fibre products.

In the UK, the internal study by Forest Research on imports of woodfuel notes that importation of wood pellets by the UK is expected to increase in the coming years, rising to about 10 million tonnes per year by 2015 and, more speculatively, to between 15 and 20 million tonnes by 2020. Currently, supplies of small roundwood and wood chips (usually coniferous) for the manufacture of wood-based panels in the UK come primarily from UK forests. (It should be noted that wood processing is a global industry – the boardmills in the UK exist because suitable forest resources are there and are able to supply the feedstock.) The UK power sector’s reliance on imported sources of woodfuel would appear to limit risks of competition for wood resources with the UK wood-based panel sector. However, it is unclear how this situation will be affected by the sharp rise in demand for woodfuel for power generation that is projected for the coming years.

The extent to which the preceding analysis for the UK translates to other EU27 Member States is unclear. At EU/global scale, Moiseyev *et al.* (2011) carried out an economic analysis of the potential contribution of forest bioenergy to the EU target for utilisation of renewable energy sources. The study concluded that, as woodfuel prices increase, woodfuel imports would also increase, but there would also be some ‘redirection’ of wood from competing industrial users, such as manufacturers of wood-based panels and the pulp and paper industry.

Table 2.10 Possible changes to forest management and wood use to meet increased demand for bioenergy

Activity (change)	What would happen otherwise	Comments
Small roundwood of early thinnings and some branchwood (mainly hardwoods), poor quality sawlogs.	This is business as usual, already happening.	Local, small-scale domestic heating.
Sawmill co-products.	This is business as usual, already happening.	Particularly for internal heat and power generation in sawmills and boardmills.
Extraction of harvest residues (previously not harvested).	The harvest residues would be left on site, or burnt on site as part of site management (for new tree establishment).	For heat and power production.
Additional recovery of waste wood.	The waste wood would not be recovered.	
Introduction of thinning of small-diameter trees, generally in young stands, that were previously uneconomic to harvest.	The thinning operations would not be carried out at all, generally with detrimental consequences for subsequent stand development (e.g. high tree density, small tree sizes, suppressed understorey vegetation).	
Introduction of harvesting (thinning and felling) in forest areas previously not managed for production (e.g. because this was uneconomic). Early, small-diameter thinnings, branchwood, some small roundwood and sawlog offcuts used for bioenergy. Sawlogs and some small roundwood used for manufacture of material products.	The thinnings and fellings would not be carried out at all. Consequences would be site-specific (e.g. depending on the details of how the harvesting is carried out, tree species involved, whether stands are plantations or semi-natural). In some situations, a private landowner may decide to convert the land to another productive use (potentially involving deforestation).	This would be additional harvesting for co-production of materials and bioenergy, which would occur because the additional revenue from the bioenergy 'tops up' the total revenue and makes the harvesting operations economic.

Table 2.10 (continued) Possible changes to forest management and wood use to meet increased demand for bioenergy

Activity (change)	What would happen otherwise	Comments
Diversion of recovered waste wood from use as feedstock for manufacture of certain wood-based panels (e.g. particleboard), for use as bioenergy instead.	Depends on future demand for wood-based panels. Is demand decreasing anyway? Alternatively is there increasing demand or are there policy aims/incentives to increase use of wood-material products? In scenarios of increasing demand or incentives, diversion of recovered waste wood is less likely.	
Diversion of sawmill co-products from use as feedstock for manufacture of paper, card and wood-based panels (e.g. particleboard, fibreboard), for use as bioenergy instead.	Depends on future demand for paper, card and wood-based panels. Is demand decreasing anyway? Alternatively is there increasing demand or are there policy aims/incentives to increase use of wood-material products? In scenarios of increasing demand or incentives, diversion of sawmill co-products is less likely.	
Diversion of harvested small roundwood from use as feedstock for manufacture of paper, card and wood-based panels (e.g. particleboard, fibreboard), for use as bioenergy instead.	Depends on future demand for paper, card and wood-based panels. Is demand decreasing anyway? Alternatively is there increasing demand or are there policy aims/incentives to increase use of wood-material products? In scenarios of increasing demand or incentives, diversion of small roundwood is less likely.	

Table 2.10 (continued) Possible changes to forest management and wood use to meet increased demand for bioenergy

Activity (change)	What would happen otherwise	Comments
Enrichment of areas of 'scrub' and degraded forest to create productive 'high' forest, managed for production. Early, small-diameter thinnings, branchwood, some small roundwood and sawlog offcuts used for bioenergy. Sawlogs and some small roundwood used for manufacture of material products.	Most likely the land areas would remain as 'scrub' and degraded forest. In some situations, a private landowner may decide to convert the land to another productive use (potentially involving deforestation).	The enrichment of forest areas would be to achieve additional harvesting for co-production of materials and bioenergy, which would occur because the additional revenue from the bioenergy 'tops up' the total revenue and makes the harvesting operations economic. However, still unlikely to occur in the absence of specific incentives (i.e. for forest restoration).
Shortening of rotations in forest areas already under management involving harvesting, to optimise for total biomass production rather than sawlog production (e.g. adjustment of rotations towards time of maximum MAI, see Appendix 2).	Rotations would remain longer than time of maximum MAI, to optimise for sawlog production.	Likely to be an extreme scenario, because of the loss of revenue associated with reduced sawlog production.
Diversion of harvested sawlogs from use as feedstock for manufacture of sawn timber, for use as bioenergy instead.	Depends on future demand for sawn timber. Is demand decreasing anyway? Alternatively is there increasing demand or are there policy aims/incentives to increase use of wood-material products? In scenarios of increasing demand or incentives, diversion of sawlogs is less likely.	Likely to be an extreme scenario, because of the loss of revenue associated with reduced sawn timber production.

Table 2.10 (continued) Possible changes to forest management and wood use to meet increased demand for bioenergy

Activity (change)	What would happen otherwise	Comments
Conversion of forest areas already under management involving harvesting, to 'short rotation biomass forests' for bioenergy as a sole product.	Land would remain as forest with long rotations (e.g. close to or greater than time of maximum MAI, see Appendix 2).	A very extreme scenario. Overall, short rotation bioenergy forests are significantly less productive (and therefore of much less economic value) than forest stands on the same sites that are managed on rotations closer to the time of maximum MAI (see Appendix 2).
Introduction of harvesting (thinning and/or felling) in forest areas previously not managed for production (e.g. because this was uneconomic). All harvested wood used for bioenergy as the sole product.	The thinnings and fellings would not be carried out at all. Consequences would be site-specific (e.g. depending on the details of how the harvesting is carried out, tree species involved, whether stands are plantations or semi-natural). In some situations, a private landowner may decide to convert the land to another productive use (potentially involving deforestation).	A very extreme scenario.
Conversion of cropland or grassland areas to 'short rotation biomass forests' for bioenergy as a sole product.	Land would remain as cropland or grassland.	Effectively a form of afforestation. An extreme scenario, unless there are specific incentives for such land-uses.
Conversion of cropland or grassland areas to forest stands managed for production. Early, small-diameter thinnings, branchwood, some small roundwood and sawlog offcuts used for bioenergy. Sawlogs and some small roundwood used for manufacture of material products.	Land would remain as cropland or grassland.	Afforestation. A very extreme scenario, unless there are specific incentives for afforestation.

There are some limited formal data to support the view that the price of woodfuel has been increasing relative to the prices of other wood products. Data on prices of various wood feedstocks and products over the period 1952 to 2011 have been reported by the UN-ECE (2012). This includes fairly complete data information for five EU27 Member States for the period 1998 to 2011 (Austria, Denmark, Finland, Germany and Italy). The data are strictly for imports and exports of wood into and out of countries, rather than representing internal trade in wood; patterns in prices for imports and exports appear to be similar for the five EU27 Member States considered here. Figure 2.11 shows trajectories of prices for types of wood product over the period 1998 to 2011. The trajectories represent the mean price for wood imported into the five EU27 Member States indicated earlier, expressed per cubic metre of solid wood. The prices are expressed in this form to enable direct comparison, but this has required some assumptions to be made about the wood content of certain product categories (e.g. pulp and wood-based panels), which may introduce some uncertainty into the results.

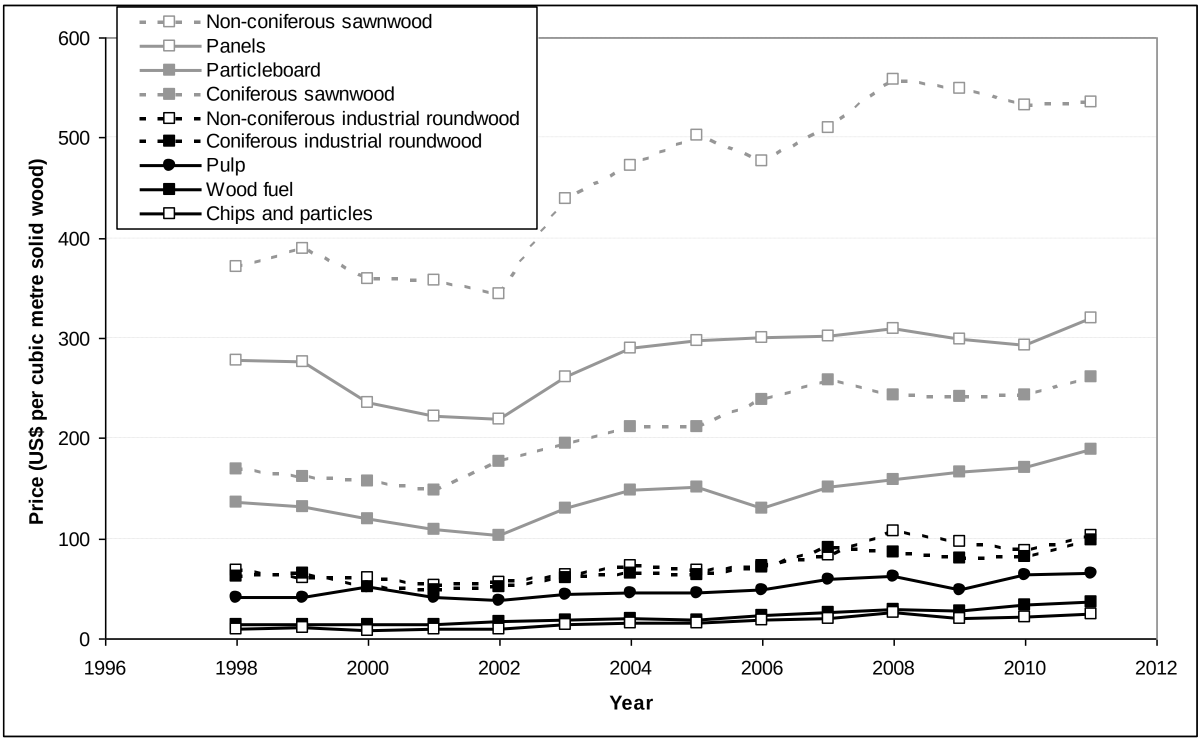

Figure 2.11. Recent trends in estimated mean prices per tonne of solid wood imported by five EU27 Member States.

Figure 2.11 suggests a clear ranking in the prices of wood product categories, in descending order:

- Non-coniferous sawnwood.
- Panels (all wood-based panels, including particleboard but also high value products such as veneer and plywood).

- Coniferous sawnwood.
- Particleboard including oriented strand board (included in panels but also shown separately in Figure 2.11).
- Industrial roundwood (coniferous and non-coniferous) and pulp.
- Woodfuel, wood chips and particles.

It is notable that, over the entire period, woodfuel and woodchips are the lowest-price products, with wood chips (also a potential feedstock for particleboard) fairly consistently at about 70% of the price of woodfuel. Coniferous industrial roundwood, an important feedstock for particleboard, currently has a price about 2.5 times that of woodfuel. The prices of all wood products have increased over the period 1998 to 2011 (note that no adjustments have been made for inflation). However, if prices relative to 1998 are considered, as in Figure 2.12, sharp differences are observed in the rate of increase for different products. In particular, solid wood products have increased in price over the period 1998 to 2011 by between 15% and 60% (typically 50%), whereas woodfuel and wood chips have increased in price by more than 150%. Figure 2.13 shows the consequences of these price changes over time for the prices of solid wood products relative to the price of woodfuel, for the period 1998 to 2011.

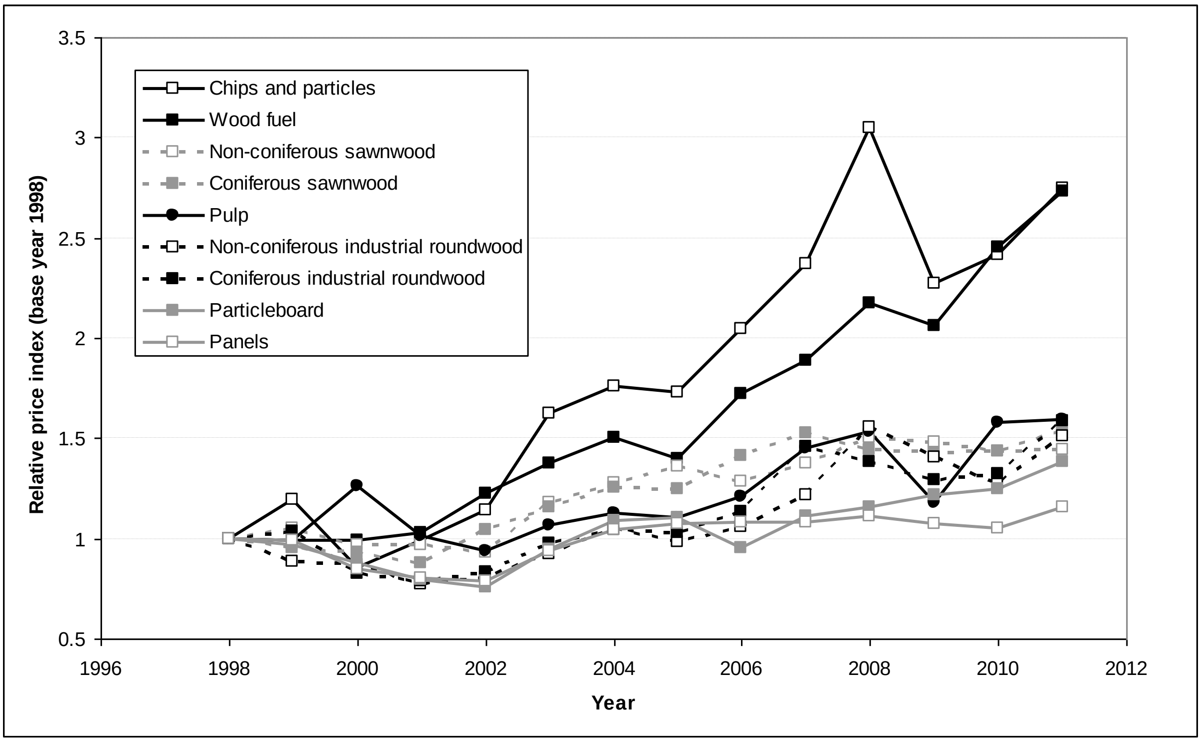

Figure 2.12. Recent trends in estimated mean prices per tonne of solid wood imported by five EU27 Member States.

Clearly, the price differentials between solid wood products and woodfuel are currently significant, but it is also clear from Figure 2.13 that such price differentials have been decreasing markedly over the last 25 years. There must come a point where, as concluded by Moiseyev *et al.* (2011), increases in woodfuel prices lead not only to increased woodfuel imports but also to some 'redirection' of wood from competing industrial users. As noted in Sections 2.3 and 2.5, it remains the case that certain raw wood products and co-products have properties that are optimal for the manufacture of certain specific finished wood products. These properties are likely to remain critical in determining how raw wood is prioritised for consumption within the forest and wood processing sectors. In addition, some parts of the wood processing sector may be 'buffered' against competition for wood feedstocks from demands for woodfuel, specifically in situations involving co-production. For example, sawmills produce large quantities of offcuts in the form of sawdust and chunks of wood, which could be processed into woodfuel (e.g. wood pellets) and sold on to the energy sector.

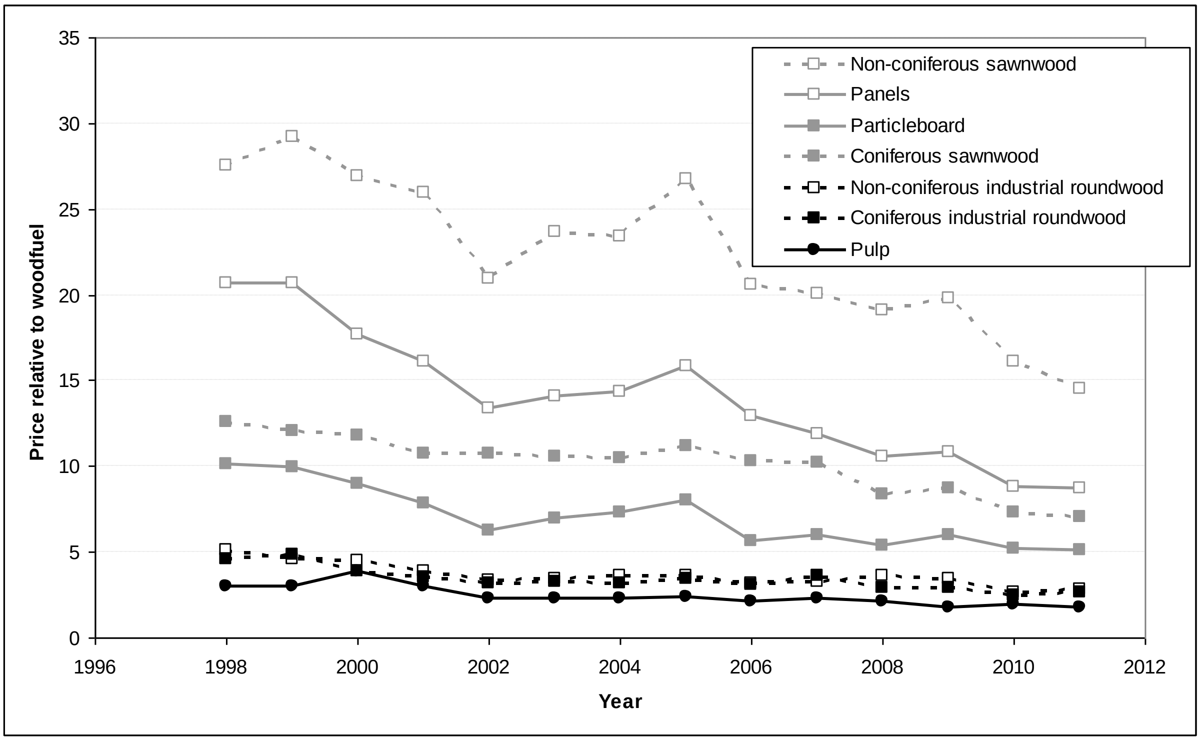

Figure 2.13. Recent trends in estimated mean prices per tonne of solid wood imported by five EU27 Member States.

Further in-depth consideration of price dynamics of woodfuel and other wood products, and of the implications for patterns of wood use, is well beyond the scope of this current report. Nevertheless, such interactions between prices of various wood products, and their consequences for the consumption of wood for different applications, need to be represented as part of scenarios for bioenergy consumption and supply, as developed in

Task 2 of this project. These scenarios also need to encompass the other main possibilities for meeting future demands for forest bioenergy as identified above, i.e. through increased levels of harvesting in forest areas within and outside the EU27, either specifically to produce more bioenergy, or as part of a wider mobilisation of wood resources to provide a range of solid wood products and energy services. The implications of increased harvesting in forests for carbon stocks and GHG emissions are discussed further in Section 3 of this report, in particular in Sections 3.5 and 3.6.

2.8. Conclusions on forests, forest management and wood utilisation

This section of the report has been concerned with presenting a general discussion of forests, forest management and wood utilisation, in order to establish an essential context for a technical discussion of forest bioenergy and associated GHG emissions. As such, the key technical discussion of this report is presented in subsequent sections. Nevertheless, it is appropriate to identify specific insights relevant to the Task objectives (see Section 1.3) that arise from points made in this section.

Considering first factors that may lead to sensitivity in the GHG emissions associated with forest bioenergy (objective 1 of this Task), it may be inferred that:

- Forests are not managed just for wood production, but generally for multiple objectives (Sections 2.3 and 2.4).
- Trees are felled as part of a cyclic process in which trees are also planted or regenerated, and growing trees are managed over their lives to ensure good quality trees are retained to develop to maturity (Section 2.3 and Figure 2.2).
- Generally speaking, sustainable forest management conforms to variations on this general theme (Sections 2.3 and 2.4). However, regional and local variations in forest management (see Table 2.4) are likely to be an important factor in determining GHG emissions associated with production of forest bioenergy.
- The species composition and potential growth rates of forest areas are variable (Section 2.4). The GHG emissions of bioenergy produced from forests are likely to be sensitive to such variability.
- It is extremely uncommon for whole stands of trees to be felled and all of the harvested wood to be used for bioenergy. Generally, whole trees are used for bioenergy when they are very small and otherwise would be 'felled to waste', when they are small diameter, or when they are of large diameter and also of poor stem form (and so unsuitable for producing high grade sawn timber). However, potential for competition for 'lower-grade' wood material between the bioenergy sector and the particleboard and pallet sectors, needs to be acknowledged (Sections 2.6 and 2.7 and Figure 2.7).
- The wood processing sector is complex, with a web of wood flows providing feedstocks for the manufacture of structural sawn timber, plywood, pallets and fence posts, particleboard and fibreboard, paper and other products including bioenergy. It is common for bioenergy feedstocks to be derived from co-production of higher value timber products. It is very unlikely that wood will be diverted from the manufacture of

high value wood products to supply forest bioenergy, however, there are risks that co-products could be diverted from the manufacture of particleboard, fibreboard and paper to meet growing demand for bioenergy feedstocks.

- Generally, there are certain key scenarios by which the forest sector and wood processing sector might respond to the increased demand for bioenergy – production from forests already under management could be increased (intensified), forests not currently managed for production could be 'mobilised' (to produce more wood products as well as bioenergy), certain wood feedstocks could get diverted from other uses (see earlier), or there could be more efficient exploitation of harvesting residues and waste wood. These scenarios will have different consequences for GHG emissions, as explored further in Section 3 of this report.
- The GHG emissions of forest bioenergy are likely to be sensitive to the types of wood feedstock used to produce the bioenergy and the origins of these feedstocks in the forest and wood processing sectors (Sections 2.3 and 2.4, see in particular Figures 2.2 and 2.7).

These points are explored further in Sections 3 and 5 of this report.

Given the purpose of this section in providing context for the main technical discussion in the rest of this report, relatively few specific and substantive conclusions can be drawn concerning the sensitivity of GHG emissions of forest bioenergy to calculation methodologies (objective 2 of this Task). However, it is apparent from the discussion in this section that studies of forest bioenergy may obtain different results, depending on the accuracy and level of detail with which key aspects of the forest bioenergy production system are represented in calculations (see preceding bullet list). This issue is central to the discussion in the ensuing sections of this report, particularly Sections 4 and 5.

The discussion in this section offers a number of insights concerning methodology for calculation of GHG emissions associated with the use of forest bioenergy (objective 3 of this Task). In particular, it may be concluded that:

- Regional, local and case-specific details of forests and their management need to be fully represented in any assessment of GHG emissions associated with the production of forest bioenergy (Section 2.4).
- The complexity of the wood processing sector needs to be represented accurately (Section 2.5). Flows of wood from the forest through to ultimate end use need to be tracked in order to characterise in detail the types of feedstock contributing towards supplies of forest bioenergy. The potential complexity of flows of wood may complicate the LCA calculations needed for the assessment of GHG emissions associated with forest bioenergy, suggesting that this area of methodology requires particularly careful development and specification.
- Interactions between demands for various wood products, and their consequences for the consumption of wood for different applications, need to be represented as part of scenarios for bioenergy consumption and supply (Sections 2.6 and 2.7). These scenarios also need to encompass the other main possibilities for meeting future

demands for forest bioenergy as identified above, i.e. through increased levels of harvesting in forest areas within and outside the EU27, either specifically to produce more bioenergy, or as part of a wider mobilisation of wood resources to provide a range of solid wood products and energy services.

Points concerning the potential sensitivity of results for GHG emissions to variations in forest management and bioenergy production systems, and to methods of calculation, are explored in detail in Sections 3 and 4 of this report. In addition, many of these points require further consideration as part of the construction of scenarios for bioenergy consumption in Task 2 of this project.

2.8.1. Key messages concerning forests, forest management and wood utilisation

Forest bioenergy is typically a co-product of wood material/fibre production

Typically, forest bioenergy is produced as a complementary co-product of wood material/fibre products. It is unusual for forest bioenergy to be the sole product from harvested wood.

Forest bioenergy consumption in the EU has increased and is likely to increase significantly in the period to 2020

The consumption of wood for energy in the EU has been increasing in recent times. The demand for wood in the EU is very likely to increase in the period to 2020 and potentially beyond, with most of this due to a significantly greater increase in the demand for wood for energy.

Forest management will need to change to meet demands for forest bioenergy

In order to fill a gap between future demands for wood and potential supply, it will be necessary to intensify management of EU forests in order to increase removals of primary wood and/or import more wood into the EU and/or mobilise the availability of sources of other woody biomass. This may be achieved through a number of changes to forest management and/or patterns of wood use, which may be more or less likely to actually occur.

Certain harvested wood feedstocks and forest management practices are more likely than others to be involved in the supply of forest bioenergy

In the period to 2020, demand for forest bioenergy seems likely to be met through increased extraction of harvest residues including poor-quality stemwood and trees, the use of sawmill co-products and recovered waste wood. Some small roundwood may be used as a source of bioenergy. It is less likely that forest bioenergy will involve consumption of wood suitable for high value applications, such as sawlogs typically used for the manufacture of sawn timber.

In terms of changes to forest management, a rise in demand for forest bioenergy is already stimulating interest in the extraction of harvest residues and in the introduction of silvicultural thinnings in young stands. In some regions, it is possible that the additional revenue from forest bioenergy is giving incentives for harvesting operations in forests (thinning and/or felling) for co-production, where this would not otherwise occur. Demand for forest bioenergy would need to be very intense for harvesting to be introduced in otherwise unmanaged forest areas, or for forest management to be fundamentally restructured, solely to produce bioenergy. Activities such as enrichment of unproductive forest areas and creation of new forest areas would most likely require very intense demand for forest bioenergy or additional incentives.

Competition for forest biomass for energy use or for paper and board may occur, but there are also existing market trends

The use of sawmill co-products may be based on additional supply associated with increased production of sawn timber, or may involve the diversion of some of the existing supply from the manufacture of wood-based panels. Similarly, some small roundwood used for bioenergy may involve increased co-production with sawn timber, or diversion of supply from the wood-based panel and paper industries. It is difficult to assess the extent to which these activities may occur. Meeting demands for forest bioenergy may involve some direct competition with the wood-based panels and paper industries, or may involve ‘picking up’ existing supply in situations where demand for wood-based panels and paper is already declining.

Forests are managed for multiple objectives and increased demand for forest bioenergy is very unlikely to change this situation

In the EU and elsewhere, generally forests are managed for many purposes, one of which is to supply forest bioenergy. Production of forest bioenergy is thus most likely to occur as an integrated part of forest management and wood use for a range of objectives. A requirement to produce forest bioenergy seems unlikely to become the principal driver of forest management unless demand for forest bioenergy becomes very intense.

3. Overview of forest biogenic carbon and its management

3.1. Purpose

The key purposes of the ensuing discussion are:

- To review current understanding of the dynamics of forest carbon stocks.
- To consider the relative importance of forests as reservoirs of carbon and producers of wood.
- To consider the relative importance of harvested wood as a source of energy and of materials and fibre, for potentially achieving GHG emissions.
- To assess how forest carbon stocks and wider GHG dynamics of wood production systems may respond to management interventions aimed at increasing production of forest bioenergy, and the implications for GHG emissions.
- To distinguish as clearly as possible the factors associated with forest management and wood use that determine biogenic carbon dynamics associated with forest bioenergy, e.g. effectively as ‘low risk’, ‘limited potential’ or ‘high risk’.

As highlighted in Section 1.2 of this report, forest biomass has a somewhat lower carbon content compared with fossil fuels but a significantly lower calorific value. The consequence is that burning wood to generate a quantity of energy can release more carbon to the atmosphere than would be the case for natural gas or fuel oil (for example) and a similar amount of carbon compared to burning coal. The potential for forest biomass as a source of bioenergy involving low, zero or negative emissions thus depends crucially on the capacity for carbon sequestration in forest vegetation to balance or exceed the loss of carbon to the atmosphere when harvested wood is burned.

It follows that, when considering the full life cycle GHG emissions[13] of different forestry and wood use options, it is important to understand the influence of carbon stock changes in forests on GHG emissions, as this represents a crucial contribution to the ultimate result. As outlined in Section 1.2, and explored more thoroughly in Section 5 of this report, there is a considerable body of scientific research on the GHG emissions of forest bioenergy. This research suggests very variable results for GHG emissions compared with fossil fuels and often arrives at seemingly contradictory conclusions. Whilst this research and associated literature has revealed many useful insights, it has also led to some confusion concerning the consequences of harvesting and utilising wood for GHG emissions, and has also caused the general perception that the GHG emissions associated with forest bioenergy utilisation (also wider timber and wood fibre utilisation) are complex and uncertain.

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[13] As already noted in Section 1, the definition of the term ‘greenhouse gas emissions’ is fundamental to this report. Specific and narrow definitions are needed in some contexts, and these definitions are provided in the glossary to this report (see Appendix 1) and also discussed more fully in Sections 4.4 and 4.5. However, in some contexts, the term may be applied quite broadly, as is the case for much of the content of the early sections of this report.

As explained in Section 1.2 of this report, there is, in fact, broad agreement (or at least consensus) about levels of GHG emissions associated with the use of forest bioenergy in certain specific situations; there is less clarity over how GHG emissions may vary for the multitude of ways in which forests may be managed and forest biomass can be utilised to provide a source of bioenergy. As a first step towards building a picture of how the GHG emissions of forest bioenergy relate to specific circumstances, such as the approach to forest management and the type of forest biomass used, this section presents an introductory discussion of the role of forest carbon stocks as biogenic carbon in contributing to the GHG emissions of forest bioenergy. Particular consideration is given to interactions with forest management, the different ways of using wood, and the implications of demands for increased bioenergy production and increased wood supply in general. However, the discussion in this section is not intended to be an exhaustive treatment of the subject. For descriptions of some of the more basic and fundamental aspects of forest carbon and GHG dynamics, reference should be made to existing examples in the literature, such as Morison *et al.* (2012) and Section 3 of Matthews *et al.* (2014).

3.2. Forest carbon pools and GHG dynamics

As illustrated in Figure 3.1, the complete carbon balance of a forest covers the carbon pools of living biomass (above and below ground), dead organic matter (dead wood and litter) and organic soil carbon. It is important to stress that both emissions and sequestration of carbon may occur in forests. Estimating the balance of emissions and sequestration requires an understanding of how natural processes affecting greenhouse gas dynamics interact in response to the interventions of humans.

The main GHG concerned in forest GHG balances is carbon dioxide (CO_2) associated with carbon stock changes. Other GHGs include nitrous oxide (N_2O) from, for example, nitrogen inputs (when fertilising forest land), and methane (CH_4) which is involved in the GHG balances of forests growing on highly organic soils such as peatlands.

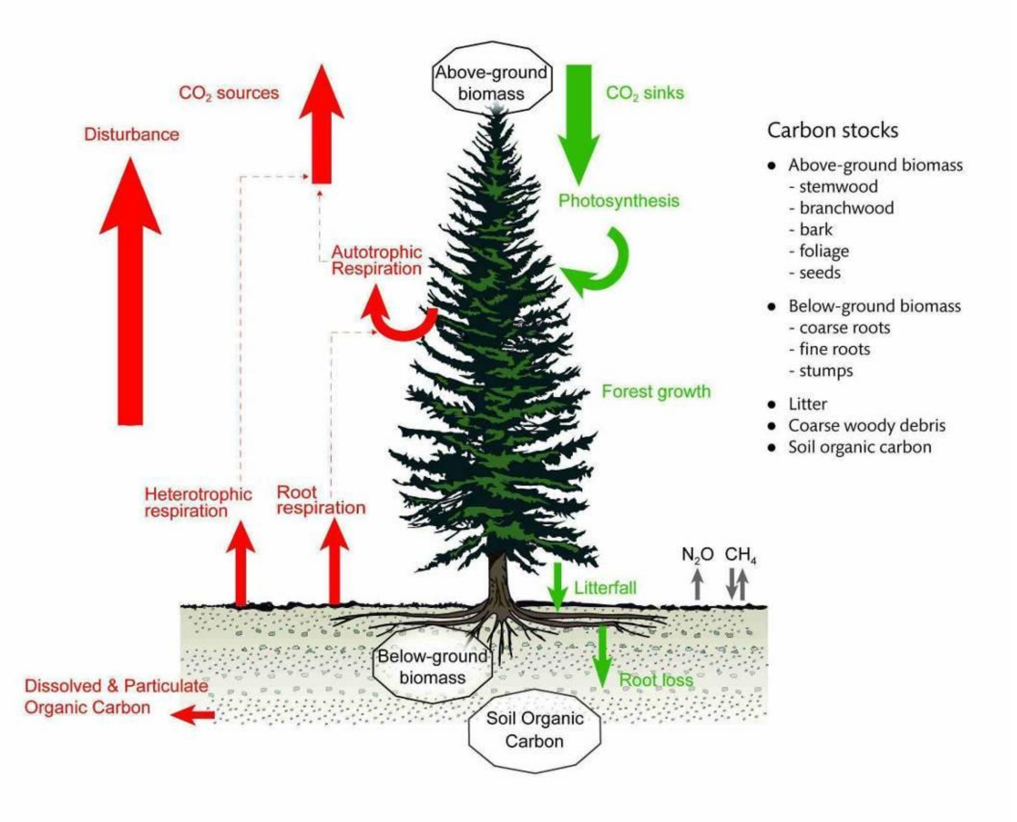

Figure 3.1. Illustration of the carbon pools and naturally occurring GHG dynamics associated with the forests. After Morison *et al.* (2012).

3.3. Forest carbon stocks and flows in EU27 and the world

FAO (2010) has reported statistics on carbon stocks in the biomass of standing (i.e. living) trees forming forest areas in various countries and regions, and key results are summarised in Figure 3.2. In 2010, tree carbon stocks in global forests were estimated at nearly 300 GtC. As noted in Section 2.4.1, forest area is distributed fairly evenly amongst the major regions of the globe. However, contributions to global tree carbon stocks are somewhat more variable. Carbon stocks in trees in EU27 forests represent approximately 3.5% of the global carbon stocks (somewhat under 10 GtC, see Figure 3.2). A similar estimate is observed for forests in Oceania. Tree carbon stocks as a percentage of the global total vary between about 20% for Africa, about 12% for Other Europe, Asia and Central and North America, and about 35% for South America.

The estimates of forest carbon stocks in the previous paragraph do not include carbon in forest soils, deadwood and litter. Pan *et al.* (2011) have estimated that total global forest carbon stocks around the year 2010 amounted to 861 GtC. This estimate is made up of contributions due to live trees, deadwood, litter and soil of 363 GtC, 73 GtC, 43 GtC and 383 GtC respectively. Pan *et al.* also report that, considered geographically, tropical forests contribute 471 GtC, boreal forests contribute 272 GtC, whilst temperate forests contribute 119 GtC. Expressed on a per-hectare basis, carbon stocks in tropical and boreal forests are estimated at about 240 tC ha^{-1}, whereas the equivalent estimate for temperate forests is 155 tC ha^{-1}. Pan *et al.* note that, although tropical and boreal forests make the biggest contributions to global carbon stocks (in terms of both total and per-hectare carbon stocks), there is a fundamental difference in the distribution of carbon amongst the different forest pools, with tropical forests having 56% of carbon in biomass and 32% in soil, whilst boreal forests have 20% of carbon in biomass and 60% in soil.

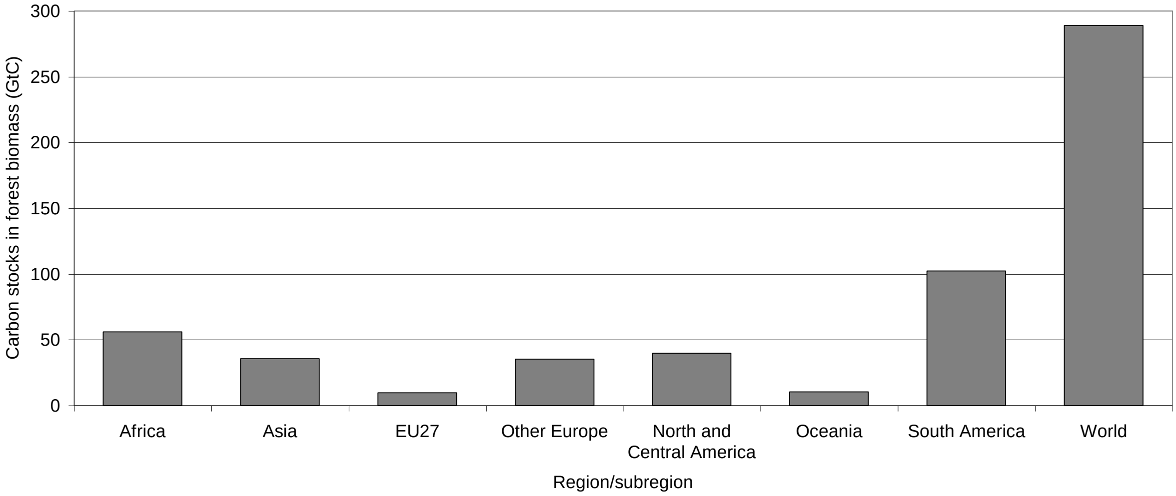

Figure 3.2. Tree carbon stocks in forests for regions of the world for the year 2010. (Source: FAO, 2010.)

The estimate of 363 GtC in the biomass of live trees reported by Pan *et al.* (2011) is markedly larger than the estimate of about 300 GtC suggested by FAO statistics. There are a range of underlying causes for the difference in these two estimates. However, it should be noted that the estimates reported in FAO (2010) are based on an intentionally simple and straightforward interpretation of growing stock estimates from National Forest Inventories, whereas the estimates of Pan *et al.* (2011) are based on a combination of inventory data, long-term field observations, and statistical and process models.

Table 2.2 in Section 2.4.1 illustrated how forest area in the EU27 is distributed unevenly. This is also true of forest carbon stocks, as shown in Figure 3.3. Seven Member States account for almost 70% of EU27 tree carbon stocks (Germany, Sweden, France, Poland, Finland, Romania and Italy in descending order of the share of carbon stocks). Comparison of Figure 3.3 with the area estimates in Table 2.2 demonstrates how particular characteristics of forests can vary between Member States. For example in Section 2.4.1 it was noted that Finland and Spain have similar areas of forest. However, the carbon stocks in the forests of Spain and Finland are quite different, reflecting differences in forest characteristics (e.g. species composition, age distribution, stocking density of stands).

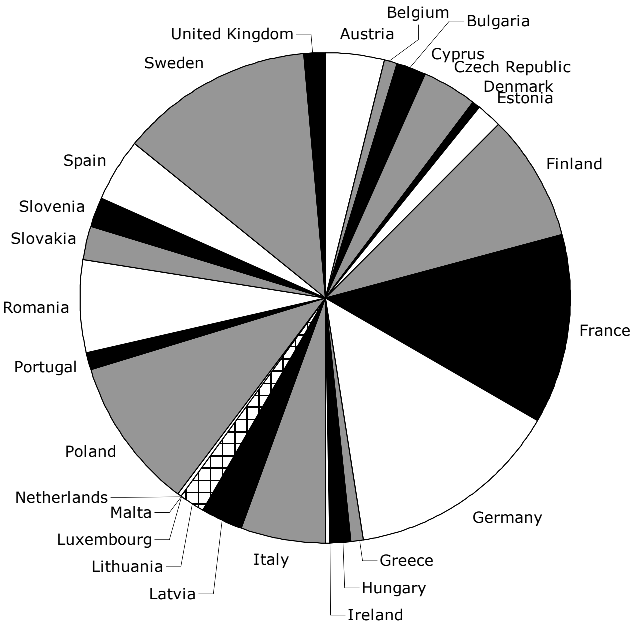

Figure 3.3. Distribution of tree carbon stocks in forests amongst Member States of the EU27 for the year 2010 (total carbon stock in trees is slightly less than 10 GtC, as estimated from results reported in FAO, 2010).

Pan *et al.* (2011) have attempted to estimate forest carbon stock changes, based on a combination of inventory data, long-term field observations and statistical and process models. The estimates of Pan *et al.* also include contributions due to deadwood, litter and soil. In Table 3.1, the estimates presented in Pan *et al.* are interpreted to infer carbon stock changes in forests for major regions of the world over the period 1990 to 2010. These are compared with simpler estimates for carbon stock changes in living trees based on FAO (2010). The two sets of results display drastic differences, with an estimated increase in global forest carbon stocks of 1.12 GtC yr^{-1} based on Pan *et al.* (2011), and an estimated decrease of 0.52 GtC yr^{-1} based on FAO (2010). This disagreement is due to several factors, most likely including:

- More comprehensive consideration of forest carbon pools in the study of Pan *et al.* (2011).
- Reliance on simple extrapolations of National Forest Inventory data as part of the compilation of results reported by FAO (2010).
- More detailed analysis and modelling approach adopted by Pan et al (2011), in particular, the representation of continuing accumulation of carbon stocks in existing forest areas in the tropics, and also refined representation of the accumulation of carbon in tropical forest areas regenerating after felling or natural disturbances.

Table 3.1 Estimates of carbon stock changes in forests for regions of the world over the period 1990 to 2010

Country/region	Estimated carbon stock change[1] (GtC yr^{-1})	
	Based on Pan *et al.* (2011)	Based on FAO (2010)
Europe and Russian Federation	0.72	0.14
North America	0.23	0.11
Central and South America	−0.09	−0.42
Asia[2]	0.01	−0.08
Oceania	0.06	−0.02
Africa	0.19	−0.25
World	**1.12**	**−0.52**

Notes to Table 3.1:

1 Positive values indicate carbon stock increases, whilst negative values indicate carbon stock decreases.

2 Estimate from Pan *et al.* does not include the Indian subcontinent and a significant part of Western Asia.

The preceding discussion emphasises the potential risks associated with simplistic approaches to calculation of forest carbon stocks and stock changes and the need to adopt appropriate and sufficiently comprehensive methods for estimating forest carbon dynamics. This is also true when attempting to characterise levels of carbon stocks associated with different types of forests (e.g. with regard to tree species and growth rate) and types of forest management. It is very important that the characterisation of forest areas in terms of carbon stocks is undertaken in conjunction with an accurate appreciation of site and growing conditions relevant to the region being considered, including approaches to forest management in the region.

The results reported by Pan *et al.* (2011) indicate that carbon stocks in forests are increasing in most regions of the world, with the exception of Central and South America (mainly due to deforestation in South America). Generally in tropical regions, carbon stock changes appear to involve a quite delicate balance between the continued growth of existing forest areas, deforestation, and the regrowth of forest areas that have been felled or subjected to natural disturbance. Forest carbon stock changes in boreal and particularly temperate regions are estimated as making the bulk of the contribution to the global increase in carbon stocks. Forests in the USA make the predominant contribution in North America, whereas the estimated increase for Europe and the Russian Federation appears to be due to contributions that are distributed widely across these regions. The relatively large increases in forest carbon stocks in these regions have occurred, and are occurring, due to a number of factors as already observed for the tropics, but recent afforestation represents an important driver of forest carbon stock increases, particularly in the EU27 (see for example discussion in Vilén *et al.*, 2012).

A programme of woodland expansion undertaken in a number of EU27 Member States over the past century has significantly increased the area of young forest stands. Past management of existing forests has also contributed to EU forests having a large proportion of young forest stands (Vilén *et al.*, 2012). Currently, the carbon stocks of these young forests are increasing. However, the rate of forest expansion has dropped significantly in more recent decades, whilst the existing areas of young forest are growing older (and their growth rate is declining). Often, these forest areas are under management for timber production and are approaching the time of their first rotation (i.e. at which point the stands comprising the forest areas may be clearfelled and replanted). Under these circumstances, the rate of increase in forest carbon stocks in the EU27 is declining and may be close to reversal (Nabuurs *et al.*, 2013). Similar observations may be made for Other Europe and for Central and North America, although the influence of past afforestation is less strong in these regions.

The issue of forest carbon stock changes in various regions including the EU may not appear to be of obvious relevance to the question of how to manage forests and how to use harvested wood in terms of mitigation of climate change. Nevertheless it should be recognised that one of the reasons for changes in forest carbon stocks is the current management of significant areas of forests for the production of timber and bioenergy (also the low priority currently attributed to afforestation in some regions of the globe). The existing and likely future pattern of carbon stock changes thus forms part of the context in which options for future forest management and wood utilisation are assessed, essentially representing the baseline against which changes in forest management and/or wood use may be judged.

3.4. Interplay between human management and natural processes

Human management of forests can have a strong influence on the pattern of GHG emissions and carbon sequestration, although the associated responses may follow intricate cycles. Managed forests are part of a dynamic system and so these processes are never entirely under human control. Forest systems are susceptible to natural disturbances e.g. forest fires, storms, drought and pest outbreaks, which can lead to substantial release of carbon to the atmosphere or reduced sequestration from the atmosphere (see for example Lindroth *et al.*, 2009: van der Werf *et al.*, 2010).

Forestry systems typically exhibit short-term and long-term trends and cycles in forest carbon stocks and associated net GHG sequestration or emissions. It is important to allow for these trends and cycles in any assessment of the influence of forest management, including harvesting, on forest carbon stocks and their dynamics. Management interventions in forests can have variable effects on carbon stocks over time. For example, when a new stand of trees is planted, the trees can take decades to grow to maturity, implying that carbon sequestration takes place over quite long timescales. In contrast, harvesting of trees from a stand reduces carbon stocks very quickly. Different components of forestry systems (e.g. vegetation, litter, soil and harvested wood) can also respond to management with different ‘reaction times’.

As discussed further in Sections 3.9, 4.7 and 4.9 of this report, it is important that one-off changes, trends and cycles in GHG sequestration and emissions are allowed for appropriately in assessments of GHG emissions. Such changes, trends and cycles can take place over time in forest systems in relation to the harvesting and use of forest bioenergy.

3.5. Spatial scale and scale of biomass harvesting

Scale is important – in terms of spatial scale, it is particularly important to distinguish the carbon stock changes that would be observed in an individual tree, or an individual stand of trees, as opposed to what would be observed for a population formed of many stands of trees (i.e. a forest). This point has been illustrated, for example, in a discussion of forest GHG balances by Matthews *et al.* (2014, see in particular Sections 3.2 and 3.3), which shows how cycles in forest carbon stocks within individual stands tend to ‘even out’ when considering whole forests (see Figure 3.4). The example in Figure 4 is based on 5,600 ha of Sitka spruce grown under UK conditions, on a 56 year rotation, with immediate restocking on felling. Each year, trees comprising 17.9 ktC of wood are felled (through clearfelling of one fifty-sixth of the forest area), of which 11.4 ktC is harvested and 6.5 ktC (forming the ‘harvesting residues’) is left in the forest and eventually oxidises. However, this is exactly matched by carbon sequestration of 17.9 ktC due to the ongoing growth/re-growth of trees forming the other fifty-five fifty-sixths of the forest. Further discussion of this point can be found in Sections 3.2 and 3.3 of Matthews *et al.* (2014), see also Maclaren (1996, 2000) for the original discussion and examples.

It is also important to consider scale in terms of the magnitude and type of harvesting interventions within forests. For example, if the scale of harvesting of trees is increased significantly (i.e. management through thinning or felling in forests is intensified), this will cause reductions in carbon stocks even when considering the spatial scale of whole forests, in the short term and potentially also in the long term. In some situations, increasing the productivity of forest stands may also increase carbon stocks. These points have been explored extensively in the scientific literature (see for example Kaipainen *et al.*, 2004: Harmon and Marks, 2002), and are also considered further in Section 3.6 of this report.

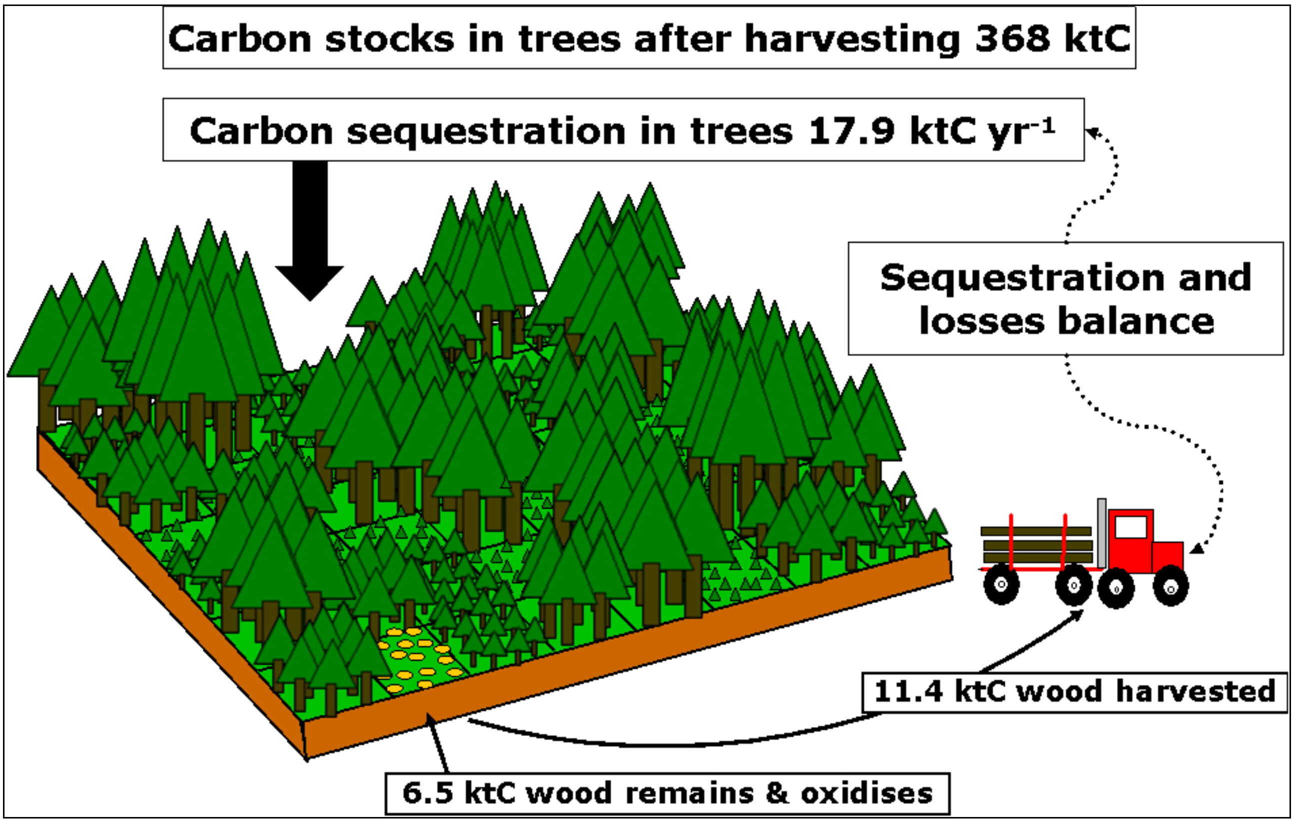

Figure 3.4. Illustration of how a balance may be maintained across an area of forest between tree growth and the harvesting and extraction of wood.

3.6. The twin roles of biogenic carbon in the form of forest biomass

As already noted in Section 1.2 of this report and as must now be very apparent from the discussion so far, a central concern for the potential use of forest bioenergy arises from the fact that the resource of biogenic carbon constituted by forest biomass makes two contrasting contributions in terms of climate change mitigation:

1. The carbon stocks in forest biomass, litter and soil represent a natural reservoir of carbon sequestered from the atmosphere. This process of carbon sequestration is continuing at significant levels under current conditions and, in principle, could be ‘managed’.
2. Forest biomass can be harvested and used as a source of bioenergy which can be used in place of fossil energy sources and/or to make 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 non-wood materials.

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

As discussed in Sections 2.6 and 2.7 of this report, the consumption of forest bioenergy is expected to rise and there may also be increased consumption of wood for materials and fibre products (Mantau *et al.*, 2010). To meet these demands, forest biomass harvesting, extraction and/or patterns of wood utilisation will need to be 'intensified' by one means or another. The types of activity that might be involved in such 'intensification' have been considered in Section 2.7, where it was noted that different activities, particularly those involving forest management, can have variable impacts on forest carbon stocks. It is fundamentally important that any changes in forest carbon stocks are assessed and included when calculating GHG emissions associated with the harvesting of forest biomass for products including bioenergy. This point is of central importance to the subject of this report, and is worth illustrating with some examples. Sections 3.6.1 to 3.6.3 describe three such examples based on results produced from simulations made using the Forest Research CARBINE forest carbon accounting model. These are all based on the example of a forest formed of relatively fast growing stands of Sitka spruce as grown in the UK, and as illustrated in Figure 3.4, Section 3.5. The results for carbon stocks in the examples include living trees, deadwood, litter and carbon retained in harvested wood products. For simplicity, carbon stocks in soil are not included.

The examples considered together, along with other possible examples not illustrated such as afforestation, reveal that actions to increase the supply of forest bioenergy can have very variable effects on forest carbon stocks. However, generally, these effects are predictable. When considering options for the management of forest areas to increase the supply of forest bioenergy whilst sustaining carbon stocks, it may be important to consider the potential for a 'package' of measures undertaken in a population of stands on a site-by-site basis across large scales (Nabuurs *et al.*, 2008). This might involve, for example, a systematic and coordinated programme of management across forest 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 forest areas. Currently, there has been limited exploration of the potential for such options.

3.6.1. Influence of rotation on forest carbon stocks

Figure 3.4 in Section 3.5 illustrates the management of a significant forest area involving periodic harvesting and regeneration of forest stands, on a rotation of 56 years. The continuous harvesting and regeneration of stands involves a balance between forest carbon sequestration and extraction of harvested wood that maintains a constant carbon stock across the forest as a whole. The magnitude of the forest carbon stocks depends on the choice of rotation, as shown in Figure 3.5. The figure also shows the biomass productivity that can be achieved in UK Sitka spruce forests, depending on the selected rotation period (see also Appendix 2 for related discussion). 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 forest rises monotonically as the rotation applied to forest 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. In terms of total above ground biomass, managing the Sitka spruce stands forming the forest 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 forest carbon stocks associated with rotations of 55 and 69 years are 64 and 90 tC ha^{-1} respectively.

Figure 3.5 illustrates how the choice of rotations applied to forest areas involves trade-offs between achieving high productivity for different types of wood product and high forest carbon stocks, for example:

- Choosing rotations to maximise total above ground biomass production (which may be desirable if paramount priority is given to bioenergy production) involves reduced potential for sawlog production.
- Choosing relatively long rotations (e.g. greater than 80 years in the case of Figure 3.5) to achieve high carbon stocks is likely to involve significantly reduced potential total biomass and sawlog productivity.
- Choosing relatively short rotations (e.g. less than 45 years in the case of Figure 3.5), 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 low forest carbon stocks.

Such points are very important when considering the adjustment of rotations in forest areas in order to increase the supply of forest bioenergy. For example, many forest areas in the EU and elsewhere 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 forest areas (with implied GHG emissions associated with biogenic carbon). On the other hand, there are also examples of forest 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 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, and implied GHG emissions or carbon sequestration.

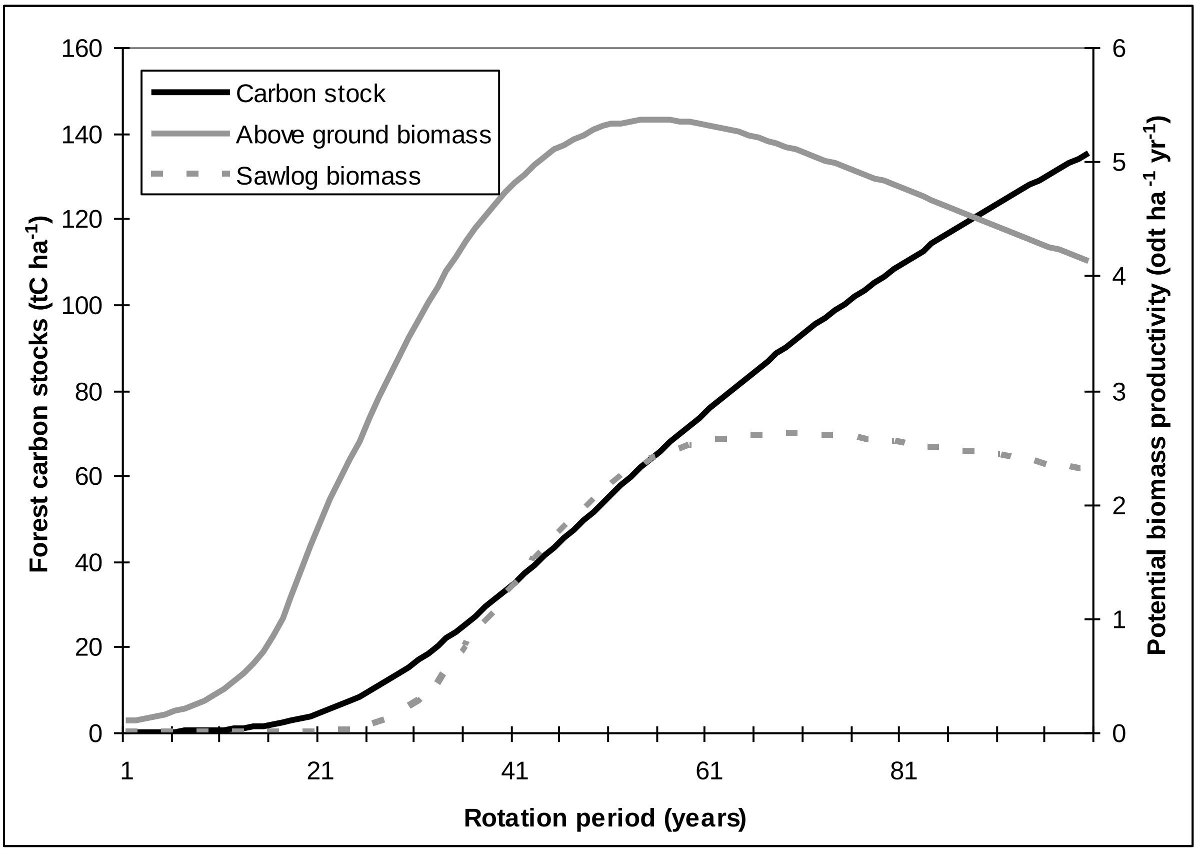

Figure 3.5. Illustration of the influence of rotation period on forest carbon stocks and biomass productivity.

3.6.2. Increased extraction of harvest residues

In the example forest system illustrated in Figure 3.4, Section 3.5, the individual stands forming the forest are harvested every 56 years. The stemwood is extracted and used to supply material products and bioenergy. However, the harvest residues (deadwood, branchwood, roots etc.) are left on site. The harvest residues decompose over a period of years or decades but, if the scale of the whole forest is considered, a stock of harvest residues is sustained, which makes a contribution to the overall forest carbon stocks. If a decision is taken to extract some or all of the harvest residues to increase the supply of forest bioenergy, there will be an associated reduction in forest carbon stocks, as illustrated by the example in Figure 3.6. The extraction of harvest residues starts in year 10 in the example, and involves the harvesting of 50% of branchwood and deadwood, with no harvesting of roots. Note that the scale of the y−axis in Figure 3.6 does not start at zero.

In this example of the extraction of harvest residues, there is an associated reduction in forest carbon stocks from about 146 tC ha^{-1} to about 143 tC ha^{-1}. This takes place over more than 50 years, reflecting the rotation period applied to the forest stands. The carbon stock reduction is relatively modest (3 tC ha^{-1} or 2%) but is undeniable and needs to be allowed for when estimating GHG emissions related to biogenic carbon associated with this kind of forest bioenergy feedstock. Any GHG emissions due to associated changes in soil organic matter also need to be included.

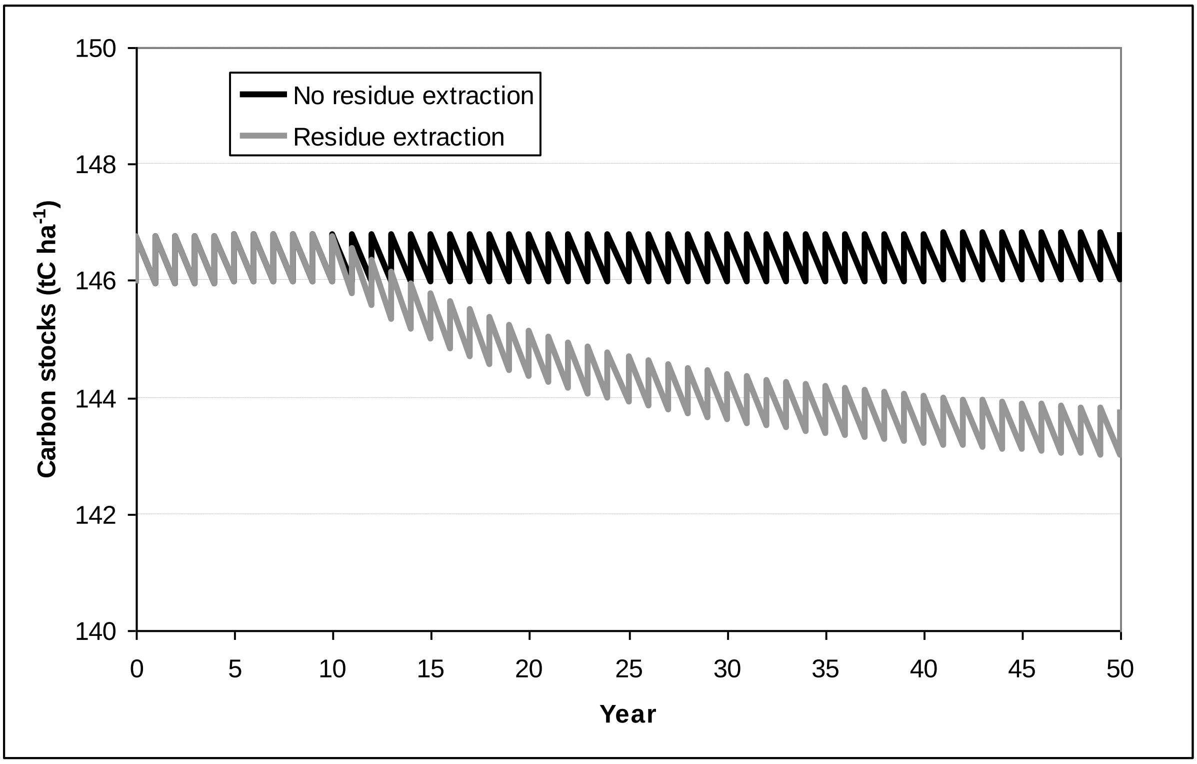

Figure 3.6. Illustration of reduction of forest carbon stocks due to increased extraction of harvest residues.

3.6.3. Introduction of harvesting in unmanaged forest with high carbon stocks

In the absence of harvesting or other disturbances to the growing stock, potentially, forest areas can accumulate large carbon stocks. In principle, the carbon stocks would be equivalent to those for an 'infinite' rotation period (see discussion of example involving rotations in Section 3.6.1, notably Figure 3.5). The introduction of harvesting in such forest stands, involving application of a finite rotation period will lead to a reduction in forest carbon stocks, as illustrated by the example in Figure 3.7. This example involves the transformation of an area of forest formed of relatively old trees (150 years) to create a forest formed of stands managed on a rotation of 56 years, such as illustrated in Figure 3.4, Section 3.5. The transformation starts in year 10 in the example, and involves the progressive felling and regeneration of the original forest area over a period of 56 years.

In this example of the introduction of harvesting in previously unmanaged forest areas with high carbon stocks, there is an associated reduction in forest carbon stocks from about 305 tC ha^{-1} to about 146 tC ha^{-1}. The main reduction takes place over more than 50 years, reflecting the rotation period applied to the forest stands. The reduction continues at a slower rate for at least another 50 years, reflecting the dynamics of carbon stocks in deadwood and litter. The carbon stock reduction is significant (159 tC ha^{-1} or more than 50%) and clearly needs to be allowed for when estimating GHG emissions related to biogenic carbon associated with production of forest bioenergy based on this type of management. Any GHG emissions due to associated changes in soil organic matter also need to be included.

It should also be noted that, in the example in Figure 3.7, if harvesting is not introduced, the unmanaged forest continues to sequester a modest but discernable level of carbon stocks, rising from about 305 tC ha^{-1} to about 320 tC ha^{-1}. This is a clear example of forest carbon stock dynamics associated with what can be described as a 'counterfactual land use', i.e. the carbon stock dynamics that would occur in terrestrial vegetation if a specified activity (in this case the introduction of harvesting in unmanaged forests) were *not* to be carried out. Reference to a counterfactual land use case is also implicit in the examples in Sections 3.6.1 and 3.6.2. When assessing GHG emissions associated with changes to land use or land management, it is very important to allow for the counterfactual land use. This point is illustrated further in examples given in Section 4.5 of this report. However, the assessment of carbon stock dynamics for the particular case of vegetation systems involving 'no harvesting' or 'no management' can be problematic, and results can be uncertain (see Sections 3.11 and 3.12).

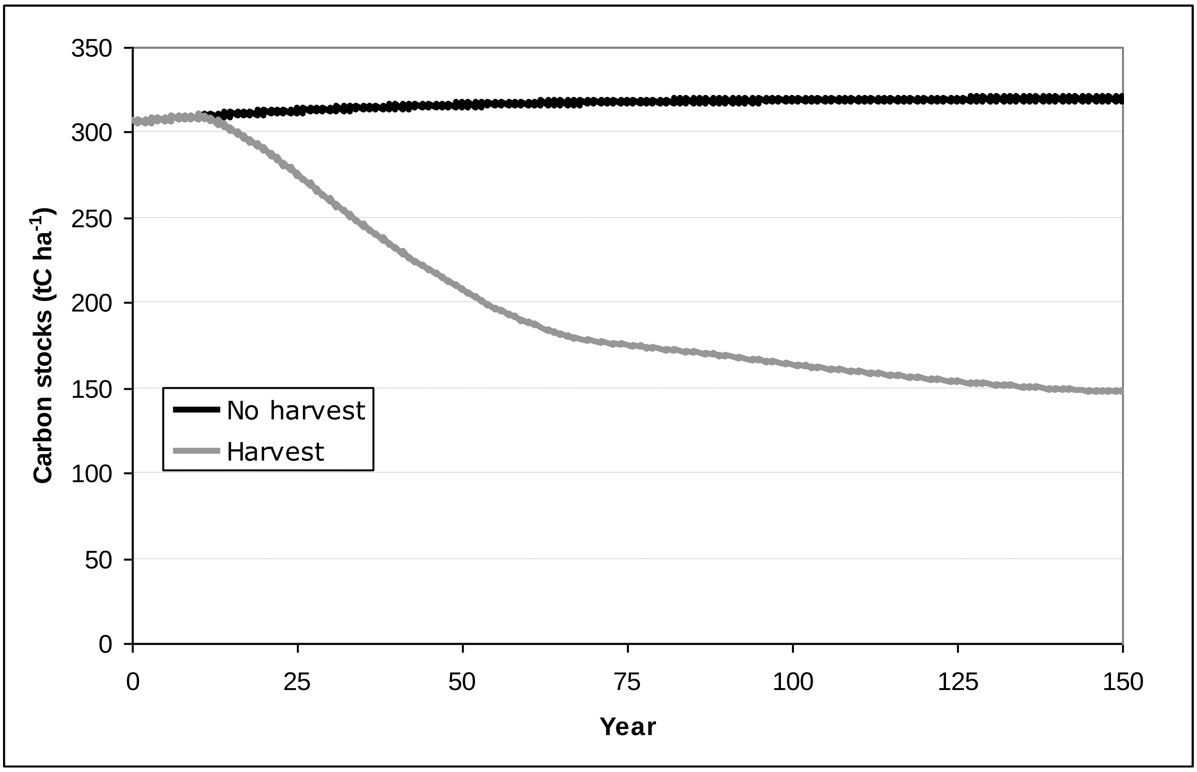

Figure 3.7. Illustration of reduction of forest carbon stocks due to introduction of harvesting in previously unmanaged forests with high carbon stocks.

3.7. Biogenic carbon in the form of harvested forest biomass

The carbon cycle of forests extends into the life cycles of harvested wood products. As explained in Sections 2.3 and 2.5 of this report, harvested wood is used in a variety of ways to provide a range of materials and energy feedstocks. Moreover, the production and processing chains from harvested wood to finished products can be complex, frequently involving co-production, the manufacture of composite wood materials and the use of recycled wood feedstocks alongside newly harvested wood.

A number of research studies have demonstrated that the manufacture and use of wood-based materials generally involves low GHG emissions compared with situations in which non-wood materials are used to make equivalent products (see for example Peterson and Solberg, 2005: Gustavsson and Sathre, 2006: Gustavsson *et al.*, 2006). One very important consequence is that *the mix* of materials and bioenergy produced from harvested wood has a significant influence on overall GHG emissions, e.g. compared to a scenario in which wood is not harvested (see for example Matthews *et al.*, 2014). In some situations, the harvesting of wood to produce bioenergy as a complementary co-product alongside certain material wood products can involve low GHG emissions being associated with the overall production system. This is particularly pertinent when it is recalled that forests are rarely managed for the supply of bioenergy as a sole product (see Section 2.3). However, if the mix of wood products is important in determining overall GHG emissions, then evidently *changes in the mix* of materials and bioenergy produced from harvested wood will cause changes (reductions or increases) to the GHG emissions for the overall production system. The discussion in Sections 2.6 and 2.7 of this report concerning trends in the mix and in the prices of wood products should be referred to in this context.

The complete characterisation of the life cycles of solid wood products, in terms of the fate of biogenic carbon requires consideration of the re-use, recycling and disposal of wood products at end of life. The treatment of solid wood products at end of life can have a significant influence on the overall GHG emissions due to use of products, as demonstrated for example by the results of Matthews *et al.* (2014). Decisions about whether to burn (with or without recovering the energy), recycle or dispose of wood products to landfill also have a strong influence on the timing with which biogenic carbon contained in products is released back to the atmosphere. The use of waste wood as a feedstock for bioenergy is generally viewed as preferable to disposal to landfill and beneficial in terms of GHG emissions, particularly as the waste wood resource may be under-utilised (see Section 2.5). However, there could be detrimental consequences for GHG emissions if an increased demand for waste wood as a bioenergy feedstock was to result in diversion of waste wood from use in recycling, e.g. as a feedstock for wood-based panels (based on results reported by Matthews *et al.*, 2014).

The literature on forest bioenergy often refers to the concept of 'biomass cascading', implying the active management of harvested wood through a sequence of uses, the 'classic' example involving use in solid wood products, then re-use or recycling as a feedstock for wood-based panels, and burning as a source of energy only ultimately after repeated use in solid products.

3.8. Influence of forest bioenergy conversion technologies and 'counterfactuals'

The effectiveness of forest bioenergy as an efficient energy source and its potential for reducing GHG emissions exhibit some sensitivities to the conversion technologies for which it is used as a feedstock. This project is concerned with the use of solid bioenergy for heat and/or power (i.e. rather than use in liquid form as biofuels for transport), and in this context relevant conversion technologies include:

- Power only generation (generally involving combustion, although potentially covering gasification and pyrolysis conversion technologies).
- Power only generation through co-firing of biomass in coal-fired power stations.
- District heating.
- Small-scale and large-scale (commercial/industrial) combined heat and power (CHP).
- Small-scale heating.

In general, the effectiveness of bioenergy is related to the efficiency of the conversion system. Large-scale and small-scale CHP systems can be very efficient, although often there are practical obstacles to their deployment. Power only generation in a dedicated biomass facility tends to involve relatively low efficiency. Forest bioenergy is recognised as particularly suited to small scale heat applications, which can be relatively efficient (see for example SDC, 2005). At the other extreme of scale, the co-firing of wood with coal in existing coal-fired power plants is often suggested as an option for generating electricity from wood that is quick to implement and relatively low cost, because a substantial part of the facilities are already in place and much of the capital investment may have already been repaid.

The potential importance of the counterfactual case for land use or land management in determining the GHG emissions of forest bioenergy sources has already been highlighted in Section 3.6. Indeed, the need to account for counterfactual land use or land management in assessments of forest bioenergy is a central concern of this report. The effectiveness of forest bioenergy is also sensitive to the 'counterfactual energy source', i.e. the energy that would be consumed if the forest bioenergy were not used. There is also an interaction with the conversion technologies involved.

It is important to appreciate the concept of 'counterfactual' energy sources for forest bioenergy, and more generally, 'counterfactual' products for solid wood products. When making an assessment of options for forest management aimed at climate change mitigation, particularly when comparing options involving conservation of carbon stocks in forests with options involving harvesting of forest bioenergy and/or wood products, it is extremely important to characterise the 'counterfactuals' for the forest bioenergy and wood products reliably. In this context, the counterfactuals for solid wood products are the sources of materials that would be utilised if wood was not harvested from the forest.

The identification of appropriate counterfactual energy sources can be highly uncertain in some cases. For example, forest bioenergy used in small scale heat systems may displace existing heating systems based on natural gas, oil or coal, or electricity. It may thus be difficult to determine exactly what 'mix' of energy sources is likely to be displaced as a result of any efforts to expand the deployment of small scale heat systems based on forest bioenergy. Other cases may be more certain, for example, forest bioenergy co-fired with coal for power generation is clearly displacing the use of coal.

Counterfactuals for solid wood products exhibit high sensitivity in terms of differences in GHG emissions. For example, medium density fibreboard (MDF) can be used to make furniture, e.g. an office filing or storage cabinet, or to make a non-structural partition in a room of a building. If an office storage cabinet is not made of MDF, it might be made of sawn timber, which would involve lower GHG emissions but displacement of sawn timber from another application. Alternatively, it might be made from sheet steel, involving higher GHG emissions. If not made from MDF, a partition in a room might be made from plasterboard, which would involve marginally different associated GHG emissions. Thus, the benefits or otherwise of using MDF are highly dependent on the applications it is used for, and on assumptions about what the alternative would be to using MDF in such applications.

The challenges posed by the problem of determining meaningful counterfactuals for harvested forest biomass and the calculation of associated GHG emissions are considered as part of the discussion in Sections 4.6 and 4.10 of this report dealing with essential concepts and key issues in LCA.

3.9. Short-term and long-term consequences of forest management interventions

As discussed in Section 3.4, the management of forests can have a strong influence on the pattern of GHG emissions and/or carbon sequestration, but these responses often follow intricate cycles. Whilst this is true, in general (as already considered in Section 3.6), a number of studies have identified issues related to the timing of GHG emissions and carbon sequestration in response to intensified management of forests, particularly where this involves increased thinning, shortened rotations, the introduction of harvesting in unmanaged forests or increased extraction of biomass (see Sections 2.7 and 3.6). In such situations, typically the reactions in terms of forest carbon stock changes and contributions to GHG emissions due to use of harvested wood (e.g. as bioenergy or as solid wood products) can be characterised as:

- Initial reductions in forest carbon stocks (perhaps over a few years but sometimes much longer) with consequent implied increased GHG emissions (although this depends, to some extent, on how the harvested wood is used).
- Stabilisation of forest carbon stocks in the longer term, but at a lower level than observed before forest management was intensified.
- Short-term and long-term increases in levels of wood supply, with consequent additional potential to displace consumption of fossil energy sources and/or non-wood materials (although, again, this depends to some extent on how the harvested wood is used).

This indicates that, for a number of possible sources of additional forest bioenergy, there must be an initial period during which associated GHG emissions are increased, after which there is a ‘switch-over’ to net decreases in GHG emissions. A number of research studies have reported such a pattern in GHG emissions of forest bioenergy sources, with estimates of the period to the point of switch-over ranging from 1 year to 100 years or more. Such timing issues, particularly contrasting short-term and long-term effects, are the subject of much study in the literature and are discussed further in Sections 3.6 and 4.9, and particularly Section 5 of this report.

3.10. Growth rate of forests as a key factor

It has long been established that the potential growth rate of trees forming forest stands is an important factor in determining the consequences for GHG emissions of decisions about forest management (e.g. when deciding whether to harvest trees, and, if so, by what management approaches) and the utilisation of harvested wood (see for example Nabuurs *et al.*, 2008; Marland and Marland, 1992; Schlamadinger and Marland, 1996; Marland and Schlamadinger, 1997). There are several reasons why potential growth rate can be so important:

- Generally speaking, the faster the growth rate, the quicker carbon can be sequestered, e.g. when an area of non-forest land is converted to forest land through afforestation. (It must be noted that this ignores certain important subtleties such as the fact that tree growth is usually measured in cubic metres of volume rather than tonnes of carbon and is usually based on the volume of stemwood in trees rather than total volume or biomass, i.e. including branches and roots. Nevertheless the statement holds in broad terms, particularly when comparing situations where reported growth rates are very different.)
- The maximum carbon stock that can be ‘carried’ on an area of land is not very strongly correlated with growth rate. (This is for a number of reasons, for example, because tree mortality due to competition between trees tends to be more intense in forest stands with higher growth rates, which ultimately acts against any sequestration of carbon in trees.) Consequently, when forest carbon stocks are disturbed, by natural processes or by harvesting, generally they can be replenished to pre-disturbance levels more rapidly where growth rates are higher.
- The faster the growth rate, the more wood can be harvested from a given area and the greater the subsequent potential for reducing GHG emissions through use of wood as bioenergy and solid wood products, displacing more of the potential demand for fossil energy sources and non-wood materials.

The key significance of growth rate and consequent productive potential is recognised, for example, in the theoretical simulation results of Marland and Marland (1992), Schlamadinger and Marland (1996) and Marland and Schlamadinger (1997), as illustrated in Figure 1.2 in Section 1.2 of this report.

As discussed in Section 2.4, mean forest growth rates over typical rotations in boreal and temperate regions, including the EU range from less than 2 m^3 ha^{-1} yr^{-1} up to perhaps 30 m^3 ha^{-1} yr^{-1} in exceptional circumstances, with typical rates being around 4 to 8 m^3 ha^{-1} yr^{-1}. It is very likely that options for managing forests to meet climate change mitigation targets (i.e. reducing GHG emissions and/or sequestering carbon) will be sensitive to growth rates over this range, implying a regional and perhaps site-by-site approach for the evaluation of management options.

3.11. Avoidance of harvesting as a forest management option

Relatively recently (Searchinger, 2012), the view has been expressed that, whilst the continuation of existing management of forests for wood production through harvesting does not necessarily involve reductions in forest carbon stocks (see Section 3.5), nevertheless the effect of continued harvesting is generally to maintain forest carbon stocks at relatively modest levels. As a corollary, it is noted that, potentially, carbon stocks in forests would be larger if there was no harvesting. The question has thus arisen, would the suspension of harvesting lead to greater benefits in terms of forest carbon sequestration? Specifically, would these exceed the benefits associated with the use of harvested wood for bioenergy or wood-based materials?

It is important to recognise that the case of 'no harvesting' or 'no use' needs to be a genuinely meaningful and realistic forest management option, if it is to be used as a comparator against which to assess all other cases for forest management. However, it is notable that studies and critical discussions of forest bioenergy that refer to such a scenario do not define or discuss what 'suspension of harvesting', or 'suspension of management' or 'no use' would actually entail in practice. Either the scenario is referred to as a theoretical concept, or there appears to be an implicit presumption that existing and future management in forest stands can be abandoned comprehensively, and the affected land areas can be left to develop without further human intervention. Moreover, the prospect of abandoning management in forests seems somewhat at odds with the principle of multi-purpose forest management, as discussed in Section 2.3. The 'no management' case would, therefore, appear to be in need of a practical definition and specification.

The idea that harvesting can be suspended in forests to allow additional forest carbon stocks to be sequestered has led to the suggestion that estimates of GHG emissions for forest bioenergy involving harvesting and wood production should always be calculated relative to the case of no harvesting (Searchinger, 2012). However, this is an aspect of forest carbon assessment and methodology for calculating GHG emissions that is open to question. The position taken in this project is that the 'no-harvest' case *may or may not be* an appropriate comparator against which to assess other cases for forest management and wood use, *depending on the specific question(s) posed* by a particular assessment of forestry and wood consumption. In many situations, it may be more appropriate to represent the 'no-harvest' case distinctly and estimate GHG emissions and carbon sequestration for this case explicitly. As stressed in Section 4, it is the strong view of the authors of this report that a clear statement of the question(s) to be addressed is an essential pre-requisite for an effective and meaningful assessment of forest bioenergy, or any other scenario for forest management and wood use. Concomitantly, failure to clearly and unambiguously state the research question(s) to be addressed constitutes a major cause of confusion, uncertainty and misinterpretation in studies of forestry and wood utilisation.

3.12. Influence of natural disturbance events

The natural (and in some cases anthropogenic) disturbance of forest areas (e.g. due to storms, disease, fire) generally has negative consequences for carbon stocks. The risks of significant, large-scale disturbance events tend to be mitigated by the systematic control of levels of growing stock in forest stands associated with management involving harvesting. It is particularly important to consider the possible consequences of disturbance when assessing forestry cases involving minimising or complete avoidance of management (notably harvesting), as in many situations, the consequent accumulation of old, large trees and high carbon stocks will greatly increase the risks of disturbance events (Schelhaas *et al.* 2003). So far, disturbance processes and their effects have not been represented adequately in the assessment of forest management options, although some studies have made initial steps to address this issue (Lindroth *et al.* 2009).

There is limited acknowledgement of the very high uncertainty that should be attached to projections of future forest carbon sequestration under scenarios in which all harvesting is avoided. Whilst ongoing carbon sequestration is a likely outcome in the short term, it is important to note the high uncertainty attached to estimates of medium-term and long-term carbon dynamics and also the increasing risks of natural disturbance. Consequently, high uncertainty should be attached to theoretical carbon sequestration achieved by low-management or no-management forestry options.

In cases where there is significant, large-scale incidence of forest disturbance, perhaps due to 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 forest areas recover and re-grow, and will also strongly influence the timing of GHG emissions and carbon sequestration (see for example Thurig *et al.*, 2009; Köster *et al.*, 2011). It should also be emphasised that some forms of disturbance can sometimes preclude salvage logging (e.g. when a forest fire burns wood beyond the point that it can be used), and can cause relatively immediate release of carbon stocks, which would act against the objective of conserving carbon stocks in forests.

3.13. 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 *et al.*, 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 forestry.

Studies which have attempted to quantify the potential impacts due to iLUC on activities aimed at GHG mitigation, generally through management of agricultural land (e.g. Plevin *et al.* 2010), have shown that results are highly sensitive to the detailed assumptions made in carrying out analyses, with estimated emissions arising from iLUC ranging from zero to 'very large'. An ongoing debate about the risks and potential impacts of iLUC is seriously hampering the development of GHG mitigation policies involving land management and land-use change, mainly in the agriculture sector.

Although potential risks related to iLUC are recognised in the forest sector, as already noted, iLUC is identified primarily as an issue in the agriculture sector and is, therefore, not regarded as a key subject for consideration in this report. The issue of iLUC is most likely to arise in scenarios involving land use change as an essential theme, e.g. where demands for bioenergy are met through afforestation activities in the context of forestry. The approach taken in this project for such scenarios (for energy crops more generally as well as afforestation) is to constrain the relevant activities so as to avoid significant risks of iLUC. 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).

3.14. International and EU accounting for biogenic carbon emissions

In principle, GHG emissions from forest bioenergy are already accounted for, at least partially, as part of existing international efforts to limit climate change. As signatories (Parties) to the Kyoto Protocol[14], EU Member States have legally binding commitments to limit or reduce national GHG emissions. The EU15 also has its own collective target. Targets for levels of GHG emissions have to be met over commitment periods, the first of which has run from 2008 to 2012, with a second running from 2013 to 2020. The EU has a number of policies and measures which express the EU's collective commitment to reduce GHG emissions, which are complementary to wider commitments to the Kyoto Protocol, including a Decision on accounting for GHG emissions occurring in the Land Use, Land-Use Change and Forestry (LULUCF) sector (EU, 2013a). The Kyoto Protocol and the EU Decision specify accounting rules for various activities, which countries apply in demonstrating progress towards target levels of GHG emissions.

For the first commitment period of the Kyoto Protocol, accounting rules for LULUCF required Parties to account for GHG emissions (and/or CO_2 sequestration) occurring as a result of deforestation and afforestation activities taking place since 1990. Other accounting rules enabled Parties to account for GHG emissions (and/or CO_2 sequestration) occurring due to other LULUCF activities, potentially involving the management of e.g. existing croplands, grazing lands and forests. However, Parties could

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[14] United Nations (1998) Kyoto Protocol to the United Nations Framework Convention on Climate Change. (Full text available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf)

elect either to account or not to account for these various activities. The EU Decision did not exist during the first commitment period of the Kyoto Protocol.

For the second commitment period of the Kyoto Protocol, accounting rules for LULUCF activities have been strengthened somewhat, and the EU Decision has come into operation. The accounting rules of both the Kyoto Protocol and the EU Decision now require Parties to account for GHG emissions (and/or CO_2 sequestration) occurring as a result of the management of forest areas already in existence before 1990, as well as continuing to account for deforestation and afforestation activities taking place since 1990. A detailed explanation of the new accounting rules for forestry in the second commitment period would be lengthy and potentially distracting. In short, if changes to the management of forest areas result in overall reductions in forest carbon stocks, compared with levels that would have been expected in the absence of the changes to forest management, then the GHG emissions implied by these carbon stock reductions must be accounted for. (On the same basis, changes to forest management resulting in increased carbon stocks, compared with the levels expected otherwise, may be claimed as a credit, although subject to a cap.)

As a consequence of these accounting rules, if levels of harvesting in forest areas were to be intensified to meet increased demand for forest bioenergy, any permanent carbon stock changes in forests resulting from the increased harvesting would need to be accounted for. It may be noted that the Kyoto Protocol during the second commitment period and the EU Decision on LULUCF also include accounting rules for carbon stocks retained in (and ultimately released from) harvested wood products. However, in the case of harvested wood used for bioenergy, the GHG emissions due to combustion of the wood are represented as occurring instantaneously (i.e. at time of harvest).

It follows that, certainly in principle, the accounting rules of international policies aimed at limiting GHG emissions already cover the GHG emissions associated with biogenic carbon consumed as forest bioenergy (specifically, where consumption of forest bioenergy is increasing above previously expected levels). However, it is important to understand certain complications and limitations of the current accounting approaches. Specifically, the GHG emissions occurring as a result of carbon stock changes in forests (which are, in turn, the result of increased harvesting) need to be accounted for by the Parties (countries) in which the affected forest areas are situated. In this case, a ‘consuming country’ would not need to account for any GHG emissions associated with the biogenic carbon of forest bioenergy, but the ‘producing countries’ would have to account for those emissions, assuming the ‘producing countries’ were EU Member States or otherwise Parties to the Kyoto Protocol. This may create a certain tension between countries trading in forest bioenergy, since it would appear that the consumption of forest bioenergy is effectively being incentivised, whereas its production is potentially being disincentivised. The situation is more serious in the case where a ‘consuming country’ is an EU Member State or otherwise a Party to the Kyoto Protocol, and the ‘producing country’ is not. In such cases, any GHG emissions due to increased levels of harvesting in the forests of the 'producing country' would not be accounted for at all. At the very least, there is an implication that this leads to perverse incentives for the consumption of forest bioenergy from sources that are not covered by existing domestic and international policies aimed at limiting GHG emissions.

3.15. Non-GHG climate effects of forests (albedo and aerosols)

Before closing this section of the report, mention should be made of other effects of forests on global climate apart from those due to processes and cycles involving the major GHGs. However, it must be stressed that such effects are not the focus of this project and the following discussion is not comprehensive. The other main phenomena involve the interactions of forest areas with land surface albedo, and with atmospheric aerosols.

The term 'albedo' refers to the reflectivity or reflection coefficient of the Earth's surface, which is measured as the ratio between solar radiation reflected back from the surface, and the original solar radiation incident upon it.

Aerosols are certain types of chemicals which, when present in the atmosphere, can reflect and scatter sunlight directly. They may also form into 'particles' which encourage the formation of clouds and can also make clouds whiter, also contributing to the reflection and scattering of solar radiation.

The phenomenon of albedo is a very complex function of surface and radiation characteristics, involving land cover type, specifics of the vegetation, snow cover, soil moisture, and the incident angle and wavelength of radiation (Henderson-Sellers and Wilson, 1983; Ni and Woodcock, 1999). Changes in land use may also affect albedo.

The 'climate benefits' of carbon sequestration in forests, e.g. achieved through afforestation, can be offset by changes in climate forcing resulting from changes in surface albedo. This is particularly the case in boreal and other snow-covered regions (Bright *et al.*, 2012; Haberl *et al.*, 2013), because darker trees capture more heat than snow does (Bonan and Pollard, 1992; Betts, 2000; Claussen *et al.*, 2001; Randerson *et al.*, 2006; Bala *et al.*, 2007). On the other hand, this may mean that, potentially, the climate effects of CO_2 emitted as a result of tree harvesting (and consequent reduced tree cover) may also be offset by related changes in albedo (Amiro *et al.*, 2006; Bright *et al.*, 2011; O'Halloran *et al.*, 2012). Outside boreal and snow-covered regions, and particularly for areas covered by deciduous forests, the effects due to changes in albedo are generally weaker (Bonan, 2008; Anderson *et al.*, 2010; O'Halloran *et al.*, 2012).

The climate forcing effects due to changes in surface albedo are further modified by the effects of aerosols and clouds. In general, these contributions tend to attenuate any effects due to changes in albedo (Schwaiger and Bird, 2010). Biophysical factors such as reflectivity, evaporation and surface roughness all influence the ultimate effects on climate, and variously act synergistically and antagonistically (Kulmala *et al.*, 2004; Bonan, 2008; Jackson *et al.*, 2008; Spracklen *et al.*, 2008; Anderson *et al.*, 2010). A growing body of research suggests that trees can play an important role in the production of aerosols and in cloud formation and whitening (e.g. through the release of organic vapours such as terpenes), contributing a potentially significant cooling effect (Kulmala *et al.*, 2004; Spracklen *et al.*, 2008; Paasonen *et al.*, 2013; Topping *et al.*, 2013).

It remains the case that there are significant knowledge gaps and uncertainties concerning the interrelations between the biogeochemical and physical processes influencing climate forcing, and their specific relationships to forests. However, a case is emerging for considering such effects alongside the contributions made by biogenic carbon in forests, and more widely by GHG emissions (and CO_2 sequestration) contributed by forestry activities.

3.16. Synthesis of findings on forest carbon stocks and forest biogenic carbon

The discussion in this section has been concerned with setting out the essential science and related issues underlying the role of forests in the carbon cycle, with relevance to forest bioenergy. This has included consideration of the biogenic carbon in forest biomass, its potential contributions to climate change mitigation, and the potential influence of forest management, particularly with regard to the production of forest bioenergy. There has been brief discussion of related subjects, such as existing approaches to accounting for biogenic carbon in forests and other influences of forests on regional and global climate. In accord with objective 1 of this Task, the preceding discussion has considered many factors that may lead to sensitivity in the GHG emissions associated with forest bioenergy. It may be inferred that a number of key factors contribute to variable but predictable outcomes in terms of the GHG emissions of forest bioenergy, as summarised in Table 3.2.

For each factor in the Table 3.2, it is possible to characterise scenarios that will contribute towards, detract from, or be indifferent towards an objective of reducing GHG emissions.

Table 3.2 Summary of factors contributing to outcomes in terms of the GHG emissions of forest bioenergy

Factor	Influence on GHG emissions of forest bioenergy	See Section(s)
Forest management scenario	GHG emissions associated with forest bioenergy are sensitive to the approach taken to forest management for production of wood, including for bioenergy. A number of broad scenarios for forest management can be identified, which can be ranked in terms of GHG emissions likely to be associated with any forest bioenergy produced, from 'most effective' in achieving low GHG emissions (or reduced emissions, compared with the emissions that would occur if the bioenergy was not produced via forest management) to 'least effective', as: • Increased wood production through afforestation (also avoiding the possibility of iLUC). • Increased wood production as part of the elevation of carbon stocks in degraded forests. • Continued wood production as part of 'business as usual' (sustainable yield management) of forests. • Increased wood production through intensified harvesting in forests (e.g. introduction of harvesting in forest areas not previously under management for wood production), *with* accompanying measures to enhance growing stock (e.g. increasing tree density on restocking, restocking with better growing/more productive trees). • Increased wood production through shortened rotations and/or more intense thinning in forests already in production. • Increased wood production through intensified harvesting in forests, *without* accompanying measures to improve growing stock (see previous point).	3.6, 3.13
Mean forest growth rate	Generally, the faster the growth rate of forests, the quicker carbon can be sequestered (and also replaced after the disturbance of forest carbon stocks). Also, more wood can be harvested from a given area of forest and there is greater subsequent potential for reducing GHG emissions through use of wood as bioenergy and solid wood products.	3.10

Table 3.2 (continued) Summary of factors contributing to outcomes in terms of the GHG emissions of forest bioenergy

Factor	Influence on GHG emissions of forest bioenergy	See Section(s)
Soil carbon stocks	GHG emissions associated with forest bioenergy can be sensitive to the status of soil carbon stocks. When considering the creation of new forest areas (afforestation) with the intended management aim of producing (or co-producing) forest bioenergy, generally, the lower the initial soil carbon stocks, the greater the potential to sequester additional soil carbon stocks and the less likelihood of causing reductions in soil carbon stocks. Afforestation may therefore be most effective (in terms of soil carbon stocks) on lands with degraded soils, as part of land regeneration. When considering introducing harvesting in areas of forest previously not under management for wood production, or considering increasing the levels of harvesting in existing production forests, the additional harvesting (and any associated soil disturbance) is less likely to result in significant GHG emissions on soils with intrinsically low carbon stocks, the reverse being the case for soils with intrinsically high carbon stocks. In general, forest management may need to be considered on a site by site basis with regard to soil carbon stocks. On soils with intrinsically very high carbon stocks (e.g. deep peats), management to conserve soil carbon stocks is likely to be an important objective in the context of climate change mitigation.	3.2
Bioenergy counterfactual	The production and utilisation of forest bioenergy can be ranked in terms of its potential effectiveness in reducing GHG emissions with respect to ‘counterfactual’ energy sources, from most effective to least effective, as: • Coal > Fuel oil > Natural gas > Other renewables. Occasionally, forest bioenergy can directly displace the consumption of grid electricity (e.g. when a wood-fired heating system directly replaces an electrical heating system). The effectiveness of such cases will be variable, depending on the existing mix of energy sources used in generating electricity.	3.8

Table 3.2 (continued) Summary of factors contributing to outcomes in terms of the GHG emissions of forest bioenergy

Factor	**Influence on GHG emissions of forest bioenergy**	**See Section(s)**
Bioenergy conversion technology	The GHG emissions associated with the production and use of forest bioenergy (when expressed per unit of energy produced, e.g. in units of gCO_2-eq. per MJ or $kgCO_2$-eq. per MWh) are sensitive to the type of conversion technology involved in consumption of the bioenergy. Scenarios can be ranked as ‘most effective’ (i.e. low GHG emissions per unit energy) to ‘least effective’, as: • Large-scale combined heat and power (large scale then small scale) • District heating • Small scale heating • Power only (co-firing in coal-fired power station) • Power only (dedicated biomass).	3.8

Table 3.2 (continued) Summary of factors contributing to outcomes in terms of the GHG emissions of forest bioenergy

Factor	Influence on GHG emissions of forest bioenergy	See Section(s)
Production scenario	GHG emissions associated with forest bioenergy are sensitive to the approach taken to supply bioenergy feedstock. At least four broad production scenarios can be identified, which can be ranked in terms of GHG emissions likely to be associated with any forest bioenergy produced, from 'most effective' in achieving low GHG emissions (or reduced emissions, compared with the emissions that would occur if the bioenergy was not produced via forest management), to 'least effective', as: • Production from waste wood sources generated at the end of life of solid wood products. • Co-production alongside the manufacture of solid wood products (e.g. offcuts from sawn timber production) and production from harvesting residues. • Forest bioenergy as the sole product of raw harvested wood (i.e. all harvested wood is used exclusively for bioenergy). Certain important qualifying points need to be attached to these conclusions: • The scenario of forest bioenergy as the exclusive product of raw harvested wood refers literally to situations in which all wood harvested from forests is used for bioenergy. It does not refer to situations, typical of conventional forest management, in which some individual whole trees (stemwood and possibly also branches) of small size or poor stem form are used entirely to produce bioenergy as part of the production of a mix of types of raw harvested wood for a range of uses (see Section 2.1). • The production of forest bioenergy is least effective when feedstock is derived by diverting wood (regardless of source, i.e. raw wood, co-products or waste wood) from the manufacture of solid wood products.	3.7
Solid wood co-products counterfactuals	• The scenario of co-production of forest bioenergy alongside solid wood products is most effective when the solid wood co-products have high potential to displace GHG emissions of 'counterfactual' products, and less effective when this is not the case.	3.8

3.17. Conclusions on forest carbon stocks and forest biogenic carbon

It is now appropriate to summarise key insights from the preceding discussion relevant to the Task objectives (see Section 1.3).

First of all, it should be observed that the quantities of biogenic carbon sequestered in forests are significant (Section 3.3). Currently, the continued accumulation of carbon stocks in forests in the EU27 results in sequestration equivalent to approximately between 5% and 10% of current GHG emissions in other sectors in the EU27. Globally, the current contribution of carbon sequestration in forests may amount to approximately 15% of GHG emissions in other sectors. However, this contribution of forests, compensating to some extent for GHG emissions due to activities in other sectors, is likely to decline eventually, and potentially reverse. A number of factors are influencing the current and likely future development of forest carbon stocks, including the present and evolving management of forests.

Considering factors that may lead to sensitivity in the GHG emissions associated with forest bioenergy (objective 1 of this Task), Table 3.2 in Section 3.16 has analysed a number of key factors that contribute to outcomes in terms of the GHG emissions of forest bioenergy, which can be summarised as shown in Figure 3.8. The figure illustrates how the effectiveness (or otherwise) of the harvesting and use of forest bioenergy (in terms of achieving low GHG emissions and/or reductions in GHG emissions compared with other options) may depend on a number of factors. By implication, the 'least effective' options involving bioenergy use appear on the left hand side of the figure, while the 'most effective' options appear on the right hand side. However, the consequences of different options for bioenergy use can be very context-specific. Note, in particular, that the figure does not show the relative importance of the various factors or any effects due to interactions between them.

The analysis in Figure 3.8 could be viewed as an elaboration of the diagram illustrating a connection between basic forest characteristics (primarily, but not exclusively growth rate) and potential options for forest management to reduce GHG emissions originally presented in Matthews and Robertson (2005), slightly reinterpreted by Matthews *et al.* (2007), and repeated here as Figure 3.9. The picture in Figure 3.9 suggests the possibility for priorities or emphasis attached to different forest management and wood-use options to be matched to forest characteristics. In this context, the term 'preferred uses' implies how the mix of forest management prescriptions, i.e. aimed at conservation of carbon stocks, production of solid wood products or bioenergy, might be optimised from the perspective of biogenic carbon, depending on the productive potential and characteristics of forest areas, or land on which new forests could be established. However, only one generic and quite loosely defined characteristic is considered and the question arises as to whether such an approach can be 'mapped' meaningfully and usefully onto the various factors considered in Figure 3.8. This is considered further as part of the detailed review of literature in Section 5 of this report.

The discussion in this section is not intended primarily to inform understanding of the sensitivity of the GHG emissions associated with forest bioenergy to calculation methodologies (objective 2 of this Task). However, it is apparent from the summary analysis in Table 3.2 and Figure 3.8 that the results of a particular study of GHG emissions of forest bioenergy will depend on the comprehensiveness and accuracy with which the forest bioenergy production and conversion system is represented, notably with regard to the factors identified. It is also important that such studies include a clear and complete statement describing the forest bioenergy production and consumption system(s) actually under study, otherwise the applicability and relevance of any results is likely to be ambiguous and potentially confusing. These points are also of vital importance with regard to characterising a methodology which is suitable for calculation of GHG emissions associated with the use of forest bioenergy (objective 3 of this Task).

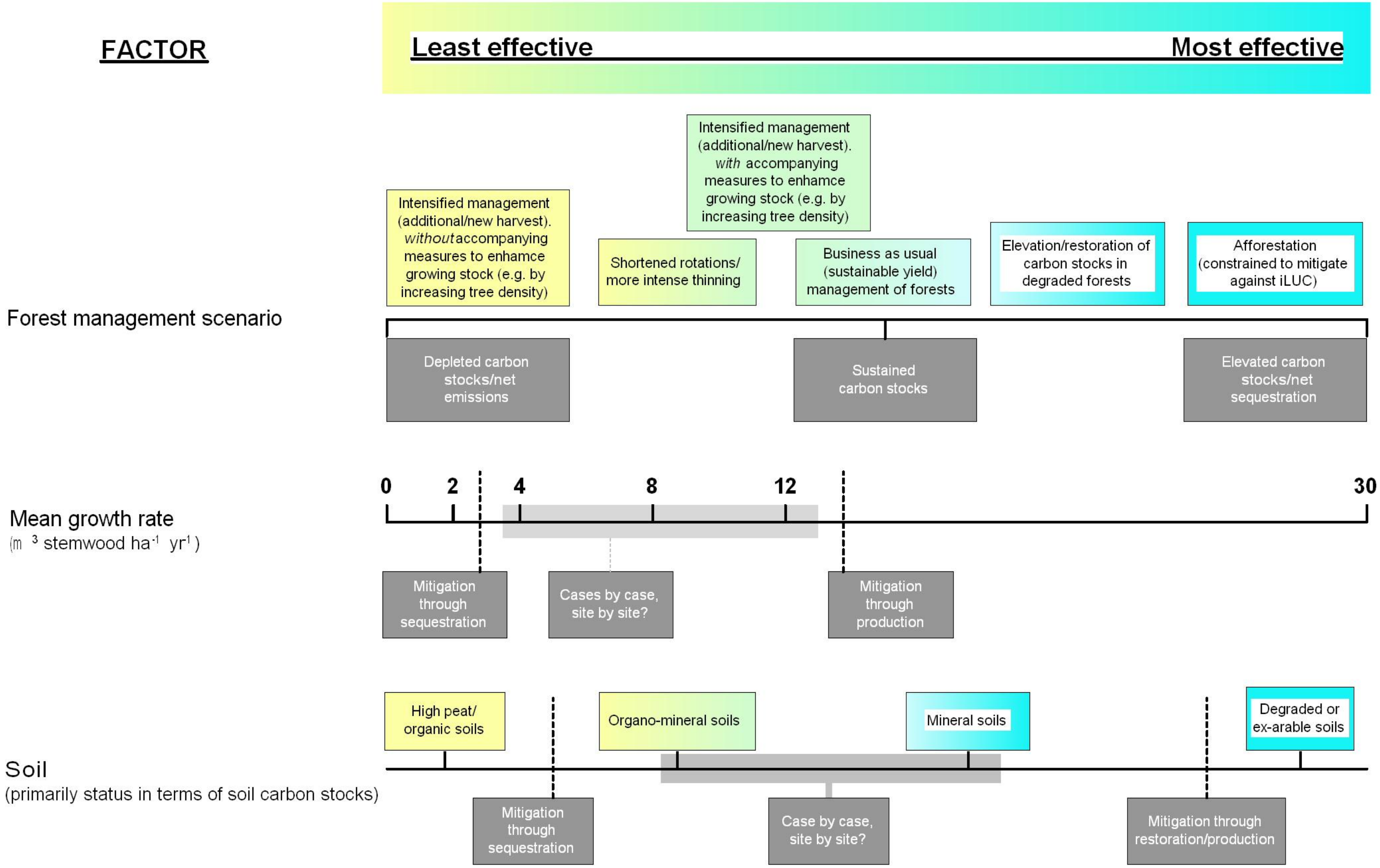

Figure 3.8. Illustration of how the GHG emissions associated with the harvesting and use of forest bioenergy may depend on a number of factors.

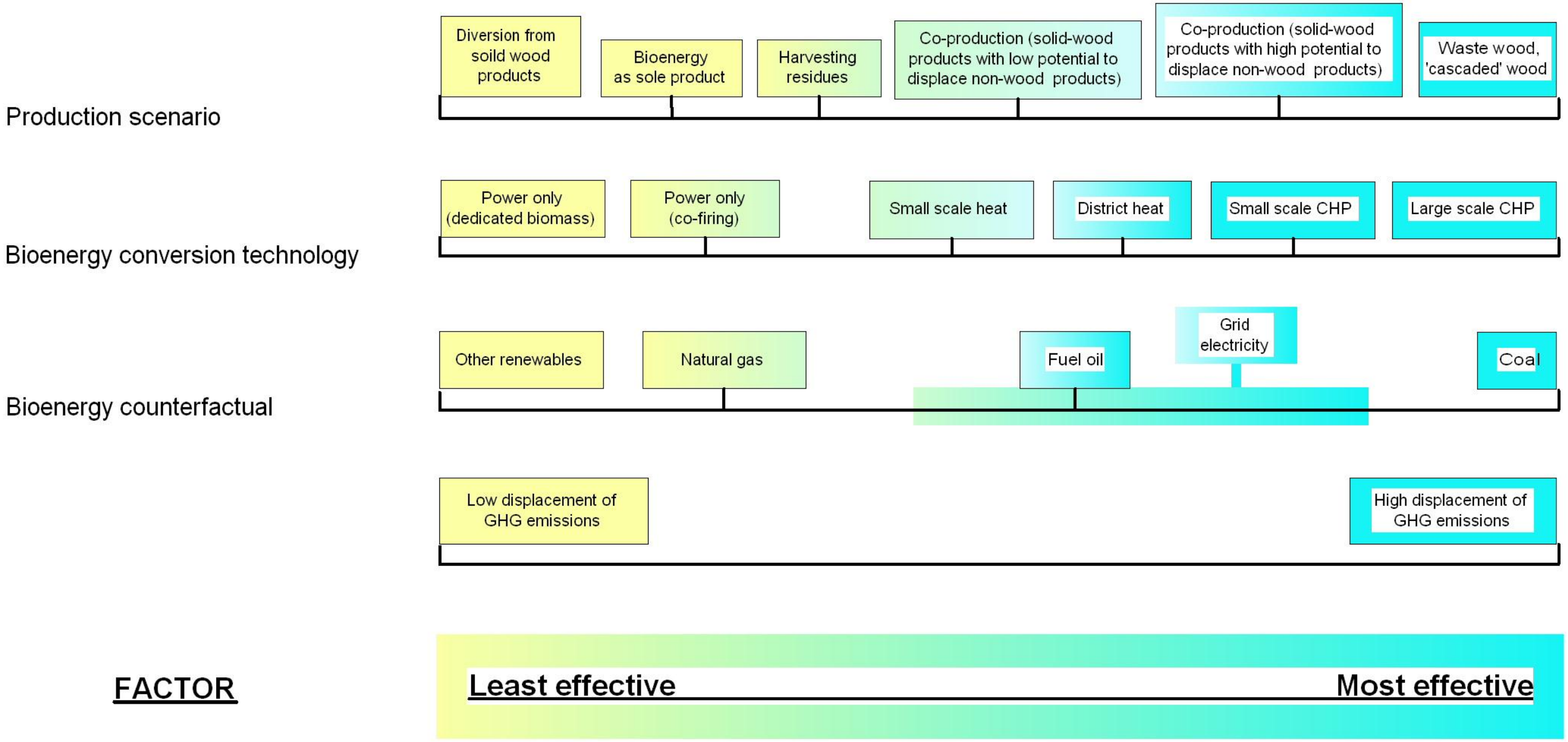

Figure 3.8 (continued). Illustration of how the GHG emissions associated with the harvesting and use of forest bioenergy may depend on a number of factors.

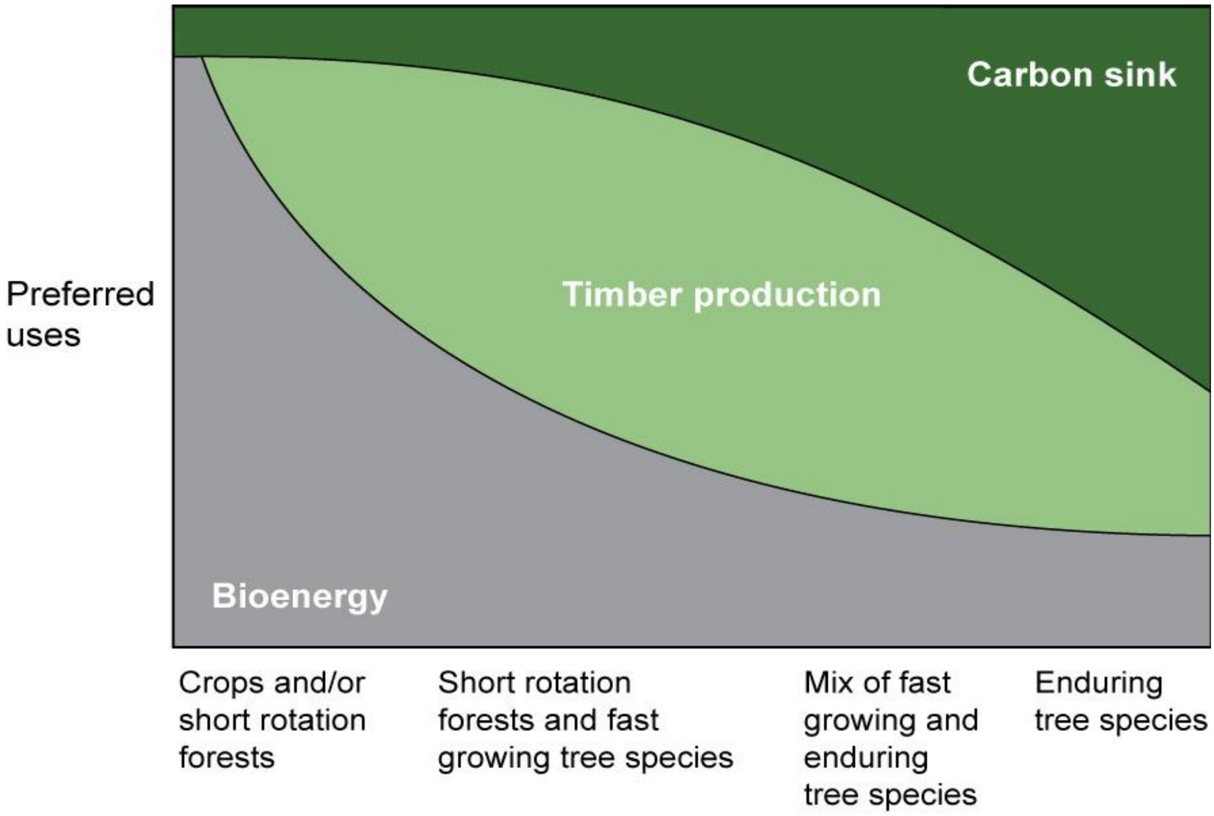

Figure 3.9. Simplistic illustration of how land/forest management for carbon stocks and biomass utilisation might be matched. (Sources: Matthews and Robertson, 2005; Matthews *et al.* 2007.)

3.17.1. Key messages concerning forest biogenic carbon and its management

Sensitivity of GHG emissions due to biogenic carbon

Biogenic carbon can make a very variable contribution to the GHG emissions associated with forest bioenergy. Consequent GHG emissions can vary from negligible levels to very significant levels (similar to or greater than GHG emissions of fossil energy sources). In some specific cases, forest bioenergy use may be associated with net carbon sequestration. Many factors influence GHG emissions of forest bioenergy due to biogenic carbon. These factors have been analysed in the preceding discussion and their influences have been summarised in Table 3.2, Section 3.16 and Figure 3.8, Section 3.17. GHG emissions are very sensitive to these factors but outcomes are predictable, at least in principle.

Additionality of GHG emissions and reductions

Although perhaps not explicitly stated, there is a general presumption in the discussion presented in this section of a focus on GHG emissions that would occur as a result of changes in the level of consumption of forest bioenergy. Any contribution of biogenic carbon to GHG emissions associated with *existing* consumption of forest bioenergy effectively forms a component of baseline levels of GHG emissions. The critical question is concerned with the effects that a change in the scale of consumption of forest bioenergy would have on baseline levels of GHG emissions, i.e. whether they would increase or decrease. This needs to be clearly understood and allowed for in assessments of contributions of biogenic carbon to GHG emissions of forest bioenergy. This point is explored further in Section 4.

Baseline forest management

As part of the assessment of the effects of changes in levels of consumption of forest bioenergy, it is necessary to include appropriate assumptions about the age distribution of existing forests, deforestation and afforestation into scenarios for future land use and forest management to meet demands for forest bioenergy. This is required for the construction of a baseline scenario, representing 'business as usual' development of the management of forests, against which any policy scenarios may be evaluated. Furthermore, it is necessary to consider the possible influences of changes in demands for forest bioenergy on the age distribution of forests and on future rates of deforestation and afforestation.

It is also necessary to characterise the existing management of relevant forest areas, and the effects of management on the development of forest carbon stocks. As with deforestation and afforestation, this is required for the construction of a baseline scenario, representing 'business as usual' development of the management of forests, against which any policy scenarios may be evaluated. Furthermore, it is necessary to consider the possible influences of changes in demands for forest bioenergy on future patterns of forest management.

Relevance of scale

The concept of scale is relevant to the assessment of GHG emissions associated with the consumption of forest bioenergy in two senses.

Firstly, forest bioenergy systems need to be assessed at an appropriate spatial and temporal scale. The spatial scale needs to reflect the complete terrestrial vegetation system involved in supplying bioenergy. Examples of relevant spatial scales, variously depending on context, include the complete areas of forests supplying a particular consumer with bioenergy, all of the forests situated within a country or group of countries, or all of the forests managed by a commercial company or land owner. The scale of an individual forest stand is generally of less relevance except for very specific, detailed purposes. The temporal scale needs to capture the variable effects of forest bioenergy on GHG emissions over time. GHG emissions calculation methodologies need to address sensitivities of results to interactions between human management of forests and natural processes and in particular the generally contrasting short-term and long-term consequences of forest management interventions.

Secondly, the contribution of biogenic carbon to GHG emissions of forest bioenergy is sensitive to the scale of consumption. For example, a modest increase in consumption might be achieved through marginal adjustments to existing management of forest areas, with limited effects on forest carbon stocks. However, a significant increase in consumption, for example as illustrated by the 'high wood mobilisation' scenarios considered in the EUwood study (Mantau *et al.*, 2010) and EFSOS II study (UN-ECE, 2011) would require changes to forest management such as those illustrated by scenarios in Table 2.10, Section 2.7. Many of these scenarios for changes in forest management would involve significant and variable influences on the development of forest carbon stocks. Consequently, the variable effects of scale of consumption need to be allowed for in assessments of the contribution of biogenic carbon to GHG emissions of forest bioenergy.

Related to the issue of scale, it is important to recognise that transitions in the level of consumption of forest bioenergy, and consequent responses of forest carbon stocks, can involve long timescales. This is particularly true when considering significant increases in consumption of forest bioenergy, which would require major changes to the management of large forest areas over time.

Counterfactuals

For assessments of GHG emissions of forest bioenergy involving changes to the management of forests and/or changes to patterns in the use of harvested wood, it is essential to characterise realistic and justifiable 'counterfactuals'. Often it is relevant to study the change from 'business as usual' in patterns of land use, i.e. forest management, thus making the construction of a 'business as usual' scenario relevant as part of the definition of the counterfactual. For harvested wood products, counterfactuals involve the 'business as usual' patterns for wood use, and also a set of assumptions about what energy sources and materials might be used instead of forest bioenergy and harvested wood products. When defining such counterfactuals, it is important to recognise that the use of wood for material and fibre products, and as a feedstock for chemicals, may become more important than forest bioenergy in the future, as part of the development of a bioeconomy, or an otherwise decarbonised economy.

LULUCF accounting rules

Existing EU and international accounting systems for biogenic carbon in forests and harvested wood, supporting international efforts to limit GHG emissions, serve very specific purposes and are unsuitable for more general application as calculation methods for assessing the GHG emissions associated with forest bioenergy.

4. Life cycle assessment: essential concepts and key issues

4.1. Purpose

The purpose of this section is to:

- Introduce the essential elements of LCA methods and calculations.
- In particular, to clarify why different LCA studies can, quite validly, produce different results.
- Establish the prime importance of determining a clear goal for any LCA study to address.

The discussion in this section is not intended to be an exhaustive account of the theory and application of LCA.

4.2. The genesis and principles of LCA

LCA has its roots in 'energy analysis', essentially dating from the early 1970s (Chapman, 1975; Boustead and Hancock, 1979), when the principal concern was with constraints on the supply of fossil energy sources and the implications for energy security. Subsequently this has expanded into the science of 'industrial ecology' (Socolow *et al.* 1994), which involves the more general study of the interactions between human activities and the environment. In industrial ecology, a range of tools have been developed for analysing environmental impacts ranging from the specific impacts due to the manufacture of an individual product, to global impacts of a set of manufacturing processes or a set of human activities. A family of methods derived from the first law of thermodynamics (i.e. that energy cannot be created or destroyed) form basic analytical tools for industrial ecology. These tools include the methods of substance flow analysis and material flow analysis (Bringezu *et al.* 1997; den Hond, 2000), showing the lineage back to energy analysis. At the product or process level, LCA extends to these methods by attempting to quantify the environmental impacts of the use of materials and services, in particular, the impacts of specific production and processing systems (Rebitzer *et al.* 2004). LCA encompasses a methodological framework for estimating and assessing the environmental impacts related to the 'life cycle' of a specified product, process or service (ISO 2006:14040; ISO 2006:14044).

The question may arise, are there other techniques apart from LCA, which might be used to assess the GHG emissions associated with the production and use of forest bioenergy? It is the view of the authors of this report that, if LCA did not exist as a formal approach for such purposes, it would need to be invented. LCA is a systematic methodology for assessing the effects on the environment of a human activity, such as an agricultural practice, an industrial process, a commercial enterprise or a whole economic system. An integral part of this methodology involves calculating 'balance sheets' for specified human activities. As such, LCA has much in common with financial accounting – it is concerned with assessing, monitoring or regulating the 'performance' of an existing activity, or appraising the 'potential performance' of a possible new or changed activity.

However, in contrast to financial accounting, LCA generally deals with balance sheets for physical variables[15] rather than money, such as the expenditure of energy and raw materials, the outputs of goods, machines, services and waste, including GHG emissions.

The suitability of LCA as a methodology for assessing GHG emission of bioenergy and other systems is occasionally challenged (see, for example, Delucchi, 2011, 2013). Generally, such challenges are based on important difficulties in providing suitable information for LCA and, usually, do not translate into substantial criticisms of the fundamental principles and methodologies of LCA itself. These difficulties are associated with aspects such as the modelling of indirect land-use change and vegetation carbon stock dynamics which would present problems for any assessment technique, no matter how this was formulated.

The concern of LCA with physical variables may lead to the misapprehension that there should be a single, definitive result for an LCA of a specified activity. However, as explored in this section, LCA has more in common with financial accounting than just a preoccupation with balance sheets of one kind or another. LCA is essentially a socio-economic or, perhaps more precisely, a techno-economic tool. Consequently, results for a physical system depend on the techno-economic context in which the system is being assessed. This means that the details of LCA calculations and reported results must be specified and carried out so that they are appropriate for addressing the techno-economic question being addressed. Concomitantly, the results of LCA studies need to be interpreted with a clear understanding of the techno-economic questions originally posed.

4.3. The main approaches of LCA: consequential and attributional LCA

An absolutely critical step in LCA involves clearly stating the goal of the exercise, which requires an absolutely clear understanding of the research question which the LCA is intended to address. Much, if not all, of the details of actual LCA calculations flow naturally from a clearly and unambiguously stated question. Problems arise when an LCA is performed without having established and stated an essential question to be answered and/or when the detailed LCA methods actually applied are inappropriate for addressing the stated question. This issue is of great relevance when considering published LCA studies, particularly if trying to compare results from different studies.

Relatively recently, a notable attempt has been made to offer guidance on how to identify appropriate methodologies and conventions when undertaking LCA for different objectives by distinguishing two fundamentally different classes of LCA, referred to as ‘consequential LCA’ and ‘attributional LCA’ (Curran *et al.* 2005; Finnveden *et al.* 2009; Brander *et al.*, 2009).

Although fundamentally different, the distinction between the approaches of consequential and attributional LCA can sometimes be quite subtle. They also share

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[15] It may be noted that LCA has been extended to include wider variables, such as indicators of social values, but such extensions are outside the scope of the discussion in this report.

many common features, essentially being variants of the same basic methodology. Brander *et al.* (2009) have attempted to summarise the key differences between the two approaches by describing their key features with respect to a number of aspects of LCA. A somewhat elaborated and amended version of the description of Brander *et al.* is shown in Table 4.1.

Currently, there is much debate over the interpretation and application of consequential LCA and, especially, attributional LCA. The basis of disagreements is often the lack of clear definition of these methodologies and associated terms. The existing standard of the ISO 14040 series (ISO 2006:14040; ISO 2006:14044), does not really resolve these disagreements since its crucial role in emphasising the need for first establishing the goal of LCA, and then ensuring a transparent framework in presenting how this was achieved in producing results, is frequently overlooked. Instead, resolution is usually sought in the detailed options for undertaking LCA that this standard documents, rather than in its fundamental principles. One particularly notable attempt to provide guidance, by clarifying and expanding these detailed options, is provided in the JRC's International Reference Life Cycle Data System (ILCD) Handbook (JRC, 2010). It is particularly helpful that the ILCD Handbook defines the aims of consequential modelling in LCA as, "…identifying the consequences that a decision in the foreground system has for other processes and systems in the economy…" (JRC, 2010, pages 71 and 72) and that, "One important aspect of consequential modelling is that it is not depicting the actual process of e.g. the suppliers of a specific product supply-chain as an attributional model does, but it is modelling the forecasted consequences of decisions" (JRC, 2010, page 164). Such guidance supports the definition and application of consequential LCA in areas of policy analysis.

The objective for this project, as stated in Section 1, is "a qualitative and quantitative assessment of the direct and indirect greenhouse gas (GHG) emissions associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU under a number of scenarios, in order to provide objective information on which to base further development of policy on the role of biomass as a source of energy with low associated GHG emissions". Given this objective, it should be evident from the descriptions presented in Table 4.1 that consequential LCA is the correct approach to adopt for the purposes of such an assessment. It should also be apparent that the approaches of attributional LCA and consequential LCA may generate very different results, e.g. for GHG emissions, and this can be a major reason for the diversity of estimates presented in the scientific literature for GHG emissions associated with forest bioenergy.

Recently, a very important contribution to the debate over the relevant application of attributional and consequential LCA has been provided by Plevin *et al.* (2013). In particular, this warns against the use of attributional LCA in the evaluation of policy decisions. This warning is based on a thorough and well-argued examination of the limitations of attributional LCA and the capabilities of consequential LCA. Fundamentally, Plevin *et al.* (2013) recommend that those conducting LCA "…consider carefully and systematically the questions they are attempting to answer and ensure that the form of the LCA used is appropriate to answer those questions". In this regard, it is stated that attributional LCA "…is not designed to answer the questions of whether a change in energy system use results in climate-change mitigation benefits". Instead, it is concluded that "decision making is best supported by an analysis that anticipates the effects of the decision…" and this requires the use of consequential LCA so that it can "support robust decision making". Many aspects associated with the subsequent application of consequential LCA in policy analysis are discussed and important recommendations are made.

Table 4.1 introduces a number of key concepts that are highly relevant to understanding the correct application of LCA methods, and also the potential for diversity in the results generated by different LCA studies. Particularly important concepts include:

- The definition of the system under study
- Delineation of the system boundary
- System boundary expansion
- Calculation and representation of GHG emissions
- Allocation of GHG emissions to co-products.

These aspects of LCA methodology are explored in Sections 4.4 to 4.7. It is also necessary to consider:

- The relevance of a functional unit in LCA studies, and how this may be defined
- How to represent GHG emissions and their impacts over time
- The necessity (or otherwise) of referring to a baseline in GHG emissions calculations.

These subjects are considered in Sections 4.8 to 4.10 respectively.

Table 4.1 Summary of key differences between attributional and consequential LCA (modified from Brander *et al.*, 2009)

LCA aspect	Attributional life cycle assessment (ALCA)	Consequential life cycle assessment (CLCA)
Question the method aims to answer	What are the total emissions (and resulting impacts on the environment) from the processes and material flows identified as associated with the life cycle of a product?	What is the change in total emissions (and resulting impacts on climate) as a result of a marginal change in the production (and consumption and disposal) of a product?
Application	ALCA is applicable for understanding the emissions (and resulting impacts on the environment) identified as associated with the life cycle of a product. ALCA is also appropriate for consumption-based emissions accounting. ALCA is not an appropriate approach for quantifying the change in total emissions resulting from policies or other decisions that change the output of certain products.	CLCA is applicable for informing consumers and policy-makers on the change in total emissions (and resulting impacts on climate) arising from a proposed or actual decision or action. As important examples, the decisions or actions may be to do with purchasing a product or determining a policy. CLCA is not appropriate for consumption-based emissions accounting because it quantifies changes in GHG emissions associated with changes in activities, rather than total GHG emissions attributable to a specific product or service.
System boundary	The processes and material flows identified as used in the production, consumption and disposal of the product.	All processes and physical flows which are directly or indirectly affected by a marginal change in the output of a product, e.g. through market effects, substitution (i.e. displacement of existing use of products), use of constrained resources, etc.
Marginal or average data	ALCA tends to use some sort of average data in calculations, e.g. the average 'carbon intensity' of a national electricity grid.	CLCA tends to use marginal data in calculations when appropriate, e.g. the 'marginal long-term carbon intensity' of a national electricity grid. However, in some specific situations, reference to average data may be appropriate.

Table 4.1 (continued) Summary of key differences between attributional and consequential LCA (modified from Brander *et al.*, 2009)

LCA aspect	Attributional life cycle assessment (ALCA)	Consequential life cycle assessment (CLCA)
Market effects	ALCA does not consider the market effects of the production and consumption of the product.	CLCA considers the market effects of the production and consumption of the product, related to the decision (and implied changes in production and consumption of a product).
Allocation methods	ALCA allocates emissions to co-products based on common characteristics such as economic value, energy content, mass, or some other quantity relevant to the objective of the LCA study.	CLCA uses system expansion, by means of the application of substitution credits, to quantify the effect of co-products on emissions. As such, in principle, allocation is strictly not appropriate as part of CLCA but, in practice, it may be difficult to completely avoid allocation, e.g. as part of detailed intermediate calculations required for an LCA study.
Non-market indirect effects	ALCA does not include other indirect effects. (Generally, these are not relevant.)	CLCA should include all other indirect effects, such as the interactions with existing policies or the impact of research and development on the efficiency of the production of other products.
Uncertainty	ALCA can have low uncertainty because the relationships between inputs and outputs are generally stoichiometric. However, ALCA results can involve large uncertainties in some situations, e.g. due to uncertainties in production data or parameters such as emissions factors used as the basis for LCA calculations. There is also an intrinsic sensitivity in ALCA related to the selection of allocation methods.	CLCA is very often highly uncertain because, as part of representing the effects of changes, it relies on assumptions or models that seek to represent complex socio-economic systems that include feedback loops, random elements and likely present and future behaviour.

4.4. System definition and system boundary delineation

As already stressed in Section 4.2, the first step in an LCA study involves defining the goal and scope of the study. This is followed by the development of a life cycle inventory (LCI), which forms the basis for a life cycle impact assessment (LCIA), the results of which are then interpreted. The definition of the object or system being studied, and the system's 'function', are central elements of an LCA study. This involves describing quantitatively and qualitatively the object or system that is being analysed (e.g. an individual product, a production process, the provision of a service or some other human activity). The extent of the object or system under study can be specified quite flexibly, thus enabling the use of the LCA framework for research questions related to single products or more widely to a company, an 'activity' or a country or region, the latter sometimes being referred to as scenario or system-level studies.

Intimately associated with the definition of the system and its function, is the delineation of an appropriate 'system boundary'. The identity of a system can be established by a system boundary, which is an imaginary line drawn around all the activities that are relevant to the analysis being conducted. It should be noted that, whilst it is common for the system boundary to be considered a spatial concept, it also has a temporal dimension which is of equal importance. The specific spatial and temporal location of a system boundary is important because it subsequently defines what is included, and, therefore, what is excluded from the system and its analysis.

A forest-related example of a system and its (spatial) system boundary is shown in Figure 4.1a. It must be emphasised that this example, along with the others presented in this section, represent highly simplified illustrations for the purposes of explaining key principles of LCA methodology. As such, they should not be taken as exemplars of general LCA methodology. The example in Figure 4.1a illustrates how the delineation of the system boundary not only determines the system being studied, but also implicitly specifies many of the calculations needed for an LCA study. In this case, the 'system' consists, spatially, of a forest stand of exactly 1 hectare in area. This is clearly delineated by the systems boundary in Figure 4.1a. For this example, the temporal system boundary is a period of 10 years in the development of the forest stand, such as the period formed by the years 2004 to 2013. During this period, the trees forming the forest stand continue to grow and accumulate carbon stocks, and there is also a thinning intervention in which some trees are felled and some of the wood removed (harvested) from the stand. To simplify the example, the consideration of emissions in Figure 4.1a is limited to carbon dioxide (CO_2). Flows of CO_2 into and out of the system are shown by arrows crossing the system boundary.

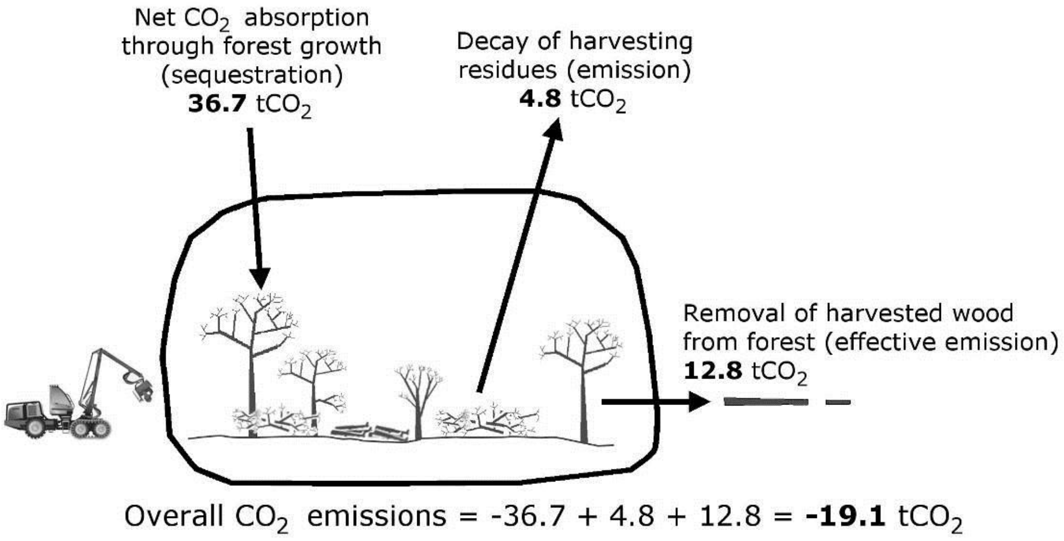

Figure 4.1a. An example of a 'system' and its associated 'system boundary' (thick black line). The system consists of a 1 hectare stand of trees. The system consists of a 1 hectare stand of trees.

To calculate the CO_2 emissions for the system in Figure 4.1a, all that is necessary is to:

- Identify all of the flows of CO_2 that pass across the system boundary.
- Quantify each of these CO_2 flows.
- Work out the sum of all the flows of CO_2 across the system boundary, allowing for whether CO_2 flows into the system or out of it, so as to calculate the overall flow of emissions.

For this purpose, the convention is adopted that a flow into the system takes a negative sign, whereas a flow out of the system takes a positive sign. In effect, this represents the exchange of CO_2 between the 1 hectare stand of trees and the atmosphere over a 10 year period. As shown in Figure 4.1a, the continued growth of the trees forming the stand over the specified 10 year period results in the net accumulation of 36.7 tCO_2 into the system, adding to the existing carbon stocks in the living biomass of the growing trees, deadwood, litter and soil organic matter. This forest carbon sequestration is the net result of tree growth through the process of photosynthesis, minus losses due to respiration of the living trees, soil microbes etc., and decay of deadwood, litter and soil organic matter. For simplicity, the net outcome of these processes (sequestration of 36.7 tCO_2) is shown in Figure 4.1a, rather than the individual contributions due to photosynthesis, respiration and decay.

In addition to the net sequestration of CO_2 in the stand of trees, the thinning intervention causes the removal of 12.8 tCO_2 contained in the tissues of harvested wood. Over the same period, the decay of the harvesting residues left in the forest after the thinning event results in an emission of 4.8 tCO_2 occurring over the 10 year period encompassed by the temporal system boundary. Although most, potentially all, of the CO_2 sequestered in the harvested wood may still be retained (in solid wood products) well after the 10 year period has elapsed (and therefore has not in fact been emitted to the atmosphere), the removal (flow) of carbon in the harvested wood still counts as an emission, because the flow has crossed the system boundary. This is a direct consequence of how the system has been defined and where the system boundary has been drawn.

As explained above, the overall CO_2 emissions for the system shown in Figure 4.1a are calculated as the sum of the CO_2 flows crossing the system boundary, allowing for their direction of flow (in or out), which in this case is:

$$-36.7\ tCO_2 + 4.8\ tCO_2 + 12.8\ tCO_2 = -19.1\ tCO_2$$

(overall, sequestration into the system).

It is important to appreciate that the result obtained for the forest system in Figure 4.1a is just one of a number of possible results that can be calculated, depending on how the system is defined and where the system boundary is drawn, both spatially and temporally. Two other possibilities for the spatial system boundary are illustrated in Figures 4.1b and 4.1c.

In Figure 4.1b, the system boundary encloses the forest stand as in Figure 4.1a, and also the wood harvested from the forest stand. In this case, most of the CO_2 sequestered in the harvested wood is retained within the system, because the wood has been converted into products which are still in existence at the end of the 10 year period encompassed by the temporal system boundary. However, during this period, some of the harvested wood decays or is destroyed (perhaps during the processing of wood into finished products). This results in an emission of 0.9 tCO_2, which crosses the system boundary as shown in Figure 4.1b. The change in the system boundary from that shown in Figure 4.1a to the one shown in Figure 4.1b has the effect that an emission of 0.9 tCO_2 needs to be counted in association with the harvested wood, instead of an emission of 12.8 tCO_2. This gives an overall result for CO_2 emissions of:

$$-36.7\ tCO_2 + 4.8\ tCO_2 + 0.9\ tCO_2 = -31.0\ tCO_2.$$

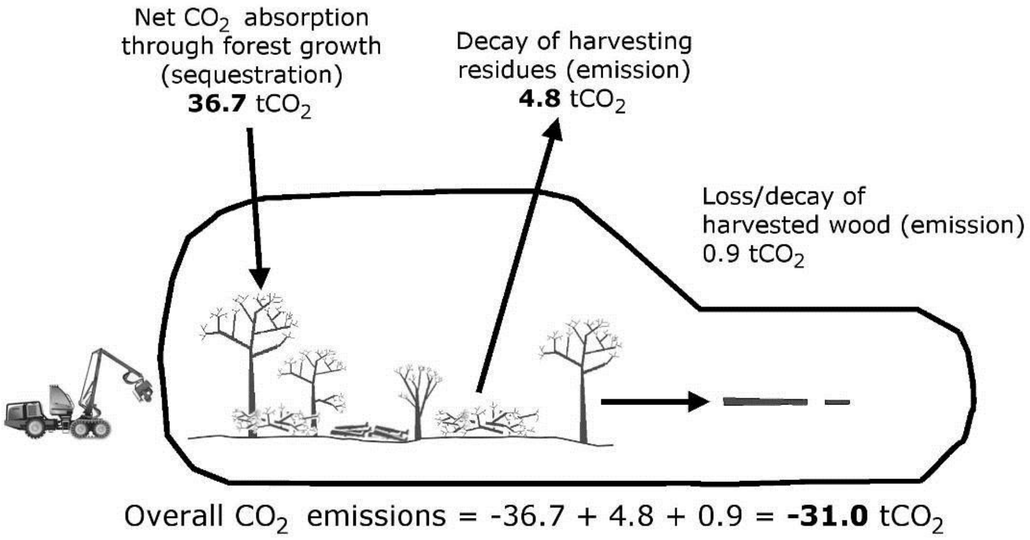

Figure 4.1b. An example of a 'system' and its associated 'system boundary' (thick black line). The system consists of a 1 hectare stand of trees and the wood harvested from the stand.

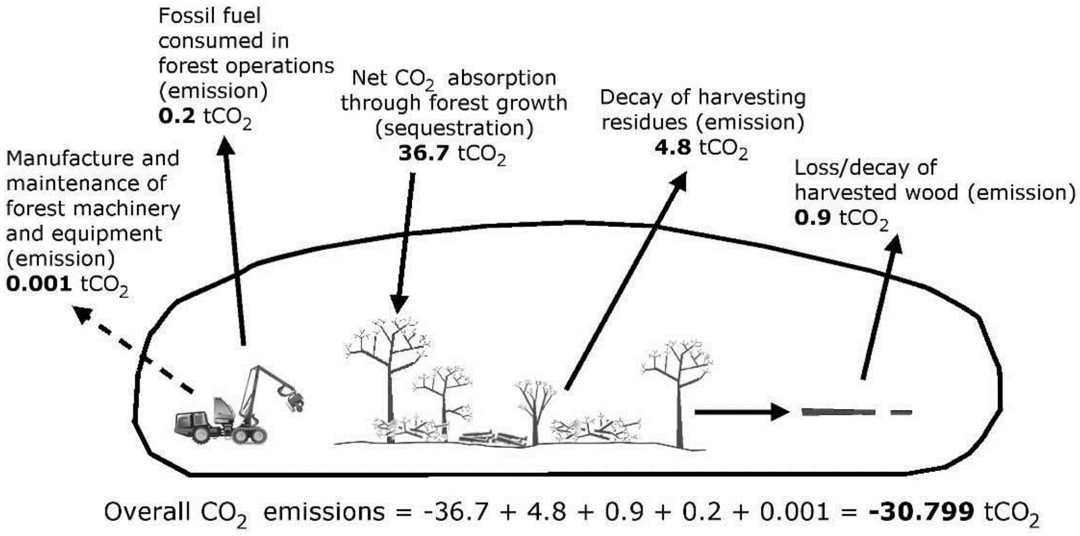

Figure 4.1c. An example of a 'system' and its associated 'system boundary' (thick black line). The system consists of a 1 hectare stand of trees, the wood harvested from the stand and the activities of machines involved in forest management operations.

In the final example shown in Figure 41c, the system boundary also encloses the machinery and fossil energy sources used or consumed in forest operations (i.e. as part of management of the forest stand). During the 10 year period under consideration, 0.2 tCO_2 are emitted by machines carrying out management operations in the forest stand. An allowance may also be made for the CO_2 emissions arising from the manufacture and maintenance of the machines. However, this will not be the full amount, since the machines will be used in many areas of forest, not just this one, and will generally be in operation before and/or after the 10 year period encompassed by the system boundary considered in these examples. Counting some of the emissions due to machine manufacture and maintenance adds a further 0.001 tCO_2 in this example. Overall CO_2 emissions for the system boundary in Figure 4.1c are calculated as:

$$-36.7\ tCO_2 + 4.8\ tCO_2 + 0.9\ tCO_2 + 0.2\ tCO_2 + 0.001\ tCO_2 = -30.799\ tCO_2.$$

The examples in Figures 4.1a to 4.1c demonstrate how, for essentially the same subject, relatively small and simple variations in system definition and the delineation of the system boundary used in LCA calculations can lead to different results for the GHG emissions associated with the system. Yet, none of these calculations are intrinsically ‘right’ or ‘wrong’. Crucially, each of these choices may be correct, depending on the goal and scope of the LCA study:

- The system and system boundary in Figure 4.1a might be the right one to choose when monitoring the management of a forest stand in some circumstances, e.g. to show that management is consistent with the principle of sustainable yield (see Section 2.3).
- A system boundary similar to that shown in Figure 4.1b is actually in use for calculating GHG emissions from forests and associated harvested wood products as part of the reporting of national GHG emissions inventories for the Land Use, Land-Use Change and Forestry Sector in accordance with international commitments to the United Nations Framework Convention of Climate Change (UNFCCC, 1992).
- A systems boundary similar to that shown in Figure 4.1c may be appropriate when estimating a GHG emissions factor for the production of raw harvested wood.

It should also be noted that different temporal system boundaries are appropriate in each of the examples in Figures 4.1a to 4.1c, specifically:

- The monitoring of sustainable yield might be based on a 10 year period, depending on the detailed context. However, the longer term pattern over successive 10 year periods would need to be considered when making judgements about whether management is sustainable.
- Reporting of GHG emissions as part of national GHG inventories involves a 1 year period, with inventories reported annually.
- It may be appropriate for a GHG emissions factor for raw wood production to be calculated over a period encompassing one or more complete ‘forest management cycles’ (see Section 2.3).

Clearly, results for GHG balances will be sensitive to the choice of temporal system boundary.

It is worth pausing to reflect on the conclusions of the preceding discussion. So far, the two main approaches to LCA (attributional and consequential) have been reviewed, and the most basic element of LCA methodology has been considered, i.e. the definition of the system being studied and the choice of system boundary. Yet it is evident already that there is no 'single' answer to an LCA for a given subject, rather, the result can depend strongly on the way in which the system is defined and in particular on the system boundary selected. This is just one basic aspect of LCA methodology and, as described in the rest of this section, other aspects of LCA methodology may also vary and can strongly influence the result ultimately obtained. As a consequence, it is very easy for different LCA studies to generate a variety of results, sometimes apparently in conflict. With a system as sophisticated as the production and consumption of forest bioenergy (with many possible original sources of wood and process chain steps, see Sections 2 and 3), it is, therefore, unsurprising that results for GHG emissions exhibit a big range which may appear confusing and sometimes contradictory. However, as already stressed in the preceding discussion, the critical issue is to be clear about the goal of the particular LCA study being undertaken, i.e. the research question being addressed, and to interpret results for LCA in this context.

Figures 4.1a to 4.1c also illustrate another essential concept in LCA, that of '*system boundary expansion*'. This principle sounds potentially quite complex. In fact, it means simply that the system boundary in an LCA study needs to be drawn as wide as necessary (and no wider), in order to encompass all of the activities and processes relevant to addressing the research question that has been posed. A further example of system boundary expansion, of particular relevance to consequential LCA, is discussed in Section 4.5.4.

4.5. Robust definitions for GHG emissions

So far in this report, GHG emissions have been referred to in a general sense or with relevance given by a specific context. However, at this point in the discussion, it is necessary to define certain metrics for GHG emissions clearly and rigorously. These different metrics for GHG emissions serve different purposes and/or represent different quantities, so it is important to apply the correct approaches when estimating and reporting GHG emissions. It is equally important to be clear about which types of GHG emissions are being referred to (for example, when presenting or commenting on results for forest bioenergy). It should also be noted that there is no standard and widely accepted terminology for referring to and reporting GHG emissions. Indeed, this appears to be one of the causes of confusion and disagreement in the literature of GHG emissions associated with forest bioenergy. However, as stressed in the glossary of this report (Appendix 1), it is not the intention of this report to impose strict definitions on the scientific literature, either retrospectively or for the future. Instead, the report proposes definitions for key terms, such as types of GHG emissions, for consistent use subsequently in this report and wider project. Where appropriate in this report, attention may be drawn to discrepancies or inconsistencies in the application of terminology in the wider literature.

The key types of GHG emissions requiring clear and robust definitions are:

- Direct and indirect GHG emissions (see Section 4.5.1)
- Absolute GHG emissions (see Section 4.5.2)
- Attributed GHG emissions (see Section 4.5.3)
- Consequential GHG emissions (see Section 4.5.4).

4.5.1. Direct and indirect GHG emissions

The terms 'direct GHG emissions' and 'indirect GHG emissions' are not of central importance to this project, but it is important to understand how these terms are used in this project, because the term 'indirect GHG emissions' has been referred to explicitly in the specification of project Tasks (specifically Task 4). It may also be important to understand the variety of meanings these terms may have in the scientific literature.

'Direct GHG emissions' is a term which has been used variously to refer to:

- GHG emissions directly due to the use (i.e. combustion) of an energy source, e.g. coal, oil, natural gas or biomass.
- GHG emissions that occur in a specific part of an activity or process that is under consideration, e.g. when considering a specific forest operation, the GHG emissions due to consumption of fossil fuels in machinery carrying out the forest operation.
- Possibly, the sum of the quantities described in the previous two points (where relevant).

'Indirect GHG emissions' is a term that has been used variously to refer to:

- GHG emissions that occur as part of the provisioning and processing of an energy source, such as coal, oil, natural gas, biomass or electricity (i.e. the construction, maintenance and operation of the infrastructure and associated activities and processes involved in the supply and use of an energy source).
- GHG emissions from wider activities or processes, 'connected to' a specific part of an activity or process that is under consideration, e.g. when considering a specific forest operation, the GHG emissions associated with the construction and maintenance of the machinery carrying out the forest operation.
- GHG emissions that are not themselves GHGs, but which may be precursors of atmospheric GHGs, e.g. carbon monoxide, which can be a precursor of carbon dioxide.
- GHG emissions associated with bioenergy use due to the effects of indirect land use change.

It should be noticed that the lists of possible meanings for the terms given above are not exhaustive (for example, Repo *et al.*, 2011, 2012, have used the term, 'indirect GHG emissions' to mean the CO_2 emissions resulting from the combustion of forest harvesting residues, compared with the CO_2 emissions that would occur if the harvesting residues were left to decompose naturally in the forest).

The diversity of possible meanings described above is a clear example of the potential for confusion when considering published statements on GHG emissions associated with the use of forest bioenergy.

For the purposes of this project (which are quite specific), the following definitions are adopted for direct GHG emissions and indirect GHG emissions:

- Direct GHG emissions are those GHG emissions directly due to the use of an energy source, e.g. coal, oil, natural gas or biomass, or, GHG emissions due to the consumption of these energy sources, as implied by the consumption of electricity. In the case of a forest bioenergy source, essentially these are the GHG emissions directly due to the consumption and ultimate combustion of biogenic carbon to generate useful energy.
- Indirect GHG emissions are those GHG emissions from wider activities or processes, ‘connected to’ a specific part of an activity or process that is under consideration. In the specific case of a forest bioenergy source, essentially these are the GHG emissions that occur as part of the provisioning and processing of the forest bioenergy source (i.e. the construction, maintenance and operation of the infrastructure and associated activities and processes involved in the supply and use of the forest bioenergy source). It does not include direct GHG emissions as defined above.

It should be noted that it is possible for the terms direct GHG emissions and indirect GHG emissions to be used, as appropriate, in association with the terms ‘absolute GHG emissions’, ‘attributed GHG emissions’ and ‘consequential GHG emissions’, which are defined in Sections 4.5.2, 4.5.3 and 4.5.4 respectively.

4.5.2. Absolute GHG emissions

Absolute GHG emissions can be defined as the total GHG emissions occurring in association with a clearly defined activity. In this context, an activity is considered to be ‘clearly defined’ if the system has been defined and the system boundary has been delineated as described in Section 4.4. In addition, the system and its boundary need to be consistent with an unambiguously stated goal for the LCA study. Absolute GHG emissions are calculated as the sum of all GHG emissions crossing a system boundary, as described in Section 4.4. The examples in Figures 4.1a to 4.1c all illustrate the calculation of absolute GHG emissions. It must be stressed that, strictly, calculations of absolute GHG emissions are not made in comparison with some other possible activity and do not involve calculating GHG emissions compared with any sort of reference/baseline value or reference/baseline projection for GHG emissions (indeed, it would be physically and numerically incorrect to do so).

4.5.3. Attributed GHG emissions

For the purposes of this report and wider project, attributed GHG emissions are defined to distinguish them from absolute GHG emissions and consequential GHG emissions (see Sections 4.5.2 and 4.5.4), which are of principal relevance for this project. Attributed GHG emissions are defined as GHG emissions calculated and reported as part of an attributional LCA study. In practice, attributed GHG emissions may be calculated in a similar way to absolute GHG emissions, but may involve certain elaborations that can have a significant effect on results. In particular:

- Comparison may be made with reference/baseline values or reference/baseline projections for GHG emissions in some calculations, e.g. particularly relation to land use.
- Results for GHG emissions may be 'attributed' to a single product or service, or may be allocated amongst two or more co-products or services (depending on the details of the system being studied).

The details of such calculation procedures will depend strongly on the context of the attributional LCA study, i.e. its specific goal and scope.

Results for attributed GHG emissions are of very limited relevance to the objectives of this project, and further discussion of this subject is beyond the scope of this report. The important points here are that:

- Such results are unsuitable as a basis of "a qualitative and quantitative assessment of the [changes in] direct and indirect greenhouse gas (GHG) emissions associated with different types of solid and gaseous biomass used in electricity and heating/cooling in the EU [as a result of the changes in activities implied] under a number of scenarios", as required for this project (see Section 1).
- Results for attributed GHG emissions can vary significantly, depending on the objective of individual attributional LCA studies and associated calculation procedures. This represents an important source of apparent variation of results presented in the scientific literature for GHG emissions associated with the use of forest bioenergy.

4.5.4. Consequential GHG emissions

Consequential GHG emissions can be defined as the total change in GHG emissions that occurs (or would occur) as a consequence of a change (or possible/proposed change) to an existing activity. As such, consequential GHG emissions are typically calculated and reported as part of a consequential LCA study. An example of the calculation of consequential GHG emissions is given in Figures 4.2a to 4.2c. These figures illustrate the approach to system definition, system boundary delineation (and expansion), and GHG emissions calculation, appropriate to address the research question:

> **Q1.** *"What would be the consequences for GHG emissions, over a ten year period, of carrying out a thinning operation in a 1 hectare stand of trees, where, previously, no such thinning operation was planned?"*

As with earlier examples in this section, for the sake of simplicity, only CO_2 emissions are considered (i.e. there is no consideration of non-CO_2 GHGs such as methane and nitrous oxide).

Figure 4.2a shows how initially the system is defined simply as consisting of the 1 hectare forest stand as it currently exists, and as it would develop over the specified 10 year period if the proposed thinning operation were not to be carried out. The system boundary is drawn, equally simply, around the 1 hectare forest stand.

The continued growth of the trees over the 10 year period results in the sequestration of 36.7 tCO_2 in the forest stand, as already described in the example in Figure 4.1a. Unlike the example in Figure 4.1a, there is no thinning and so no losses of CO_2 from the system due to the harvesting of wood. Equally, there are no CO_2 emissions due to the decay of harvesting residues over the 10 year period.

The absolute CO_2 emissions (see Section 4.5.2) for the system shown in Figure 4.2a over the specified 10 year period are thus −36.7 tCO_2 (net sequestration).

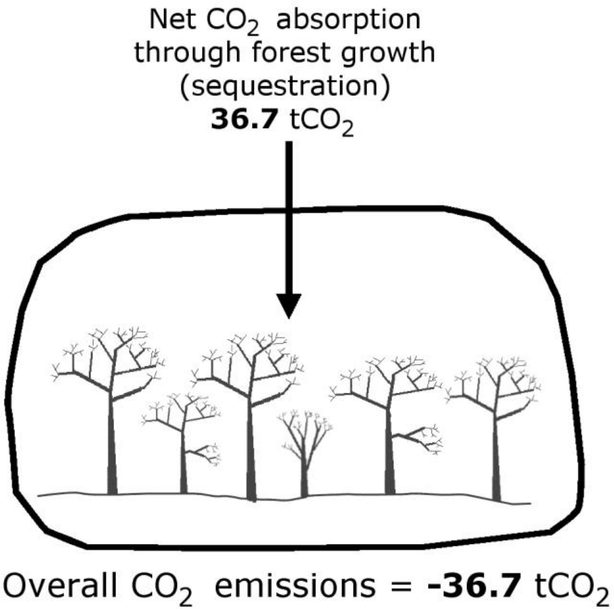

Figure 4.2a. An example of a system and its system boundary (thick black line). The system consists of a 1 hectare stand of trees, which is not subject to any harvesting (thinning or felling).

Figure 4.2b shows the system as it would exist over the 10 year period if the proposed thinning operation were to be carried out. This is an elaboration of Figure 4.1c (Section 4.4), showing how the raw harvested wood is converted into finished wood products, and also showing the wood processing facilities involved in the manufacture and utilisation of the finished products. As discussed in Sections 2.3 and 2.5, patterns of wood processing and utilisation can be quite complex, involving various processing stages, the generation of a number of co-products and a chain of flows of raw harvested wood and recycled wood. A simple case is illustrated in Figure 4.2b, with the raw harvested wood being used to manufacture two finished wood (co-)products, 'A' and 'B'. It is not important for this example to specify the exact natures of products A and B, but product A might be taken to be some sort of bioenergy feedstock, whereas product B might be taken to be some sort of structural timber product.

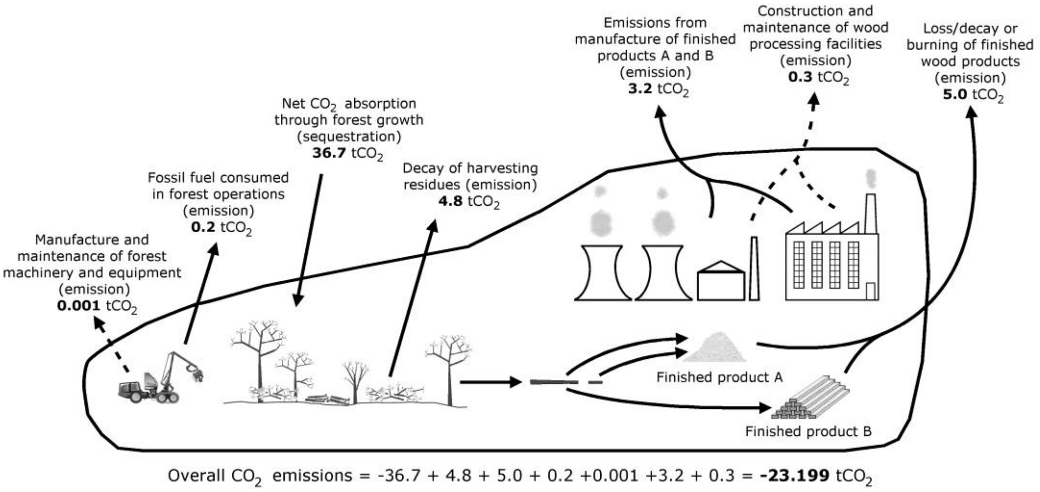

Figure 4.2b. An example of a system and its system boundary (thick black line). The system consists of a 1 hectare stand of trees, which is subject to a thinning operation. The raw harvested wood is processed to make two finished co-products.

Over the specified 10 year period, the processing facilities involved in the manufacture of finished products A and B (including the power station which burns the forest bioenergy product A to produce useful energy), consume fossil fuels and other resources. This results in CO_2 emissions of 3.2 tCO_2. As with the case of machinery involved in forest operations in the example in Figure 4.1c (Section 4.4), an allowance is made for CO_2 emissions associated with the construction and maintenance of these wood processing facilities which, in the example in Figure 4.2b, is 0.3 tCO_2 for the 10 year period. The loss, decay or (in the case of product A) burning of finished wood products results in CO_2 emissions of 5.0 tCO_2 over the specified 10 year period. (This is higher than the equivalent value of 0.9 tCO_2 given in the example in Figure 4.1c, Section 4.4. In that example, all of the raw harvested wood was assumed to be converted into solid wood products, generally with lifespans longer than the 10 year period considered in the examples in this section.)

Based on Figure 4.2b, the absolute CO_2 emissions (see Section 4.5.2) for the system representing the change in activity proposed in the stated research question are calculated as

$$-36.7 + 4.8 + 5.0 + 0.2 + 0.001 + 3.2 + 0.3 = -23.199 \text{ tCO}_2$$

It is important to observe that, in Figure 4.2b, the system boundary has been *expanded* (e.g. compared with Figure 4.2a, or Figures 4.1b and 4.1c) to ensure that all the processes and flows associated with the changed activity are included within the system boundary, so that the CO_2 emissions associated with the changed activity are fully captured in calculations.

It is also necessary to expand the original system boundary in Figure 4.2a. This is needed to ensure that all the processes and flows that would take place *in the absence of the change in activity* are included within the system boundary, and that associated CO_2 emissions are completely captured in calculations. The system boundary needs to ensure that the system representing 'no change in existing activity' is directly comparable with the changed system of Figure 4.2b. An equivalent system and associated system boundary for the 'no change in existing activity' case is shown in Figure 4.2c.

Essentially, the original system boundary of Figure 4.2a has been expanded to encompass the '*counterfactual*' goods and services. These are the activities and processes involved in providing the goods and services that would otherwise be provided by products A and B in Figure 4.2b if the change in activity proposed in the original research question were to occur (see Section 3.8). For this simple example, it is assumed that if the change in activity were to take place, products A and B would be consumed in place of alternatives produced from resources other than wood, i.e., products A and B would 'displace' the production and consumption of these non-wood products. The forest bioenergy product A might displace the production and consumption of fossil fuel for power generation, whilst the structural wood product B might displace the production and consumption of an equivalent steel or concrete product (for example).

As in Figure 4.2a, the continued growth of the trees over the 10 year period results in the sequestration of 36.7 tCO_2 in the forest stand. Additionally, the manufacture of the structural non-wood product B has associated CO_2 emissions of 17.0 tCO_2. The processing and burning of fossil fuel to produce useful energy (equivalent to what would be generated from product A) results in CO_2 emissions of 4.8 tCO_2. Similarly to the system in Figure 4.2b, an allowance is made for CO_2 emissions of 0.3 tCO_2, representing the emissions due to the construction and maintenance of the factories and power stations involved in the manufacture and processing and/or conversion of the alternative products A and B.

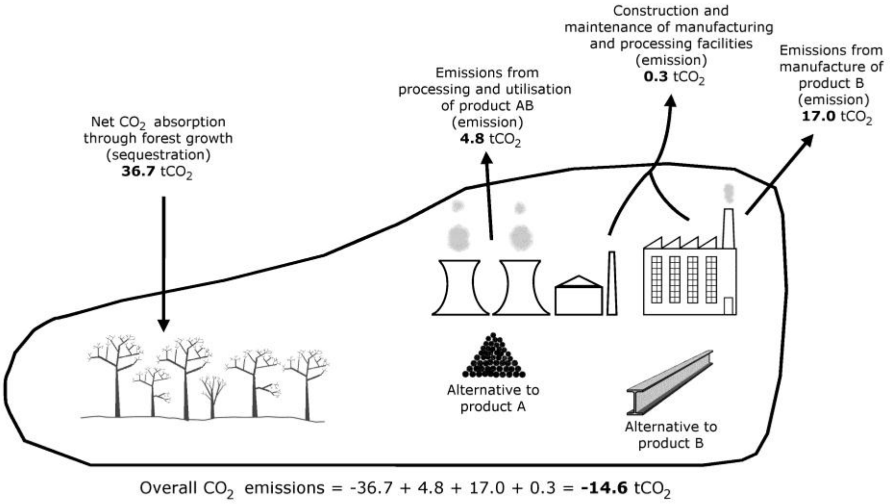

Figure 4.2c. An example of a system and its system boundary (thick black line). The system consists of a 1 hectare stand of trees, which is not subject to any harvesting (thinning or felling). Compared to Figure 4.2a, the system boundary has been expanded to include the 'counterfactuals' to the wood products A and B, produced by the system shown in Figure 4.2b.

Based on Figure 4.2c, the absolute CO$_2$ emissions (see Section 4.5.2) for the system representing no change in activity are calculated as:

$$-36.7 + 4.8 + 17.0 + 0.3 = -14.6 \text{ tCO}_2$$

As defined at the outset of this discussion, consequential GHG emissions (in this example CO$_2$ emissions) are calculated as the difference between the two results for absolute GHG emissions obtained above, i.e. the consequential GHG emissions over the specified 10 year period for the change in activity considered in Figure 4.2b, with respect to 'no change' (Figure 4.2c), are calculated as:

$$-23.199 - (-14.6) = -8.599 \text{ tCO}_2$$

The negative sign on this result indicates that the change in activity results in an overall reduction in CO$_2$ emissions to the atmosphere over the specified 10 year period. (A positive sign would indicate a net increase in CO$_2$ emissions due to the change in activity).

4.6. Scenarios in consequential LCA

As outlined in Sections 4.3 and 4.5.4, consequential LCA involves the estimation of GHG emissions for a specified change to an activity, or set of activities, in comparison with the case in which the specified change in activity does not take place. These two cases or situations, real or possible, and the associated system descriptions, may be referred to as *scenarios*.

Different scenarios can be given different names or labels for convenience, reflecting the cases or situations they are intended to represent. For example, a scenario which describes the changes to a system that may take place if a proposed policy is implemented might be referred to as a 'policy scenario'. Most importantly, the scenario representing the existing situation, or 'no change', against which any scenario (or set of scenarios) involving changes is compared, may be variously referred to in the scientific literature as the 'baseline' scenario, 'reference' scenario or 'counterfactual' scenario. Hereafter in this report and wider project, the term 'baseline' is used to refer to this scenario.

For each scenario, it is necessary to describe 'what the world looks like' if the scenario were to be realised. This description takes the form of an appropriate definition of a system and its associated system boundary, as already illustrated in Sections 4.4 and 4.5.4. Although the examples in these sections show quite simply how such systems can be defined, and how associated GHG emissions may be calculated, it must be noted that, in some circumstances, some aspects of these descriptions can be challenging and uncertain. In particular, there may be uncertainties relating to the definition of the baseline scenario. To illustrate, considering the relatively simple examples of a consequential LCA study shown in Figures 4.2b and 4.2c, the definition of the baseline scenario in Figure 4.2c requires assumptions to be made about 'what the world would look like' if the changes in activities proposed in Figure 4.2b do not in fact take place. To reflect this, the baseline scenario (Figure 4.2c) includes assumptions about 'what would happen' if the harvested wood products A and B were *not* to be produced. As explained in Section 4.5.4, this is treated quite simply in Figure 4.2c, by assuming that the availability of products A and B would 'displace' existing use of fossil fuels and a structural product manufactured from non-wood materials. Thus, the assumption is made that, if the change in activity (the thinning operation in the stand of trees) were not carried out, it would be necessary to continue to consume certain fossil fuels and non-wood materials. Such assumptions about the types of resources, products and/or services consumed in the baseline scenario may be referred to as 'counterfactual' resources, products or services or, more simply, as 'counterfactuals' (see Section 3.8).

It must be stressed that the identification and definition of appropriate counterfactual resources, products and/or services as part of the baseline description are based on a set of assumptions. Clearly, such assumptions may by highly uncertain in some circumstances. In this example (Figures 4.2b and 4.2c), the harvested wood products may not displace fossil fuel and non-wood materials as identified in the baseline scenario. Even if it is reasonable to assume that fossil fuels and non-wood materials represent realistic counterfactual products, there may still be uncertainties over the precise types of fossil fuel source and non-wood materials providing the counterfactual resources, products and/or services. There may also be uncertainties involved in assumptions about the processes involved in their manufacture and/or conversion.

Potentially, significant uncertainties may also be introduced when considering how scenarios might develop in the long term. For example, under current conditions, there might be reasonable certainty in identifying an appropriate fossil energy source as a counterfactual product for a particular type of forest bioenergy. However, generally this will become increasingly uncertain in ensuing decades, because various sources of energy will become more or less available over time, whilst the utilisation of the forest bioenergy will most likely cause shifts in the mix of energy sources used to meet future needs.

Another phenomenon which can become very important in scenarios covering long time scales is the disposal of finished wood products at end of life (this is also true for counterfactual products). Whilst some material wood products may only remain in primary use for a few years (e.g. paper, packaging), many form parts of structures that can last up to 30 or more years (e.g. fence posts, furniture), or even potentially 100 years or longer (structural timber in buildings). When wood products (or their counterfactuals) come to the end of their life in primary use, a decision has to be taken as to what to do with the material forming the product, i.e. recycle it, burn it (in the case of wood, potentially generating energy in the process) or dispose of the material, e.g. to landfill (see Figure 2.7, Section 2.5). Results generated by Matthews *et al.* (2014) have shown that the GHG emissions associated with the treatment of wood and other materials at end of life can be extremely sensitive to such decisions (see for example Figure 5.12 in Matthews *et al.*, 2014). When developing scenarios for forest management and wood utilisation, assumptions about how materials are treated at end of life may be reasonably certain when considering current practice, but are likely to be more speculative when considering longer time scales.

Given the significant potential for uncertainties, it is very important that transparency is ensured regarding any assumptions in scenarios about the use and long-term fate of wood products, and about counterfactual resources, products and services. Where necessary, the sensitivity of final results for consequential GHG emissions to these assumptions should be explored as part of LCA calculations.

4.7. Selection of temporal system boundary (time horizon) for LCA calculations

The importance in LCA studies of determining a suitable temporal system dimension (or 'time horizon') as an integral part of a system boundary (in addition to the spatial element) has been referred to at several points in the preceding discussion (see Sections 4.3, 4.4 and 4.5.4). Essentially, the same principles apply when selecting a time horizon as for the spatial system boundary, i.e. the time horizon needs to be appropriate for addressing the research question being posed. In consequential LCA, a relevant starting point for the time horizon is generally the time at which the change or changes in activities or processes are being made (or would be made). The finish point of a time horizon will tend to be very specific to the context of the research question. For example, in policy analysis, there may be a desire for a possible policy to achieve certain results or outcomes by a certain target year, or after a specified number of years. Such target years or periods translate immediately for the purposes of setting the end point to an LCA time horizon. Even then, there may be interest in understanding the longer term implications of changes made to meet shorter term targets. In this project, several temporal system boundaries have been specified at the point of project inception namely:

- From present up to a target year of 2030
- From present up to a target year of 2050
- From 2020 with time horizons of 20, 50 and 100 years.

More generally, it is important to recognise that the choice of temporal system boundary can have a big influence on the final results of an LCA study, just as for the spatial system boundary. This represents another potentially important source of variation in results of LCA studies of GHG emissions associated with the production and use of forest bioenergy.

4.8. Selection of a functional unit for LCA calculations

An important step in LCA closely related to system definition and system boundary delineation involves identifying an appropriate functional unit. The importance of this is explained in the relevant standard for LCA (ISO 14040:2006) where it is mainly considered in terms of establishing a common function for the systems, products or services under analysis, so that LCA results can be compared in a meaningful manner. The role of the functional unit is elaborated further in the ILCD Handbook (JRC, 2010). The results of an LCA study, such as GHG emissions, are expressed with respect to the functional unit. As with system definition and system boundary delineation, the selection of an appropriate functional unit for calculating results should derive from the goal of the specific LCA study and the research question being posed.

Taking the example in Figure 4.1c (Section 4.4), the functional unit could be selected to be the whole forest stand, giving the result for CO_2 emissions already presented in Section 4.4, i.e. -30.799 tCO_2. Alternatively, the functional unit could be taken as 1 hectare of the forest stand, giving the results in units of $tCO_2\ ha^{-1}$. (Since the stand is, in fact, 1 hectare in area in this example, the result is numerically the same as for the whole stand.) Another possibility in this example is to express the CO_2 emissions with respect to a cubic metre of raw harvested wood produced by the system. In Figure 4.1c, over the 10 year period considered, suppose 14 m^3 of raw harvested wood are produced from the forest stand. The CO_2 emissions can be expressed per cubic metre of raw wood produced by calculating:

$$-30.799 / 14 = -2.2\ tCO_2\ m^{-3}, \text{ or } -2200\ kgCO_2\ m^{-3}$$

Other possible functional units are an oven dry tonne or kilogram of raw harvested wood, or a tonne or kilogram of carbon contained in raw harvested wood. More generally, in principle, almost anything can be selected as a functional unit, as long as it relates to the system under study, e.g. a kilogram of product manufactured, a whole factory (giving results 'per factory'), the whole of a commercial company or even a whole country, or the complete global vegetation system. A key point is that reference to a functional unit makes it possible to make comparisons that are valid, because results are reported on a consistent basis. It may also be noted that there can be distinct advantages in selecting a functional unit that is related to the useful output or service provided by the system. For example, suppose a power station emits CO_2 emissions of 600 tCO_2 while operating over a single year, and the following year it emits 550 tCO_2. From the perspective of the functional unit of the power station, CO_2 emissions have dropped from the first year to the next. However, suppose that the power station also generated less electricity in the second year, e.g. perhaps 750 GWh in the first year and 680 GWh in the following year. If the electricity generated by the power station is chosen as the functional unit, the results are:

$$(600 / 750) \times 10^6 = 800 \text{ gCO}_2 \text{ MWh}^{-1} \text{ for the first year, and}$$

$$(550 / 680) \times 10^6 = 809 \text{ gCO}_2 \text{ MWh}^{-1} \text{ for the following year}$$

Thus, although it is still the case that the total CO_2 emissions for the power station have reduced from the first year to the next, this is seen to be associated with a drop in output, and a slight drop in efficiency.

4.9. Representation of timing and impacts of GHG emissions

The discussion in this section has included a number of examples of the calculation of GHG emissions for defined systems, generally involving a 10 year temporal system boundary or time horizon. As explained in Section 4.7, time horizons can be quite short, but often can involve periods of many decades, depending on the goal of a particular LCA study. In the examples in Sections 4.4 and 4.5, GHG emissions have been calculated very simply as the total GHG emissions occurring during the specified time horizon of 10 years. This way of expressing GHG emissions over a time horizon is often used in LCA studies, and such results can be referred to as *cumulative GHG emissions* for a specified time horizon. Typically, cumulative GHG emissions have units of tCO_2, $ktCO_2$, $MtCO_2$, or similar. Any of the previously introduced results for GHG emissions (absolute, attributed and consequential) can be expressed on such a cumulative basis. However, the main reason for using this approach in the examples included in this section has been for the sake of simplicity. More generally, LCA studies may handle the timing of GHG emissions relatively simply (similar to the approach in this section) or with considerable sophistication.

Another straightforward way of calculating and reporting GHG emissions over time is to express them as a sequence of annual estimates. This approach can be useful, e.g. for showing trends or fluctuations, but may also make the display and interpretation of results unwieldy. A simple alternative to cumulative GHG emissions is to report annualised GHG emissions. These are calculated simply by dividing results for cumulative GHG emissions by the time horizon, giving results typically in units of $tCO_2\ yr^{-1}$, $ktCO_2\ yr^{-1}$, $MtCO_2\ yr^{-1}$, or similar.

Representing the detailed timing of GHG emissions in results of LCA studies can be important. Trends or fluctuations in GHG emissions may provide insights into variable impacts of an activity (or change in activity) over time. The timing of GHG emissions can also be important in terms of the resultant impacts on atmospheric warming. In some LCA studies, trajectories of GHG emissions are processed to obtain results in terms of warming potentials, reflecting an ultimate aim behind many LCA studies of efforts to limit anthropogenic climate change.

The diversity of approaches adopted in the scientific literature to presenting the ultimate results for LCA studies of forest bioenergy can make it difficult to compare published studies and understand any differences. From the perspective of this current project, it is important to adopt approaches to the handling of the timing of GHG emissions that are consistent with the broad project objectives. Insights may be gained by reviewing the various indices developed and used in the scientific literature, as explored in Section 5.2 and Appendix 3 of this report.

4.10. Reference to a baseline in LCA calculations

The potential relevance of baseline levels and projections to the calculation of attributed GHG emissions was touched on in Section 4.5.3. The ensuing discussion is concerned with this possible role of baselines, primarily in the application of attributional LCA. However, it is very important to reiterate that, as established in Section 4.3, consequential LCA is identified as the appropriate tool to use for the purposes of this project. The essential contribution made by a baseline scenario in the calculation of consequential GHG emissions has been described in Sections 4.5.4 and 4.6. A discussion of baselines with regard to attributional LCA has been included here because this is an important area of current and ongoing controversy. Furthermore, the adoption of different baselines in calculations of attributional GHG emissions represents a major cause of apparent disagreement in published results for the GHG emissions associated with forest bioenergy. An understanding of this issue is, therefore, very important for the interpretation of results for the GHG emissions of forest bioenergy reported in the scientific literature.

The preceding discussion in this section has stressed the importance of establishing a clear goal and scope for an LCA study. Such a position is also taken in relevant ISO standards for LCA (ISO 14040, 14044). The goal and scope are important for clearly identifying the reasons for carrying out an LCA study. ISO 14040 and 14044 emphasise that important aspects of goal and scope determination include definition of the system, delineation of the system boundary, selection of a functional unit, and adopting a systematic approach to the interpretation of results that is consistent with the stated goal. However, the ISO standards do not mention the application of baselines at all, thus leaving this subject as an open issue to be specified as part of the goal and scope definition in LCA studies.

Whilst the significance and approach to specification of baseline scenarios is very clear when applying consequential LCA, unfortunately, this is not the case for attributional LCA studies, particularly in relation to the representation of activities to do with land use. More specifically, in attributional LCA, one of the most critical and contentious issues concerns the basis for deciding on the appropriateness of referring to a baseline when calculating GHG emissions, particularly with regard to land use. Effectively, there are two highly contrasting schools of thought on the question of how to select a baseline when representing land-use activities in attributional LCA.

One school of thought considers attributional LCA to be an approach for characterising (or 'attributing') the actual GHG emissions occurring due to an activity or process (see, for example, Brander *et al.*, 2009). This would imply that no baseline (or, otherwise, an explicit baseline of zero GHG emissions) is adopted when calculating GHG emissions. Such an approach gives results which are identical to absolute GHG emissions as defined in Sections 4.4 and 4.5.2, and illustrated in Figure 4.1a to 4.1c. (The results in Figure 4.2a to 4.2c also illustrate the calculation of absolute GHG emissions when considered individually; it is only when results are compared with one another that results for consequential GHG emissions are obtained; see Section 4.5.4.) In a fundamental sense, the 'zero baseline' approach can be viewed as completely consistent with some of the founding principles of LCA methodology. In effect, it upholds the principle that, for a GHG emission to 'count towards' a defined system, activity or process, the GHG emission must actually cross the system boundary (see discussion in Sections 4.4 and 4.5.2).

The other school of thought is based on a number of observations, specifically with regard to land use. The choice of baseline can be crucial for biomass and bioenergy systems because of the tight connection to land use and the dynamic nature of land-based carbon stocks (see Section 3 of this report). This second school of thought recognises that all land under human management has been perturbed from an initial state in which it was free from human intervention (e.g. a completely unmanaged forest), to the type of land use under consideration (e.g. a forest under management for production of wood). Such perturbations (referred to by some authors as 'land occupation') have a strong tendency to interfere with the natural development of land-based vegetation systems. It is argued that, unperturbed, this vegetation would adapt so as to optimise the ecological capacity of the land (e.g. to support vegetation growth and stocks of biomass and carbon). The human interventions generally result in the sub-optimal utilisation of the ecological capacity of the land (Muys, 2002), for example, by causing carbon stocks to be reduced to lower levels than would be the case in the absence of human intervention (see Section 3.11). Apart from 'land occupation', humans may also make changes to the existing management of land, involving land-use change, such as when an area of pasture is converted to a managed forest by planting trees. Some authors refer to such activities as 'land transformation'.

A number of researchers have been considering how to represent land-use activities involving 'land occupation' or 'land transformation' as part of LCA methodology (Lindeijer *et al.*, 2002; Milà i Canals *et al.*, 2007a; Koellner *et al.*, 2013). The UNEP/SETAC Life Cycle Initiative project has proposed that land use impacts in LCA should be assessed as proportional to the difference in the 'quality' associated with the activity or process being assessed, and a reference case (Milà i Canals *et al.*, 2007b; Koellner *et al.* 2013). Building on these ideas, Milà i Canals *et al.* (2007b), JRC-IES (2010) and Helin *et al.* (2012) have suggested that reference should be made to a baseline of 'no use' when making assessments of land-use activities. Milà i Canals *et al.* (2007b) suggested that, when applying attributional LCA, the appropriate baseline for land use should represent a 'state of natural relaxation' (i.e. the reversion of the land and vegetation growing on it to an unmanaged state, free from human intervention). Koellner *et al.* (2013) advocate a similar approach, proposing the use of '(quasi-) natural land cover' as a baseline when assessing the impacts of land use at a global scale. These various ideas are all consistent with the view that, when assessing GHG emissions associated with forest bioenergy, comparison should be made with a scenario in which harvesting in relevant forest areas is suspended to allow addition forest carbon stocks to be sequestered (see Section 3.11).

The implications of referring to a 'no-use' scenario in calculating the attributional GHG emissions of forest bioenergy can be illustrated by referring to the example systems and calculations already illustrated in Figure 4.2, but within this rather different context. First of all, consider the system shown in Figure 4.2b (Section 4.5.4), which describes a thinning operation in a 1 hectare stand of trees, and the processing and conversion of the harvested wood into two co-products. For the purposes of the current discussion, suppose that the thinning operation is carried out as part of the long-existing and ongoing management of the stand of trees for wood production (the temporal system boundary in the examples in Figures 4.2a to 4.2c is only 10 years, but this is not important for illustrating the principles of these calculation methods for GHG emissions). The calculation of absolute GHG emissions for this system has already been described in Section 4.5.4 (note that, for simplicity, the calculations were for CO_2 emissions only), with a final result of −23.199 tCO_2 being obtained for the 10 year period considered. According to the second school of thought, the calculation of attributed GHG emissions for this system requires this result to be compared with a baseline scenario of 'no use' (i.e. no thinning operation), which, for this example, can be taken to be illustrated in Figure 4.2a. Absolute GHG emissions for the system shown in Figure 4.2a are −36.7 tCO_2 (see Section 4.5.4). Thus, attributed GHG emissions for the example system in Figure 4.2b would be calculated as[16]:

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[16] It should be noted that, in attributional LCA, these overall GHG emissions would also need to be allocated as appropriate to the two co-products. However, this is not relevant to the current discussion and is not considered here.

$$-23.199 - (-36.7) = +13.501 \text{ tCO}_2$$

This result for attributed GHG emissions, suggesting net GHG emissions to the atmosphere, is drastically different to the result for absolute GHG emissions of −23.199 tCO_2 (suggesting net sequestration). Such disagreement in results, as illustrated by the preceding example, and the contentions and controversy surrounding the correct approach to calculation of attributed GHG emissions, have made a substantial contribution, arguably, *the substantive* contribution, to confusion and uncertainty over the GHG emissions associated with the production and use of forest bioenergy.

The rationale of the second school of thought in requiring the calculation of GHG emissions to be made relative to a baseline scenario of 'no use' (with regard to land-use) might appear strange or might be difficult to understand. For example, it could be viewed as contravening the fundamental principle of LCA methodology that requires that GHG emissions should be calculated strictly on the basis of flows across the system boundary that occur due to the activity (i.e. this should involve consideration of any flows that 'could have occurred', if the activity did not take place). However, it may be possible to justify the application of a 'no use' baseline in attributional LCA in contexts where the objective is to quantify the effects on the environment of an existing system, representing an existing activity, in comparison to the situation where the activity does not take place. It is certainly possible to understand the thinking of the proponents of such an approach by drawing an analogy with the calculation of GHG emissions associated with the use of fossil fuels.

To illustrate, consider a situation in which a certain quantity of fossil fuel, perhaps coal, is burnt to produce useful energy, and there is a requirement to calculate the associated GHG emissions. First of all, the emissions of the most important GHGs occurring directly as a result of burning the coal are calculated. Then, the contribution to GHG emissions arising from the provisioning and processing of the coal (i.e. mining, transport and processing) are estimated. Finally, emissions directly due to burning the coal and due to provisioning of the coal are then added together to give a final result, separately for each GHG.

This may appear to be a very straightforward procedure (and, indeed, it may be in reality). However, what may not be so apparent is that this approach to calculation can be viewed as being made implicitly in comparison with a 'no use' baseline. In other words, implicitly, the question is being posed:

> **Q2.** *"What GHG emissions occur as a result of consuming (burning) a given quantity of coal to generate useful energy as opposed to not consuming it?"*

In the case of fossil fuels, such interpretations are trivial and no complications arise, because the 'no use' baseline is coincident with a baseline of zero GHG emissions. Crucially, this is not generally the case for bioenergy sources, and is certainly not the case for forest bioenergy. Suppose it is accepted that the calculation of attributed GHG emissions for forest bioenergy implicitly involves posing the question:

> **Q3.** *"What GHG emissions occur as a result of consuming a given quantity of forest bioenergy <u>as opposed to not consuming it?"</u>*

Clearly it is necessary to consider how carbon stocks in forest areas would develop if the bioenergy (or indeed any other products) were not to be harvested. These carbon stock changes represent a baseline against which to compare the absolute GHG emissions associated with the production and use of the forest bioenergy. However, this does beg the further question, is the purpose of such calculations really to address questions such as formulated in (**Q2**) and (**Q3**)? It may be noticed that in certain contexts the question posed in Q3 might imply analysis that is more consistent with the methods of consequential LCA rather than attributional LCA.

The answers and resolutions to all these issues lie in making sure that the goal of any LCA study, and therefore the research question being posed, are clearly defined and understood, and that the calculation methods are consistent with the stated goal and research question. This has been a central argument of the discussion presented in this section. One possible resolution might involve adoption of a 'business as usual' baseline as an alternative to an exclusive application of a 'zero GHG emissions' or 'no use' baseline. It should be noted that, in cases where the introduction of management in forest areas previously not under management for production, the 'business as usual' baseline is the same as the 'no use' baseline. In other cases, adoption of a 'business as usual' baseline would 'factor out' naturally occurring trends and cycles in carbon stock changes, and distinguish the changes in forest carbon stocks occurring as a result of changed activities (e.g. increased or decreased levels of harvesting).

Settling the debate over appropriate application of baselines in attributional LCA studies of forest bioenergy is beyond the scope of this report and, in any case, is not necessary as part of meeting the objectives of this project. However, the preceding discussion attempts to set out the issues and, in particular, explain the thinking behind the different approaches that have been proposed for baseline selection. Following on from this, Table 4.2 lists a few examples of hypothetical LCA studies and research questions, and suggests appropriate options for baselines for each example. There appears to be no ambiguity over the selection of baselines in the examples involving application of consequential LCA. However, the baselines suggested for cases involving attributional LCA may be regarded as speculative and tentative.

Table 4.2 Possible examples of LCA studies and suggested baselines for calculation of GHG emissions associated with bioenergy sources

Goal	Research question	Scope (results, interpretation)	LCA approach	Suggested baseline (in the case of bioenergy sources)	Strengths (+), weaknesses (-) and other comments (x)
To assess the effects on GHG emissions of possible scenarios involving increased (or decreased) consumption of forest bioenergy in a country (or group of countries), also involving the continuation of existing (and possibly increased) levels of energy consumption.	What change in GHG emissions would occur if the consumption of forest bioenergy were to be increased (or decreased) by a specified quantity relative to current (and projected) levels of energy consumption?	Change in GHG emissions for the country (or group of countries). Results could also be expressed with respect to a functional unit of total energy consumption for the country (or group of countries). The time horizon should reflect the period over which the changes are intended to take place, and/or the period over which there is interest in achieving impacts on climate.	Consequential.	GHG emissions that should occur for current and projected future levels of energy consumption, including contributions due to forest bioenergy, in the country (or group of countries) under a 'business as usual' scenario (i.e. 'no change').	(+) The baseline clearly reflects the goal of assessing a change to existing activities. (-) It may not be possible to observe or verify whether the business as usual scenario represents a realistic outcome. (x) Results will be for changes in GHG emissions that occur due to the proposed activities, compared to no change in existing activities.
To assess the effects on GHG emissions of possible scenarios involving increased (or decreased) consumption of forest bioenergy in a country (or group of countries), also involving the planned decreases in levels of energy consumption.	What change in GHG emissions would occur if the consumption of forest bioenergy were to be increased (or decreased) by a specified quantity relative to current (and planned/projected decreases in) levels of energy consumption?			GHG emissions that should occur for current and projected future levels of energy consumption, including contributions due to forest bioenergy, in the country (or group of countries) under a 'business as usual' scenario (i.e. 'no change'), but which includes the planned decrease in energy consumption.	

Table 4.2 (continued) Possible examples of LCA studies and suggested baselines for calculation of GHG emissions associated with bioenergy sources

Goal	Research question	Scope (results, interpretation)	LCA approach	Suggested baseline (in the case of bioenergy sources)	Strengths (+), weaknesses (-) and other comments (x)
To provide actors with information on actual GHG emissions occurring under 'business as usual' forest management and forest bioenergy use, for a given region and over a given period, to support efforts to achieve lower GHG emissions.	What GHG emissions actually occur as a result of the existing consumption of forest bioenergy in a given region and over a given period, assuming existing patterns of consumption continue into the future?	Mean absolute GHG emissions for a specified energy source, expressed with respect to a functional unit of delivered (consumed) energy. The temporal system boundary should reflect the period specified in the goal and research question.	Attributional.	Zero GHG emissions (absolute GHG emissions are calculated as the sum of all GHG emissions crossing the system boundary, see Sections 4.4 and 4.5.2). Alternatively, a baseline of BAU GHG emissions should 'factor out' naturally occurring trends and cycles in GHG sequestration and emissions associated with forests. This baseline would also accurately represent contributions to GHG emissions in cases where bioenergy production is increased, e.g. by intensifying harvested or increasing forest biomass extraction.	(+) Results should be observable and verifiable (at least in principle). (+) Results should be suitable for 'book-keeping' or 'accounting' of GHG emissions of forest bioenergy supply/consumption chains. (-) Does not reflect the full implicit impacts of the system (in that comparison is not made with the 'no use' case). (x) In the case of co-production, results for (forest) bioenergy are very sensitive to the allocation method applied for GHG emissions.

Table 4.2 (continued) Possible examples of LCA studies and suggested baselines for calculation of GHG emissions associated with bioenergy sources

Goal	Research question	Scope (results, interpretation)	LCA approach	Suggested baseline (in the case of bioenergy sources)	Strengths (+), weaknesses (-) and other comments (x)
To provide actors with information on GHG emissions associated with consumption of different sources of energy; to support efforts to achieve lower GHG emissions.	What GHG emissions occur as a result of consuming a given quantity of a given energy source, as opposed to not consuming it?	Mean GHG emissions for a specified energy source, expressed with respect to a functional unit of delivered (consumed) energy. The temporal spatial boundary may be relevant to a period in which relevant actions are supposed to be taken, or may be based on the full life cycle of the bioenergy system(s)/ source(s).	Attributional.	GHG emissions that would occur under a 'no use' scenario. Alternatively a baseline of BAU GHG emissions would accurately represent contributions to GHG emissions in cases where bioenergy production is increased or decreased.	(+) Results should reflect the typical impacts of the complete (bio)energy system. (-) The baseline may not be realistic and/or may be uncertain (see Sections 3.11 and 3.12). (x) Depending on the scope of the LCA study, consequential LCA may be a more appropriate approach. (x) In the case of co-production, results for (forest) bioenergy are very sensitive to the allocation method applied for GHG emissions.

4.11. Conclusions on LCA principles and methodology

As previously with Sections 2 and 3 of this report, it is appropriate to summarise key insights from the preceding discussion relevant to the Task objectives (see Section 1.3). Objective 1 of the Task is concerned with identifying factors that may lead to sensitivity in the GHG emissions associated with forest bioenergy. This subject has been explored extensively in Sections 2 and 3. This section is primarily concerned with addressing objectives 2 and 3 of this Task, i.e. to inform understanding of the sensitivity of the GHG emissions associated with forest bioenergy to calculation methodologies, and to characterise a methodology which may be suitable for calculation of GHG emissions associated with the use of forest bioenergy relevant to the assessment to be made in this project.

With certain notable exceptions, the principles of LCA are relatively well-established at a general level with associated detailed methodologies and standards. However, considerable care must be exercised when reviewing and evaluating existing LCA studies, because methodologies may be applied with more or less objective and transparent reasoning. As already noted, some key details of LCA calculations have not been specified definitively.

An absolutely critical first step in an LCA study involves clear definition of the goal and scope and an unambiguous statement of the research question to be addressed. This key point, and the various points raised in the preceding discussion, require particular attention when reviewing literature on LCA studies of forest bioenergy. Decisions about the goal, research question and scope are critical in determining the details of methods applied in individual LCA studies, regardless of whether they are labelled as attributional, consequential or some other type of LCA approach (Zamagni *et al.* 2012). These details have been discussed to a greater or lesser extent in this section, depending on their relevance to this current project. Table 4.3 gives a summary assessment of the key aspects of LCA methodology with potentially very high influence on the results of LCA studies and, therefore, on the conclusions drawn. The table also suggests approaches for some aspects of LCA methodology suitable for adoption as part of the assessment required for this project.

Section 5 of this report presents an analysis of LCA studies in the scientific literature concerned with forest bioenergy, and attempts to interpret their results. However, given the assessment in Table 4.3, it may already be inferred that results and conclusions of LCA studies will be very sensitive to methodological details, and that some studies will be more relevant than others for the purposes of this project.

An absolutely crucial conclusion for this project is that details of LCA methodology need to derive directly and demonstrably from the project objectives, and this point must be carried forward transparently in the subsequent development of the project.

Table 4.3 Summary assessment of key aspects of LCA methodology

Aspect of LCA methodology	Suitable approach for current project
Adoption of attributional or consequential LCA approach.	This project is concerned with comparing GHG emissions that would occur under different scenarios for future bioenergy consumption. Therefore, consequential LCA is the appropriate approach.
System definition. System boundary delineation.	To be elaborated as part of Tasks 2, 3 and 4 of this project.
Selection of time horizon.	Time horizons have already been specified for the project at the point of project inception, namely: • From present up to a target year of 2030 • From present up to a target year of 2050 • From 2020 with time horizons of 20, 50 and 100 years.
Selection of functional unit.	A suitable functional unit is the EU27 (i.e. effects on total GHG emissions in the EU27 associated with scenarios for bioenergy consumption). Another possible functional unit would be GHG emissions expressed per unit of energy consumed in the EU27.
Detailed specification and description of scenario being studied, under current conditions and into the future.	Addressed as part of Task 2 of this project.
In consequential LCA, specification and description of 'no change' baseline scenario, under current conditions and into the future. Including specification of 'counterfactual' products and/or services and associated processes.	Addressed as part of Task 2 of this project.
In attributional LCA, decision about whether to refer to a baseline scenario of some sort (as opposed to a 'zero GHG emissions' baseline) and, if so, specification and description of baseline scenario, under current conditions and into the future.	Not relevant for this project.
In attributional LCA, the approach to allocating GHG emissions (particularly those due to biogenic carbon) to co-products.	Not relevant for this project.
Choice of metric or index for presentation of ultimate results of LCA study.	Cumulative or annualised GHG emissions for the specified time horizon may be suitable. This point is explored further in Section 5.

4.11.1. Key messages on LCA principles and methodology

LCA is the appropriate methodology

LCA is the appropriate methodology for the assessment of GHG emissions associated with the consumption of forest bioenergy. There can be challenges in representing contributions to GHG emissions due to terrestrial vegetation and its management, but this is true regardless of the methodology employed.

LCA methods and results depend on the goal and scope being addressed

LCA studies can address quite wide ranging goals, scopes and research questions. The specific methodological approaches and detailed calculation methods depend strongly on the specific goal, scope and question being addressed. As a consequence, the results of different LCA studies can vary considerably and, whilst perfectly valid for the questions being addressed, are often not comparable. Particular LCA studies under review may, or may not, be relevant, depending on the context. Ultimately, it is always important to be very clear about the goal and research question when undertaking an LCA study.

Consequential LCA is used for assessing GHG impacts of changes in bioenergy use

An approach known as consequential LCA, as opposed to an alternative of attributional LCA, should be applied when assessing the impacts on GHG emissions due to increased or decreased forest bioenergy. The purposes, modelling principles and methods of consequential LCA and attributional LCA are fundamentally different and they can produce very different results for GHG emissions. These differences need to be clearly understood.

Consequential LCA requires careful specification of scenarios

The calculation of GHG emissions in consequential LCA typically involves the development of two scenarios, i.e. the scenario of interest (describing how the world may change, e.g. if bioenergy consumption is increased) and a baseline scenario (describing how the world will develop if the changes of interest do not occur). Currently there is some confusion and ongoing debate amongst researchers with regard to the application and definition of a baseline in attributional LCA studies, particularly in the case of land use and land management. However, it is important to recognise that this debate is not relevant to consequential LCA methods, for which the position is more straightforward. A baseline scenario of ‘business of usual’ is generally appropriate in consequential LCA studies. In consequential LCA, the system being studied, and both the scenario of interest and the baseline scenario, require careful specification and generally involve many assumptions, which must be clearly stated and taken into account when interpreting results.

5. Assessment of literature on GHG emissions of bioenergy

5.1. Purpose

Sections 2, 3 and 4 of this report, respectively, have set out the essential background concerning:

- Forests, their management and the utilisation of wood for bioenergy and solid wood products
- Forest carbon stocks, forest management and the role of biogenic carbon
- Fundamental principles and practices of life cycle assessment.

These discussions effectively lay the ground for a critical review of existing literature on the GHG emissions associated with forest bioenergy and how these should be assessed. The purpose of this section is to present this critical review.

Section 5.2 reviews the various metrics used in scientific literature for expressing the climate impacts of bioenergy consumption. This specific subject is important for understanding the results and conclusions of various studies and in particular when making comparisons of different reported results.

As noted in the introduction to this report (Section 1.3), this current report is not the first to attempt a literature review and there are a number of important precedents which require careful consideration. Section 5.3 considers in detail a particularly prominent recently published review, the JRC technical report on carbon accounting for forest bioenergy (Marelli *et al.*, 2013). This provides a context in which to analyse other notable reviews and commentaries concerning scientific understanding of GHG emissions associated with forest bioenergy. Five such reviews and commentaries are considered in Section 5.4. In Section 5.5, wider consideration is given to individual scientific studies of the GHG emissions of forest bioenergy, and an attempt is made to extend and elaborate on the insights drawn by the previous reviews and commentaries on the subject. Some concluding remarks are made in Section 5.6 and key messages are presented.

5.2. Literature on metrics for quantifying GHG emissions of forest bioenergy

In the scientific literature, many different metrics have been used to measure GHG emissions or related global warming impacts of bioenergy (see e.g. Johnson and Tschudi, 2012; Bird *et al.*, 2012; Helin *et al.*, 2012; Brandão et al., 2013). Some of these metrics rely on annual or cumulative GHG emissions associated with bioenergy systems, some of them rely on cumulative radiative forcing related to the GHG emissions, and some of the indicators take into account the avoided GHG emissions from fossil energy displacement by bioenergy (e.g. Pingoud *et al.*, 2012; Cherubini, 2010). Furthermore, in some studies, GHG emissions or related impacts are measured in comparison with a predefined baseline scenario for land use, implying the calculation of ‘consequential’ or ‘relative’ GHG emissions. Other studies refer to ‘absolute’ or ‘attributed’ GHG emissions (for a discussion on this, see for example Bird *et al.*, 2010; Bird *et al.*, 2012; EEA, 2011;

Dehue, 2013; Holtsmark, 2013a). The range of metrics referred to is thus quite diverse and prolific, and requires careful consideration. A critical review of individual metrics referred to in published studies of GHG emissions of forest bioenergy is included in Appendix 3. This includes an assessment of the major strengths and weaknesses of each metric. The use of various metrics for GHG emissions and warming potentials in different published studies of forest bioenergy represents a major source of variation and is an important reason why studies present variable assessments of the potential of forest bioenergy and may reach differing conclusions.

In principle, indicators that measure annual absolute CO_2 or CO_2-equivalent emissions trajectories are the most relevant to current climate policy, which is based on the monitoring, reporting and verification of inventories of annual GHG emissions. However, it is evident that results expressed in absolute terms do not describe the impacts of changes in the consumption of bioenergy on GHG emissions. Consequential/relative GHG emissions involving comparison with an appropriate baseline scenario are more relevant in this context. GHG emissions can be measured on an annual or cumulative basis and both approaches have advantages and disadvantages. There can be problems or limitations when relying on results for GHG emissions which are reported using simple mass-based physical units such as tonnes of CO_2. GHG emissions reported in this way have similar weight regardless of the time when the emissions occur. When considering the cumulative warming potential of GHG emissions, the timing of the emissions is critically important and needs to be considered in conjunction with the specific warming potential and atmospheric lifetime of the emissions. However, it is important to note that climate studies have strongly suggested that cumulative absolute GHG emissions over a period to 2050 represent robust indicators of warming impact relevant to meeting climate policy targets (Allen *et al.*, 2009; Meinshausen *et al.*, 2009)[17]. This implies that:

- A relatively simple metric of cumulative GHG emissions might be referred to when considering climate impacts of changes in consumption of forest bioenergy, provided that the time horizon for calculating such results does not greatly exceed the year 2050.
- For time horizons beyond the year 2050, it is more appropriate to refer to metrics of climate impacts expressed in terms of warming potentials.
- It is particularly important to know whether changes in the consumption of forest bioenergy will result in increased, decreased or no change in GHG emissions by the year 2050.

Based on the review of metrics in Appendix 3, it may be further concluded that, when comparing GHG emissions or cumulative warming potential of forest bioenergy and fossil

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[17] More precisely, for a particular class of emissions scenarios considered in the climate studies, it is suggested that cumulative emissions up to 2050 and emission levels in 2050 are robust indicators of the probability that twenty-first century warming will not exceed 2 °C relative to pre-industrial temperatures (Meinshausen *et al.*, 2009). It is extremely important to stress that this conclusion only holds for the specific policy target of keeping global temperature rise this century within 2 °C, i.e. it most certainly does not hold more generally.

energy sources, relevant metrics include relative carbon neutrality factor and $\mathrm{GWP}_{\mathrm{netbio}}$ (see Appendix 3).

5.2.1. Metric for comparison of studies

A major part of the subsequent discussion in this section is concerned with a meta-analysis of published studies on GHG emissions of forest bioenergy and in particular reported results. The reference to so many types of metric for GHG emissions presents a serious obstacle to such an exercise. One possible solution is to refer to the metric most frequently reported in published studies. It may also be possible to translate results based on other metrics into the more commonly reported type of result.

The main metric selected for the meta-analysis of studies carried out for this report is most commonly referred to in the literature as 'GHG emissions payback time'. This metric was also used as the basis for an earlier meta-analysis reported by the JRC (Marelli *et al.*, 2013). A number of key papers present their main results as GHG emissions payback times.

Given the extensive reference to GHG emissions payback times in the meta-analysis in this report and in other major studies, it is important to understand what this metric represents, and also to be aware of its limitations[18].

The concept of GHG emissions payback time is derived from the observation that, for a number of possible sources of additional forest bioenergy, there must be an initial period during which associated GHG emissions are increased, relative to the alternative of using fossil energy, after which there is a 'switch-over' to net decreases in GHG emissions (see Section 3.9 and related wider discussion in Section 3). In broad terms, the GHG emissions payback time represents the period to the switch-over in GHG emissions.

The typical definition and calculation of GHG emissions payback time can be explained by an example. Section 3.6 included three examples describing how forest carbon stocks may change as a result of forest management interventions aimed at increasing the production of wood for bioenergy. One of these examples (Section 3.6.2) considered the change in forest carbon stocks that would occur in a 5,600 hectare forest, as a result of a decision to extract a proportion of harvest residues for use as bioenergy, whereas previously these would have been left in the forest. (Note this means that the *counterfactual* land use is taken to involve not extracting the harvest residues, see Section 3.6.) In this example, there is an associated reduction in forest carbon stocks from about 146 tC ha^{-1} to about 143 tC ha^{-1} (see Section 3.6.2 and in particular Figure 3.6), which takes place over roughly 50 years.

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[18] It should also be noted that the term 'GHG emissions payback time' is not particularly favoured by the authors of this report, since it is related to the term 'carbon debt' and presents similar problems for understanding and interpreting results. However, the term is used in this report, rather than adding to an already confusing array of terminology by proposing an alternative name.

Table 5.1 shows the GHG emissions due to biogenic carbon that would occur over an 11 year period from the start of extraction of harvest residues, as a result of forest carbon stock changes. The results for emissions are expressed in tonnes carbon per hectare, and on a *cumulative basis*, i.e. the GHG emissions for each year are calculated as the sum of emissions that have occurred up to that year, since the start of extraction of harvest residues. The results clearly show that the GHG emissions of the bioenergy due to biogenic carbon cannot be assumed to be zero. However, it can also be seen that the trajectory of cumulative GHG emissions for the bioenergy is non-linear – initially emissions increase relatively quickly, but in later years in the table, the cumulative emissions are gradually levelling off.

Table 5.1 Illustration to the calculation of a GHG emissions payback time

Time since start of extraction of harvest residues (years)	**Cumulative emissions since start of extraction of residues[1] (tC ha^{-1})**		
	Biogenic carbon (forest carbon stock change)	**Equivalent fossil energy source[2]**	**Difference[3]**
1	0.34	0.19	0.15
2	0.61	0.39	0.22
3	0.85	0.58	0.27
4	1.06	0.78	0.28
5	1.25	0.97	0.28
6	1.42	1.17	0.25
7	1.57	1.36	0.21
8	1.71	1.55	0.16
9	1.84	1.75	0.09
10	1.96	1.94	0.02
11	2.07	2.14	−0.06

Notes to Table 5.1:

1 Based on simulations made using the Forest Research CARBINE forest carbon accounting model. See Section 3.6 and in particular Section 3.6.2 for more information.

2 Calculated using a 'multiplier for efficiencies' of 0.6 for the forest bioenergy (see Section 1.2 and Marland and Schlamadinger, 1997). This implies that 1 tC of forest bionergy has the potential to displace GHG emissions of 0.6 tC which would occur if an equivalent amount of energy was generated using a fossil energy source. Mitchell *et al.* (2012) note that a multiplier for efficiencies of 0.8 represents a highly efficient utilisation of bioenergy, whilst a value of 0.2 represents a highly inefficient method of bioenergy utilisation.

3 There may be slight discrepancies due to rounding.

Table 5.1 also shows estimates for cumulative GHG emissions that would occur if a fossil energy source was used to produce an equivalent amount of energy to that generated using the extracted harvest residues. (This fossil energy source is taken as the *counterfactual* energy source, see Sections 3.8 and 4.6.) For the example 5,600 ha forest being modelled, a constant quantity of harvest residues are extracted each year, thus a fixed amount of fossil energy consumption is potentially displaced each year. The GHG emissions that would occur due to the use of fossil energy instead of the forest bioenergy are estimated for this example at 0.19 tC ha^{-1} per year, with the result that *cumulative* GHG emissions for the fossil energy source rise linearly, i.e. by 0.19 tC ha^{-1} each year.

A comparison of the cumulative biogenic carbon emissions due to use of the forest bioenergy, and due to the use of an equivalent fossil energy source, reveals a pattern over time. Initially, the cumulative emissions of the forest bioenergy are greater than those of the fossil energy source. For example, in the first year, the GHG emissions of the forest bioenergy are 0.34 tC ha^{-1}, whereas the emissions of the fossil energy source are 0.19 tC ha^{-1}, a difference of 0.15 tC ha^{-1}. However, because the cumulative GHG emissions due to use of the bioenergy gradually 'level off' over time, whilst the cumulative GHG emissions due to use of the fossil energy continue to rise linearly, eventually a time is reached when the cumulative GHG emissions due to use of the two energy sources is the same. This time can be referred to as the *GHG emissions payback time* for the forest bioenergy. For the example of increased extraction of harvest residues illustrated in Table 5.1, the GHG emissions payback time is around 10 to 11 years.

It is important to stress that, as illustrated by the above example, when the GHG emissions payback time is reached, this does not mean that the GHG emissions associated with a bioenergy source can be taken to be zero. Rather, the cumulative GHG emissions are the same as they would have been for an equivalent fossil energy source. In the years before the payback time, cumulative GHG emissions due to using the bioenergy are greater than those for the equivalent fossil energy source. For the years following the payback time, cumulative GHG emissions due to using the bioenergy are less than those for the equivalent fossil energy source. Thus, crucially, the use of the bioenergy source only achieves GHG emissions reductions compared to the fossil energy source from the point when the payback time is reached.

Reliance on results expressed as GHG emissions payback times for assessing and comparing different published studies of forest bioenergy has certain strengths and weaknesses.

A number of published studies report results expressed as GHG emissions payback times. Furthermore, it is often possible to infer estimates of GHG emissions payback times from different types of results presented in other published studies. Thus, by referring to GHG emissions payback times, it is possible to compare the results of quite a large number of studies. This can be regarded as an important strength of such an approach.

Unfortunately, there is no standard specification for calculating GHG emissions payback times, and studies may adopt varying calculation methods. For example, some researchers present results for a related metric referred to as 'carbon sequestration parity point', which may be viewed as a particular type of GHG emissions payback time which is calculated in a specific way. More generally, a whole class of metrics can be defined and calculated in several ways, all of which can be referred to as GHG emissions payback times. The specific details of LCA methodology adopted in studies can also affect the results ultimately reported. These issues have the consequence that results in the literature are not always strictly consistent and comparable, representing an important weakness in relying on such estimates.

Other weaknesses can be identified in referring to results expressed as GHG emissions payback times as principal results for the analysis and comparison of published assessments of forest bioenergy. Most obviously, GHG emissions payback times do not give a direct measure of the actual change in GHG emissions that would occur as a result of consuming a bioenergy source. By definition, GHG emissions payback times give a clear indication that GHG emissions are most likely increased before the payback time, and reduced thereafter. However, this does not provide information on the magnitudes of the initial increase in GHG emissions or the subsequent decrease. Ultimately, such results do not directly provide information on the impacts on climate warming that would occur as a result of consuming a bioenergy source.

In referring to results for GHG emissions payback times, as discussed earlier, it is important to note that climate studies have strongly suggested that cumulative absolute GHG emissions over a period to 2050 represent a robust index of warming impact relevant to meeting climate policy targets. This also suggests that achieving GHG emissions reductions before 2050 is important, from which it may certainly be inferred that bioenergy sources with GHG emissions payback times longer than (say) 35 years are 'high risk' in terms of their relevance to meeting climate policy targets.

On this basis, it may be concluded that forest bioenergy sources and systems might be tentatively ranked in terms of risk by considering estimates of GHG emissions payback times as 'low risk', 'moderate risk', 'high risk' and 'very high risk', as indicated in Table 5.2.

Table 5.2 Possible classification of bioenergy sources and systems based on GHG emissions payback time

GHG emissions payback time	Risk attached to bioenergy source/system
1 year or less	Low
30 years or less	Moderate
Greater than 30 years	High
Indefinite	Very high

The decision to base a significant part of a meta-analysis of literature on forest bioenergy on consideration of results for GHG emissions payback time is pragmatic, for reasons given above. The results of any such meta-analysis clearly require very careful interpretation and any conclusions must be drawn with considerable caution.

5.3. JRC technical report: Carbon accounting of forest bioenergy

This important review by the EU Joint Research Centre was published in spring 2013. It is being widely cited and has set an agenda for debate on the GHG emissions associated with forest bioenergy, and approaches to calculation. Many of the observations and points made echo those already covered in Sections 1-4 of this current report. It is, nevertheless, important to consider in some detail the analysis presented in the JRC report, and in particular, the findings and conclusions.

The following discussion of the JRC review is structured to address three essential subjects:

1. The objectives and scope of the review (see Section 5.3.1)
2. Key findings, insights and conclusions of the review (see Section 5.3.2)
3. Points requiring further clarification (see Section 5.3.3).

Brief conclusions concerning the JRC review are presented in Section 5.3.4.

5.3.1. Objectives and scope

The stated aim of the JRC review is, "to analyse the climate impact of forest bioenergy by reviewing in detail the most up-to-date information on the subject in terms of modelling approach and techniques, data availability, results and conclusions achieved by the international scientific community and published in relevant peer-reviewed journals or by internationally recognised institutions". In particular the review considers, "the main physical phenomena underpinning the forest bioenergy carbon accounting through the results available in the literature, and … quantify the possible contribution of forest bioenergy pathways to the achievement of … climate policy targets".

As with this current report, the scope of the JRC review is concerned specifically with GHG emissions associated with bioenergy rather than other aspects such as security of energy supply, socioeconomics, biodiversity and rural development. However, the report does include a section considering some other influences of forest systems and forest management on climate, notably albedo, aerosols and 'black carbon'. This latter discussion extends beyond the scope of this current report, but is clearly pertinent to any analysis of the role of forest bioenergy in avoiding dangerous climate change.

It is very important to appreciate that the scope of the JRC review is specifically concerned with understanding the potential impacts of significant increases in the consumption of forest bioenergy in the EU associated with efforts to meet existing and possible future targets for bioenergy use. The review focuses on the implications of such increased consumption of forest bioenergy on GHG emissions, and to some extent considers the implications for 'carbon accounting', or more specifically, the need to allow for contributions due to biogenic carbon in LCA calculations of GHG emissions, including certain approaches for achieving this. Other scenarios, notably the possibility of a more general mobilisation of wood resources in the EU or in other parts of the world, as part of increased consumption of wood as a source of materials and/or chemicals as well as bioenergy, appear to be regarded as out of scope.

There are two core technical discussions in the review. The first of these deals with the issue of most obvious and immediate concern, i.e. the extent of the contribution of biogenic carbon to GHG emissions of forest bioenergy resulting from carbon stock changes in forests, which would take place if production of biomass from forests was to be increased to meet rising demands for forest bioenergy. The second technical discussion addresses "market mediated effects of forest bioenergy". Such effects may involve the diversion of harvested wood from use for materials to use as bioenergy. They may also involve incomplete displacement of fossil fuels by forest bioenergy, intensified competition for the existing forest bioenergy resource, and indirect land use change. Other subjects are also considered, for example, non-GHG climate drivers and the findings of large scale techno-economic modelling studies.

5.3.2. Key findings, insights and conclusions

Probably one of the most important and valuable sections of the JRC review presents a 'meta-analysis' of results for GHG emissions of forest bioenergy as presented in recent scientific journal articles and reports. The key findings of this 'meta-analysis' are presented in Tables 1 to 3 and Figures 13 to 16 of the JRC review.

The meta-analysis considers two broad types of scenario, involving two distinct types of wood feedstock to meet increased demands for forest bioenergy:

1. Increased harvesting of stemwood, through increased felling of forest areas, or increased thinning. One scenario represents increased supply of stemwood for bioenergy achieved through planting new forest areas on marginal agricultural land. (See Section 3.6.)
2. Extraction of harvesting residues (see Sections 2.3 and 2.5), where previously these were left to rot in the forest or burnt at roadside.

Related results from one key research paper (Mitchell *et al.*, 2012) are also repeated and discussed.

Within each of the two broad scenarios considered, results reported by individual studies are classified according to certain details of the specific forest bioenergy system being studied:

- 'Area' (geographical location)
- 'Forest type' (essentially whether the forest is considered to be growing in temperate or boreal conditions)
- 'Study boundaries' (essentially the scale of forest system studied, 'representative stand', 'forest management unit' or 'landscape')
- '[Forest management] scenarios' (essentially the type of change to forest management involved in increasing the supply of forest bioenergy, such as additional felling in forest areas, increased 'management intensity', replacing existing forest with plantations, extraction of harvest residues)
- 'Fossil system' (the energy source, fossil fuel and conversions system which it is assumed the forest bioenergy should displace).

Rather than presenting results directly in terms of estimated GHG emissions for forest bioenergy, the meta-analysis summarises results expressed as GHG emissions payback times (see Section 5.2.1). The JRC review places great emphasis on the concept and metric of 'payback time'. The JRC review also discusses results reported in scientific literature for a metric referred to as, 'carbon sequestration parity point'. These results presented in the JRC review are not considered further in this section. As already stressed in Section 5.2.1, results expressed as GHG emissions payback times need to be interpreted with great caution.

Table 1 of the JRC review reports estimates for GHG emissions payback time derived from six scientific papers and reports (Walker *et al.*, 2010; McKechnie *et al.*, 2011; Zanchi *et al.*, 2011; Colnes *et al.*, 2012; Holtsmark, 2012a; Jonker *et al.*, 2013), which consider 'bioenergy production scenarios' in which additional stemwood is harvested for use as forest bioenergy. The various studies cover geographical locations in Europe (Austria and Norway), Canada and the USA. In many cases, the forest management scenarios considered involve additional harvesting in existing forests, e.g. additional felling or thinning. In some cases, forest management scenarios involve replacing existing forest with high-productivity plantations managed on short rotations.

Table 3 of the JRC review reports estimates for GHG emissions payback time derived from four scientific papers and reports (Mitchell *et al.*, 2009; McKechnie *et al.*, 2011; Zanchi *et al.*, 2011; Repo *et al.*, 2012), which consider 'bioenergy production scenarios' in which additional pre-commercial thinnings or harvest residues are extracted for use as forest bioenergy. The various studies cover geographical locations in Europe (Austria and Finland), Canada and the USA. One study (Repo *et al.*, 2012) considers the extraction of different 'fractions' of harvest residues, i.e. branchwood or stumps.

In both Tables 1 and 3 of the JRC review, a range of energy conversion systems are covered (e.g. electricity, heating, combined heat and power and bioethanol transport fuel). Fossil energy sources assumed to be displaced involve coal, oil, natural gas and fossil transport fuel.

Further results for GHG emissions payback times are presented in Figure 14 of the JRC review, which repeats estimates graphically in a paper by Mitchell *et al.* (2012). This study is notable for its modelling of GHG emissions payback times associated with additional bioenergy consumption across a wide range of scenarios involving:

- Four initial land states (agricultural land; forests managed on a rotation for production of solid-wood products; forest land subject to recent significant natural disturbance; biological mature forest, no management involving harvesting, with high carbon stocks in trees).
- Three forest growth rates ('low', 'moderate', 'high').
- Three 'biomass longevities', i.e. rates at which forest woody biomass naturally decays ('low', 'moderate', 'high').

- Six forest management scenarios involving different intensities of bioenergy harvesting (thinning of 50% of trees every 25, 50 or 100 years; clearfelling every 25, 50 and 100 years).
- Fossil energy system displaced by bioenergy as a continuous variable, represented by a 'bioenergy conversion factor', similar to the 'multiplier for efficiencies' defined by Marland and Schlamadinger (1997; see discussion of Figure 1.2, Section 1.2 in this current report).

The estimates of GHG emissions payback times as reported in Tables 1 and 3 and Figure 14 of the JRC review display a range from instantaneous to more than 1000 years. From a policy perspective, this range encompasses every conceivable situation. Potentially, some forest bioenergy sources could make vital contributions to providing energy with low associated GHG emissions. Certain other forest bioenergy sources offer only marginal improvements over fossil energy sources. In other cases, the promotion of forest bioenergy would be regarded as severely frustrating the achievement of targets for reductions in GHG emissions. In this context, it is no wonder that some commentators have described the potential contribution of (and the GHG emissions associated with) forest bioenergy as complex and uncertain. However, the wide range in estimates may not represent uncertainty as such, but may reflect systematic variation due to key factors and details of LCA methodology (see Sections 3.16 and 4.11).

Although the results in Tables 1 and 3 and Figure 14 of the JRC review are compiled from just nine studies in total, the range of scenarios and cases represented is sufficient to permit a tentative investigation to be made of structure in the reported estimates for the specific bioenergy production scenarios under consideration. Further details are given in Appendix 4.

The analysis in Appendix 4 shows the extreme range of outcomes for GHG emissions payback time as already discussed, and there is also clearly some variability in results for individual scenarios, where multiple estimates are available. However, the ordering of results in the table strongly suggests that scenarios can be ranked in terms of GHG emissions payback time, from consistently extremely long (at the top of the table) to consistently negligible (at the bottom of the table). In Table 5.3, these results are used to classify the bioenergy sources and systems considered as 'low risk', 'moderate risk', 'high risk' or 'very high risk', as discussed and defined in Section 5.2.1.

A number of detailed, sometimes tentative, observations can be drawn from the analysis in Appendix 4, perhaps of most significance:

- Fossil energy (counterfactual) scenario, in conjunction with the efficiency of forest bioenergy conversion, can be important in determining the GHG emissions payback time for additional bioenergy production. Generally the shortest payback times are associated with a fossil energy counterfactual scenario of coal; payback times are longer for oil and longest for natural gas. For some scenarios (towards the bottom of the table), the payback times are negligible or very short, regardless of fossil energy counterfactual scenario. See also Section 3.8 of this report.

- Outcomes in terms of GHG emissions payback times are very sensitive to the initial state of land (in terms of carbon stocks) before introduction of additional bioenergy production (e.g. high carbon stocks in biologically mature forest or recently disturbed forest areas).
- Payback times are generally longest for forest management/production scenarios involving increased intensity of harvesting or increased extraction of biomass for the production of bioenergy only.
- For forest management scenarios involving the replacement of systems with existing high carbon stocks with plantations dedicated to producing forest bioenergy, the potential growth rate (biomass productivity) that can be achieved by the new plantations is very important. See also Section 3.10 of this report.
- For forest management/production scenarios involving increased intensity of harvesting or increased extraction of biomass, co-production of solid wood products with forest bioenergy could be a ‘game changer’ for resultant GHG emissions payback times. However, note that only one study in Table 5.3 considers increased intensity of harvesting involving co-production (Zanchi *et al.*, 2011). The high sensitivity to counterfactuals for wood products has been established in other studies (see for example Matthews *et al.*, 2014). See also Sections 3.7 and 3.8 of this report.

Some of the preceding observations are further supported by the multi-scenario sensitivity analysis presented by Mitchell *et al.* (2012), notably those concerning fossil energy counterfactual scenario and the initial state of land in terms of carbon stocks. This study deservedly receives close attention in the meta-analysis presented in the JRC review. The findings of Mitchell *et al.* (2012) also reinforce the general importance of potential growth rate (biomass productivity) as an important factor in determining GHG emissions associated with the production and use of forest bioenergy (as expressed in terms of GHG emissions payback time in this specific context).

The JRC review reaches broadly similar, although rather less elaborated, conclusions to those offered in the preceding discussion, Appendix 4 and in Table 5.3 (see Tables 2 and 12 of the JRC review).

Thus far, the consideration of the JRC review presented here has focussed on the first of the two core technical discussions identified earlier, i.e. the extent of the contribution of biogenic carbon to GHG emissions of forest bioenergy resulting from carbon stock changes in forests. As already explained, a second technical discussion addresses the issue of “market mediated effects of forest bioenergy”. The JRC review identifies four principal market mediated effects:

1. Diversion of existing supply of harvested wood from the manufacture of solid-wood products to use as bioenergy.
2. Interactions between the use of forest bioenergy in existing and new applications, and also interactions with the consumption of other energy sources.

3 Increased forest bioenergy consumption leading to only partial displacement of fossil energy sources.
4 Indirect land use change arising from increased requirements for forest bioenergy.

The possibility of increased demand for bioenergy causing a diversion of harvested wood from the manufacture of solid wood products has already been explored in Sections 2.7 and 3.7. The JRC review discusses the importance of allowing for the potential diversion of wood feedstock from the manufacture of solid wood products for use as bioenergy, and stresses that studies that fail to consider such potential effects may come to misleading conclusions. It is also noted that such effects might be integrated into assessments of GHG emissions due to use of forest bioenergy through the approach of consequential LCA (see Section 4.3 of this current report). Several studies addressing the issue of potential diversion of wood feedstock from the manufacture of solid wood products to use as bioenergy are considered in the JRC review (Böttcher *et al.*, 2011; Guest *et al.*, 2012a; Pingoud *et al.*, 2012). These establish that GHG emissions can increase, even when wood consumption is maintained at current levels, if harvested wood is diverted from the manufacture of solid wood products for consumption as bioenergy. Two of these studies (Guest *et al.*, 2012a; Pingoud *et al.*, 2012) focus on the role of 'biomass cascading', i.e. the management of harvested wood through a sequence of uses, involving initial utilisation in solid wood products and burning of wood as a source of energy on ultimate disposal of solid products (see Sections 2.5 and 3.7 of this current report). It should also be noted that several of the scenarios modelled in the study of Mitchell *et al.* (2012) implicitly involve the diversion of harvested wood from the manufacture of solid wood products for use as bioenergy (see Table 5.3).

Table 5.3 Classification of forest management/bioenergy production scenarios in terms of risk with regard to GHG emissions

Risk	Forest management/bioenergy production scenario	Comments
'Very high' or 'high'	Harvesting of forest with high carbon stocks, and replacement with rotational forest management for production of bioenergy only.	
	Salvage logging and restoration of forests on rotational management for production of bioenergy only.	
	Additional harvesting of stemwood and 'residual wood' for bioenergy only in forest stands for fire prevention.	
	Additional harvesting of stemwood in forest areas already under management for production, for bioenergy only.	
	Diversion of harvested wood from solid wood products to bioenergy, leaving harvesting intensity unchanged.	Very sensitive to counterfactuals for forest bioenergy and solid wood products.
	Additional harvesting of stemwood in forest areas already under management for production, for bioenergy only.	Sensitive to fossil energy counterfactual.
'Moderate'	Harvesting of forest with high carbon stocks and replacement with high-productivity short rotation plantations for production of bioenergy only.	Sensitive to productivity of short rotation plantations.
	Extraction of harvest residues.	Sensitive to harvesting of stumps, soil nutrient status and to fossil energy counterfactual.
	Extraction of pre-commercial thinnings.	Sensitive to fossil energy counterfactual.
'Low'	Creation of new forests for bioenergy only on marginal agricultural land with low initial carbon stock.*	Bioenergy will not become available immediately but carbon stocks on land should increase quickly. However, this is sensitive to the initial carbon stocks of the agricultural land.
Variable, 'low' to 'high'	Harvesting of biologically mature forest with high carbon stocks for sustained co-production of solid wood products and bioenergy.	Extremely sensitive to counterfactuals for harvested wood.

Note to Table 5.3:

* The JRC review emphasises the importance of avoiding indirect land use change when creating new forest areas, particularly when this takes place on land previously used for agriculture.

The discussion in the JRC review of interactions between the use of forest bioenergy in existing and new applications, and also interactions with the consumption of other energy sources, is somewhat confusing and hard to follow. To some extent this issue appears to overlap with the possibilities of the diversion of harvested wood from the manufacture of solid wood products for use as bioenergy (see previous paragraph) and of increased forest bioenergy consumption leading to only partial displacement of fossil energy sources (see following paragraph). The JRC review observes that competition for forest resources due to increased bioenergy use (more specifically, transport biofuels) has been already identified in Schwarzbauer and Stern (2010) and Forsström *et al.* (2012). It is also noted that in a briefing for the EU parliament (Wunder *et al.*, 2012), the authors state that an increasing demand for forest bioenergy in the EU will have significant effects worldwide. These observations lead to the general conclusion that rising demands for forest bioenergy will lead to changes in the patterns of forest management, the utilisation of harvested wood (for energy and other applications), and also changes in the consumption of fossil energy sources. The critical point appears to be that additional pressure on forests and other ecosystems could drive conflicts over the use of forest resources (i.e. supplies of harvested wood) and over land use more generally. Particular concern is expressed with regard to potential risks to energy security in countries already strongly reliant on local use of forest bioenergy, including harvest residues. The JRC review concludes that the potential risks associated with bioenergy feedstocks derived from harvest residues which are being diverted to production of biofuels, and the potential GHG emissions associated with different conversion processes and feedstocks, are still not well addressed, and deserve particular attention for future scientific studies.

The JRC review highlights that published studies of GHG emissions associated with the production and use of forest bioenergy generally make the assumption that each unit of bioenergy produced replaces an equivalent unit of energy from fossil sources. However, because of the complexity of economic systems and human behaviour, this may not actually happen in practice. Rather, there may be a general increase in consumption of energy services following an improvement in the efficiency of delivering those services (or in the total potential supply of energy services). This increased consumption may have the effect that, in practice, a unit of bioenergy produced may replace less than an equivalent unit of fossil energy. The JRC review cites a number of studies (mainly concerned with efforts to increase energy efficiency) which suggest that such effects can be very significant (Chen and Khanna, 2012; Drabik and de Gorter, 2011; Druckman *et al.*, 2011; Greening *et al.*, 2000; Hochman et al, 2010; Rajagopal *et al.*, 2011; Sorrell, 2007; Thompson *et al.*, 2011; York, 2012). The JRC review notes the controversial and disputed nature of these studies. However, should such effects be real and significant, then there are clear implications for assessments of GHG emissions associated with use of forest bioenergy, and also for policies towards forest bioenergy (and other energy sources). A related issue is the potential for competition between different renewable sources of energy, and the JRC review points out that ‘blanket’ incentives for renewable energy sources could, for example, lead to some situations in which forest bioenergy with long GHG emissions payback times displaces the use of renewable energy sources with shorter payback times (e.g. photovoltaic, wind, biogas from manure). It is suggested that there may be a role here for attaching sustainability criteria to sources of forest bioenergy. However, what may seem a straightforward idea in principle is likely to be rather complicated in practice.

Indirect land use change, which may occur as a result of afforestation activities aimed at increasing the supply of forest bioenergy, has already been discussed briefly in Section 3.13. In its discussion of this subject, the JRC review observes that an additional demand of bioenergy from forests may trigger, via market demand, an expansion of forested land. Although the direct impact on vegetation and soil carbon stocks of affected land is generally positive, there may be indirect impacts due to the diversion of other lands to make up for lost agricultural production. The JRC review therefore stresses the importance of creating forests on abandoned or degraded land. It is also considered important that potential effects of indirect land use change are integrated into assessments of GHG emissions of forest bioenergy, noting examples of studies which have not undertaken such complete assessments (Galik and Abt, 2012; Sedjo and Tian, 2012). At the same time, the JRC review acknowledges the difficulty of making such assessments. It is concluded that current methodologies for including indirect land use change are crude, and it is not possible to arrive at a clear assessment of the likely magnitude of impacts due to indirect land use change. However, the JRC review considers that, based on existing literature (Cocchi *et al.*, 2011), any such impacts cannot be assumed to be negligible, highlighting the strong possibility of demand for forest bioenergy stimulating land use change, e.g. afforestation in countries such as Brazil, and regions of Africa.

The JRC review concludes that the need for a better understanding of indirect impacts such as described above should not be ignored.

As explained at the outset of this discussion, the JRC review also covers other subjects beyond those covered in the two core technical discussions identified here and described above.

The JRC review supports the view expressed in this current report (see Section 4.2) that LCA is the appropriate tool for assessing GHG emissions associated with the use of forest bioenergy, noting the general agreement on this point in the scientific community (Cherubini, 2010) and the policy community (EU Directive 2009/28/EC on Renewable Energy). However, the JRC review highlights that numerous methodological choices and assumptions have to be made when performing an LCA, with the consequence that results for GHG emissions can differ significantly, even for apparently similar systems (see Section 4 of this report).

The JRC review suggests that the main reasons for diverging results are: type of biomass sources, assumptions about alternative counterfactual land use conversion technologies, input data sources, end-use technologies, allocation method, system boundaries, reference energy system, and other assumptions including issues relating to data quality and age (Cherubini *et al.*, 2009; Cherubini, 2010). It is stressed that choice of time horizon can be critical in determining results for GHG emissions of forest bioenergy systems, particularly with regard to comparisons with a baseline scenario. These and many other observations made in the JRC review concur with the discussion in Sections 3 and 4 of this current report and, in particular, conclusions presented in Sections 3.17 and 4.11.

There is some consideration of metrics for assessment of GHG emissions associated with forest bioenergy, notably an index called GWPbio (Cherubini *et al.*, 2011ab) and another index referred to as a 'carbon neutrality factor' (Schlamadinger *et al.*, 1995). However, the JRC review does not reach any definitive conclusions on the suitability and/or advantages and disadvantages of such metrics.

The JRC review makes notable efforts to consider the potential contributions of non-GHG climate effects related to forests and their management for bioenergy production. It is concluded that the contributions of these climate forcers is still highly uncertain, but in some cases cannot be assumed to be negligible and therefore should be included in analyses of the potential for forest bioenergy to contribute to limiting climate change. Currently, the precise methods for achieving such integration in assessments would appear to be a challenge for research.

The discussion of large scale techno-economic modelling is given some prominence in the JRC review and the findings of several studies are discussed (Böttcher *et al.*, 2011; Kallio and Salminen, 2012; UN-ECE, 2011). These studies all support the view that an indiscriminate increase in consumption of forest bioenergy to meet targets for renewable energy is likely to cause a net increase in GHG emissions. In this context, the European Forest Sector Outlook Study II, EFSOS II (UN-ECE, 2011), concludes that, in order to maximise the forest sector's contribution to climate change mitigation, the best strategy would be to combine forest management focused on accumulation of forest carbon stocks with maintaining a continuous supply for solid wood products and forest bioenergy. However, it is noted that, in the long term, the capacity of forests to sequester carbon will reach an upper limit. This will mean that the only potential for further mitigation of GHG emissions is through regular harvesting, to maintain or enhance carbon stocks in solid wood products, and to avoid emissions from non-renewable materials and fossil energy sources (Aquino Ximenes *et al.*, 2012).

A number of other subjects also receive attention in the JRC review, for example, the potential for a positive response in the forest sector to increased demand for bioenergy through the introduction of certain forest management approaches; and uncertainties related to risks of natural disturbance in forest areas.

5.3.3. Points requiring clarification

Whilst the JRC review is thorough in scope and draws out many valuable insights from existing scientific literature on assessments of GHG emissions associated with the use of forest bioenergy, there are several points where commentary in the JRC review is somewhat ambiguous and some clarification is needed.

Although sections of the JRC review state the scope and problem definition, including the aim of the review, the ultimate goal is not always clear, and sometimes seems to shift. In particular, in some places the discussion in the review strongly suggests that the goal is to clarify the approach and methods required when accounting for GHG emissions associated with the consumption of forest bioenergy. Such a methodology would be relevant, for example, within a regulatory framework such as the EU Renewable Energy Directive. At other points, the discussion is clearly concerned with changes in GHG emissions that may occur, given incentives for a significant increase in the consumption of forest bioenergy, and how such potential changes in GHG emissions should be assessed. Most likely, both subjects are being addressed as valid issues within the scope of the review, but the lack of clarity and distinction between the two subjects is a potential cause of confusion.

The blurring of the boundaries between the discussions of LCA methodologies for the purposes of accounting for GHG emissions of forest bioenergy on the one hand, and of the assessment of impacts of incentives aimed at increasing consumption of forest bioenergy on the other hand, is also found in the two core technical discussions of the JRC review described in Section 5.3.2 of this current report. The first of these technical discussions, dealing with the contribution of biogenic carbon to GHG emissions of forest bioenergy, makes significant reference to a meta-analysis of results for GHG emissions of forest bioenergy as presented in recent scientific journal articles and reports. This meta-analysis has proved useful for identifying scenarios for forest bioenergy production that are likely to be associated with negligible, short or long GHG emissions payback times (see Section 5.3.2). However, the studies included in the meta-analysis seem to address varying goals and research questions, although generally there is a focus on GHG emissions associated with systems in which levels of forest bioenergy production are increased. Clearly, therefore, many if not all of these studies are assessing potential impacts of a change to existing activities, consistent with consequential LCA. There appears to be some confusion in this discussion, because the JRC review labels all of the studies included in this meta-analysis as examples of “attributional modelling”. The second core technical discussion in the JRC review, addressing “market mediated effects of forest bioenergy”, is described as being concerned with “consequential life cycle inventory modelling”. However, it is clear that at least some of the studies considered in the meta-analysis of the first technical discussion more closely resemble consequential LCA than attributional LCA. The consideration of so-called “attributional modelling” in the JRC review is further confused by the description of how a “bioenergy system” is defined. In particular the JRC review comments that, ‘this system is compared to a fossil "reference system" (sometimes called "counterfactual") in which the energy is produced with fossil energy sources'. This is evidently confusing or mixing the principles of attributional LCA and consequential LCA (see Section 4.3 of this current report).

It is notable that the JRC review focuses on the potential consequences for GHG emissions due to a significant increase in the consumption of forest bioenergy, generally based on the presumption that relevant incentives would be aimed exclusively at stimulating forest bioenergy production and consumption, rather than a wider mobilisation of wood resources to increase the use of solid wood products alongside forest bioenergy (i.e. incentivising of co-production). In many respects such a presumption is reasonable or at least understandable. Currently, existing incentives for forest bioenergy consumption, most obviously the EU Renewable Energy Directive, are exclusively concerned with bioenergy rather than with encouraging the use of wood for a wide range of applications. Moreover, the JRC review could only consider those studies available in the scientific literature, and the vast majority of these involve assessments of situations in which, specifically and exclusively, production of forest bioenergy is increased. This focus derives from the recognition of the current scale of interest in bioenergy sources (see for example Sections 2.6 and 2.7 of the current report). However, the limited information available in the JRC review on scenarios involving increased harvesting of forest biomass for co-production of solid wood products and forest bioenergy strongly indicates that these scenarios can be 'game changers' in terms of achieving net GHG emissions reductions in short timescales (see Section 5.3.2). As a consequence, scenarios involving co-production receive limited attention in the JRC review. The potential complexity and challenging nature of providing the incentives across sectors that would be needed to stimulate increased harvesting for co-production must be acknowledged. Nevertheless it is important that this potentially highly relevant scenario receives proper assessment.

In its consideration of "attributional modelling" of GHG emissions of forest bioenergy, and elsewhere, the JRC review is ambiguous in its position on the relevance of a 'no use' scenario as a baseline when assessing forest carbon stock changes associated with the production of forest bioenergy (or other wood products). At various points in the review, reference is made to use of a 'no use' scenario or 'business as usual' as a baseline in the calculation of carbon stock changes in forests. However, it is notable that, in Section 2.1.1 of the JRC review, the view is expressed that carbon stock changes in the forest, resulting from the use of the biomass for bioenergy, need to be accounted for; but the reference system (fossil fuels use) should also include what would happen to the forest carbon stock in the absence of bioenergy production. This appears to be advocating the general application of a 'no use' scenario as a baseline in the calculation of GHG emissions due to forest carbon stock changes. As discussed in some detail in Sections 3.11 and 4.10 of this current report, the status of a 'no use' scenario as a suitable baseline is open to challenge in at least some contexts. Crucially, as discussed in Section 4.10, a baseline scenario needs to be selected that is appropriate for the goal and research question addressed by a specific LCA study. The JRC review may not in fact be advocating general application of a 'no use' scenario as a baseline, but it is unclear from the discussion in the review exactly what position is taken on the selection of suitable baselines, particularly for land use.

One final point worthy of clarification concerns the representation of counterfactuals in assessments of GHG emissions over long time horizons. The JRC review observes that, for short time horizons, assumptions about fossil energy sources displaced by increased consumption of bioenergy might be based on current patterns of energy use with reasonable reliability. For long time horizons, it may be necessary to allow for trends in the patterns of energy use, for example, allowing for policies aiming to 'decarbonise' national economies or sectors over ensuing decades. However, it is also important to avoid 'circularity' in such calculations, e.g. in situations where increased consumption of forest bioenergy makes a significant contribution towards achieving the planned decarbonisation.

5.3.4. Conclusions on JRC technical report

The review presented in the JRC technical report (Marelli *et al.*, 2013) is thorough and authoritative. The scope covers most of the salient issues and literature, and the analysis and conclusions reached are largely sound. The meta-analysis of results for GHG emissions of forest bioenergy, as presented in recent scientific journal articles and reports, is particularly valuable. The review provides many valuable insights as described in this current report in Section 5.3.2. However, the aims of various discussions in the review are not always clear and this is a source of potential confusion (see Section 5.3.3). Some important potential scenarios for increasing forest bioenergy production are given limited attention, most obviously the possibility of increasing levels of harvesting in forests for co-production of solid wood products and forest bioenergy. Some key methodological issues, most obviously the selection of a baseline land use scenario for estimating GHG emissions due to changes in forest carbon stocks, are left ambiguous and unresolved, with no clear position recommended. There is also limited consideration of the methodologies actually applied by the published studies included in the review, and the potential influence of methodological choices on results.

In concluding, the JRC review stresses that, "the assumption of biogenic carbon neutrality is not valid under policy relevant time horizons (in particular for dedicated harvest of stemwood for bioenergy only) if carbon stock changes in the forest are not accounted for". This very important statement requires careful interpretation. Essentially this confirms that it is necessary to allow for any changes in forest carbon stocks associated with the harvesting of wood, including the production of forest bioenergy. By this stage in the discussion in this current report, it must be evident that such a claim is undisputable.

5.4. Other recent reviews and commentaries on GHG emissions associated with forest bioenergy

In addition to the JRC technical report reviewed in the preceding discussion, there are several other important reviews and commentaries in the scientific and technical literature that address the subject of the potential role of forest bioenergy, with particular regard to meeting targets for renewable energy and levels of GHG emissions in the EU. Six such reports and scientific papers have been identified as requiring close assessment (Trømberg *et al.*, 2011; Schulze *et al.*, 2012; Adams *et al.*, 2013; EEA, 2013; Lamers and Junginger, 2013; Ros *et al.*, 2013). These vary in length, scope and treatment of the subject of forest bioenergy but have all been identified as having some significance, variously representing substantial technical assessments, important critical insights, and/or having prominence in the ongoing scientific discussion concerning forest bioenergy, associated GHG emissions, and how these should be assessed. Reviews of each of these six reports and scientific papers are presented in Tables 5.4 to 5.9, using the same structure adopted for considering the JRC review, as discussed in Section 5.3. Some overall conclusions are presented in Section 5.4.1, including consideration of common points drawn from all the reviews, including the JRC review.

Table 5.4 Analysis of PBL/Alterra note:
Climate effect of wood used for bioenergy (Ros *et al.*, 2013)

Objectives and Scope
The introduction to the note explains that the Dutch Ministry of Infrastructure and the Environment requested an overview of the impact of wood used for bioenergy on greenhouse gas emissions and climate change. The PBL/Alterra note presents this overview. The stated main objective is to provide information that is relevant in the process of setting sustainability criteria for using woody biomass as a source of energy. The overview covers wood produced for use as bioenergy from clear felling of forests, thinning operations, harvest residues and waste wood. It is not clear whether the scenarios considered assume that additional production of wood from forests is for a mix of products (i.e. a general mobilisation of the resource for solid wood products and bioenergy), or exclusively to increase the supply of bioenergy. The emphasis is on use of forest bioenergy for power generation, but there is some consideration of biomass transport fuels. The geographical scope is primarily on Europe, with time horizons of 2030 and 2050 considered. Supporting analysis and modelling focuses on two metrics for representing the impacts on GHG emissions of increased harvesting of forest biomass, for various bioenergy feedstocks produced by a range of forest management options. The first metric is referred to as the ‘quotient of carbon losses from forests’. The second metric is GHG emissions payback time. Reference is made to results for payback times reported in the JRC technical report (see Section 5.3) supplemented by results generated using the EFISCEN model. Implications for accounting for forest bioenergy in regulatory frameworks and for sustainability criteria for solid biomass are briefly considered.

Table 5.4 (continued) Analysis of PBL/Alterra note:
Climate effect of wood used for bioenergy (Ros *et al.*, 2013)

Key findings, insights and conclusions
Based on the consideration of results for quotient of carbon loses from forests, it is concluded that increased clear felling, increased thinning and increased extraction of harvest residues exclusively for production of forest bioenergy will lead to significant reductions of forest carbon stocks (compared to 'business as usual'). It is also noted that an increased demand for forest bioenergy could stimulate forest management activities that would increase or at least sustain existing forest carbon stocks (e.g. establishment of trees at higher densities, selection of tree species to improve productive potential and forest fire suppression). It is noted that such a conclusion is also reached by Trømberg *et al.* (2011), Jonker *et al.* (2013) and in the JRC technical report. Salvage logging is assessed as involving a balance of positive and negative potential impacts on GHG emissions. The creation of new forests is identified as generally achieving net GHG emissions reductions, provided that an indirect land use change is avoided. However, caution is expressed concerning the option of replacing biologically mature forest stands with fast growing plantations dedicated to biomass production. With regard to waste wood, the principle of 'biomass cascading' is advocated, whilst noting challenges for implementation. Estimates of GHG emissions payback time produced using the EFISCEN model are broadly consistent with those presented in the JRC technical report (see Section 5.3 and Appendix 4). These results are considered further in Section 5.5.3 of this current report. A potential loophole is noted for GHG emissions from harvested wood under the Kyoto protocol (see Section 3.14 of this current report). Two options are proposed for addressing this loophole which may also have wider application. It is noted that existing criteria forming part of certification schemes for sustainable forest management already indirectly address issues relevant to forest carbon stocks (e.g. forest management in general, control of extraction of forest residues, avoidance of loss of forest quality). The conclusions stress the importance of allowing for contributions to biogenic carbon (arising from forest carbon stock changes) when estimating GHG emissions of forest bioenergy. The varying impacts of different forest bioenergy feedstocks produced by different forest management interventions are distinguished in the conclusions. It is pointed out that good forest management is essential for sustainable wood production and the role of more general wood mobilisation is mentioned as a requirement for increasing the supply of forest bioenergy. It is recommended that additional harvesting of wood (more specifically clear felling) exclusively for the production of bioenergy should be avoided.

Table 5.4 (continued) Analysis of PBL/Alterra note: Climate effect of wood used for bioenergy (Ros *et al.*, 2013)

Points requiring clarification
Probably most importantly, the note would benefit from further clarification of the actual scenarios considered, i.e. whether these are concerned with additional production of wood from forests for a mix of products (i.e. a general mobilisation of the resource for solid wood products and bioenergy), or with scenarios in which additional production is exclusively to increase the supply of bioenergy. From much of the discussion, it is apparent that the main focus is on scenarios involving increased extraction of wood for forest bioenergy only. As with the JRC technical report, scenarios involving a general mobilisation of wood resources for co-production of solid wood products and bioenergy receive almost no attention.

Table 5.5 Analysis of SUPERGEN Bioenergy Hub report: Understanding greenhouse gas balances of bioenergy systems (Adams *et al.*, 2013)

Objectives and Scope
The report aims to inform stake holders with wider energy and environmental policy or research interests on issues relating to GHG emissions of bioenergy systems. The scope is primarily concerned with bioenergy sources that may contribute to meeting energy demand in the UK. A wide range of bioenergy systems are considered including annual crops, perennial crops, forests, agricultural wastes and residues and algal systems. The emphasis is on discussion of methodological systems in LCA and to offer guidance on approaches for making assessments of GHG emissions of bioenergy sources. There is very limited consideration of actual results for GHG emissions.
Key findings, insights and conclusions
In terms of factors determining GHG emissions, the report concludes that different issues are important for different bioenergy sources. For forestry systems it is concluded that key issues are carbon stock changes that take place in forests due to bioenergy production, and the role of co-production of solid wood products alongside bioenergy production (see Table 1 in the SUPERGEN report). Potential biomass productivity is recognised as generally important for all bioenergy systems. The report emphasises the need to adopt an approach based on ‘supply chain accounting’ rather than ‘territorial’ (or sectoral) accounting when making assessments of GHG emissions of bioenergy systems, and the importance of representing associated land-use change (including changes to forest management), and comparison with an appropriate reference or baseline scenario. When considering variability for results for GHG emissions of bioenergy sources, the report makes a critical distinction between sources of systematic variation and sources of uncertainty. The report also stresses that variations in LCA methodology can be important in determining results. A number of factors are identified, and the conclusions are consistent with those reached in Sections 3.17 and 4.11 of this current report. The report stresses the crucial importance of clearly defining the goal and research question to be addressed by any LCA study.

Table 5.5 (continued) Analysis of SUPERGEN Bioenergy Hub report: Understanding greenhouse gas balances of bioenergy systems (Adams *et al.*, 2013)

Points requiring clarification
Although the report clearly explains that the question posed is crucial in determining the results produced by an LCA study (and, potentially, the differences in results of studies), it does not describe an approach for proper construction of goals and research questions. There is an implicit assumption that standard LCA methodologies define these questions; rather, the goal and research question need to define the LCA methodology. Some of the critiques of LCA methodology included in the conclusions are not wholly justified. It is claimed that LCA cannot inherently accommodate temporal effects; in fact LCA methodologies can accommodate such effects but most examples of LCA studies do not do this. It is also claimed that LCA cannot accommodate 'top-down effects' (macro-scale impacts), and is essentially a static tool that cannot represent dynamic changes. In fact there are 'statistical' LCA approaches that are analogous to input-output analysis, relevant to the capture of top-down effects. Also, LCA does not have to be a 'static' tool, although many studies adopt a static approach to analysis.

Table 5.6 Analysis of EEA report: EU bioenergy potential from a resource-efficiency perspective (EEA, 2013)

Objectives and Scope
The aim is to provide an analytical summary of the results of a more substantial report by the EEA European Topic Centre on Spatial Integration and Analysis, which re evaluated the bioenergy potential and aimed to provide insights into: • The potential GHG emissions achievable by different technologies for biomass conversion. • How to bring resource efficiency perspective into consideration of bioenergy development. • Concerns about changes in carbon stocks in forests associated with the increased production of forest bioenergy. • The implications of current trends in bioenergy cropping from an environmental perspective. Additional qualitative analysis is included concerning indirect land use change issues associated with bioenergy crops and potential carbon stock changes in forests associated with the production of forest bioenergy. The focus is therefore on a range of possible sources of bioenergy including those based on agricultural wastes. The time horizon of greatest interest is 2020, reflecting existing targets for bioenergy consumption and GHG emissions reduction in the EU. In fact, forest bioenergy receives relatively little attention in the report. A major part of the report is concerned with large scale analysis of three scenarios for future development of bioenergy consumption in the EU, which all aim to meet existing targets for bioenergy consumption, but involve varying levels of constraints in terms of targets of GHG emissions and other environmental factors.

Table 5.6 Analysis of EEA report: EU bioenergy potential from a resource-efficiency perspective (EEA, 2013)

Key findings, insights and conclusions
Varying the environmental constraints on bioenergy consumption should not significantly affect the potential for total bioenergy supply. However, it is likely to have a strong affect on the mix of bioenergy feedstocks involved in meeting the total supply. This is mainly achieved through optimising on the most efficient bioenergy production and conversion pathways in more constrained scenarios, involving a shift away from first generation bioenergy sources towards perennial crops and relatively more use for generation of heat, electricity and biogas. Different bioenergy pathways vary significantly in terms of GHG emissions and other environmental impacts. Use of agricultural wastes and residues can involve low GHG emissions and wider environmental impacts. Conversely, for biomass produced from energy crops, some feedstocks and conversion pathways can involve increased GHG emissions and detrimental effects on the wider environment. Efficiency and low GHG emissions for bioenergy need to be achieved by considering all the steps in specific process chains and potential interactions between them. Bioenergy produced from harvest residues of forests are assessed favourably in terms of resource efficiency, but uncertainty is expressed concerning GHG emissions payback times.
Points requiring clarification
It is recognised that the resource efficiency and GHG emissions associated with production and consumption of forest bioenergy require further research and clarification, particularly with regard to biogenic carbon emissions due to potential changes in forest carbon stocks.

Table 5.7 Analysis of Biofuels, bioproducts and biorefining perspective: The ‘debt’ is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy (Lamers and Junginger, 2013)

Objectives and Scope
This article aims to review the state of the art in ‘temporal forest carbon modelling’, particularly with regard to the assessment of GHG emissions of forest bioenergy. Comparison is made of studies in the scientific literature, highlighting differences in approaches to methodology, notably concerning the representation of biogenic carbon and forest carbon stock changes. Implications for policies related to forest bioenergy are considered. The scope deals primarily with the EU but, in this context, it is recognised as critically important to understand the potential contributions of imported forest bioenergy. Therefore, the scope also includes North America and, to the limited extent possible, other regions of the world that may be involved in supplying forest bioenergy to the EU. Interactions within the forest and wood processing sectors at international scale are also considered. Non-GHG climate drivers are acknowledged as potentially important but regarded as out of scope. The review of approaches to methodology covers methodological choices (modelling framework), scenario assumptions and model parameterisation. Relationships between systems studied, approaches to calculation to GHG emissions and ultimate results are explored.

Table 5.7 (continued) Analysis of Biofuels, bioproducts and biorefining perspective: The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy (Lamers and Junginger, 2013)

Key findings, insights and conclusions
Many of the findings, insights and conclusions drawn in the article show strong consistency with those arrived at in the JRC technical report (see Section 5.3) and Sections 2, 3 and 4 of this current report. A meta-analysis of GHG emissions payback times reported in the scientific literature for forest bioenergy sources exhibits clear consistency with results presented in the JRC technical report and strong similarities with the interpretation presented in Appendix 4 and Table 5.1 of this current report. These results are considered further in Section 5.5.3. The selection and construction of a reference or baseline scenario is identified as a key influencing factor in determining the GHG emissions payback time of a particular studied scenario for production and use of forest bioenergy. This is highlighted by a meta-analysis of published studies (Table 1 in the article) which identifies the range of assumptions made about baseline scenarios in individual studies. It is considered that such baseline assumptions are inevitably specific to circumstances in different geographical regions and the details of the scenario being modelled (effectively, the goal and research question being studied). The heavy dependence of LCA studies of forest bioenergy on forest sector models, and in particular forest carbon accounting models is noted, recognising that these are not always in agreement with field assessments of GHG dynamics in forest areas. Individual LCA studies are identified as varying in the detail in which they represent carbon flows and GHG emissions associated with harvested wood. The reliance of majority of the LCA studies on presenting results in terms of GHG emissions, rather than translating these into estimates of potential climate warming, is considered to be an important shortcoming in existing research. The importance of linking forest carbon accounting models with economic models representing marketing dynamics under different bioenergy scenarios is emphasised. In particular, it is noted that, "the global forest sector experiences long-term autonomous trends, such as the decade long shift of pulp production away from traditional suppliers in the Northern Hemisphere toward countries in Latin America and South-East Asia". It is suggested that variations between studies are not necessarily shortcomings or substantive methodological conflicts. Rather, these variations reflect the large range of possible scenarios for forest bioenergy use that can be studied (e.g. types of biomass feedstock, tree species, growing conditions, forest management etc.). The importance of comprehensive representation of all processes involved in forest bioenergy production and use is emphasised. It is recognised that results for GHG emissions of forest bioenergy can be very sensitive to detailed assumptions about GHG emissions associated with individual process steps. The possibility that additional supply of forest bioenergy may not displace an equivalent quantity of fossil energy is noted and viewed as requiring representation in future research. LCA studies are identified as tending to employ one or both of two possible scenarios to represent a baseline or reference scenario when calculating GHG emissions, particularly those due to biogenic carbon. The first of these is a 'business as usual' scenario, prior to introduction of changes involving production of additional forest bioenergy. The second most common scenario referred to as a baseline involves forest protection or 'no use'. The potential validity of both baselines is acknowledged but important qualifying remarks are made regarding the 'no use' scenario.

Table 5.7 (continued) Analysis of Biofuels, bioproducts and biorefining perspective: The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy (Lamers and Junginger, 2013)

Key findings, insights and conclusions (continued)
Specifically, the 'no use' scenario is acknowledged as entirely valid in some situations, but its relevance is questioned in some cases, e.g. where existing "intensive even-aged forestry, i.e. plantations" are being studied. It is noted that in reality, conversion of such systems to agriculture or industrial development may be more likely in the absence of demand for wood fibre or bioenergy. Issues concerning potential risks of disturbance are also mentioned but identified as uncertain and a subject requiring further study. A number of factors are identified as representing the main sources of uncertainty in LCA studies of GHG emissions of forest bioenergy. These include soil carbon dynamics, the reliable definition of counterfactuals and the representation of market dynamics/responses in scenarios. It is argued that a coherent approach is required when choosing reference fossil energy systems and three options are suggested, i.e. explicit substitution for a specific fossil energy source, replacement of an average energy mix, and substitution for a specific energy production technology identified as marginal (in that it would be deployed in the absence of availability of the forest bioenergy). A number of policy relevant points are identified : • Policies supporting the use of forest bioenergy to meet targets for renewable energy consumption in 2020 will have effects on the climate beyond this timescale. It is important to decide the priority for forest bioenergy in making short-term and long-term contributions towards reducing GHG emissions. • There are forest bioenergy feedstock options that can provide immediate benefits in terms of reduced GHG emissions when displacing fossil energy sources, including harvesting residues, solid wood industry co-products, salvage logging (in some contexts) and creation of new forest areas. However, it is stressed that some options should not be viewed as a 'silver bullet', noting strong dependence on the effectiveness with which they displace fossil energy sources. It is therefore considered inappropriate to adopt measures aimed simply at including or excluding different types of forest biomass feedstock for use as bioenergy. • It is noted that a significant body of LCA studies of forest bioenergy focus on production scenarios involving utilisation of stemwood or whole trees but, under current conditions, such scenarios are not common. Assessment of policies towards consumption of forest bioenergy sources needs to be set in the context of existing market trends, e.g. the steady downturn in some solid wood product sectors, potential over supply of forest biomass from associated forest areas, and interactions with other industrial sectors, e.g. non-wood construction materials.

Table 5.7 (continued) Analysis of Biofuels, bioproducts and biorefining perspective: The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy (Lamers and Junginger, 2013)

Points requiring clarification
Like other reviews and commentaries, the article starts by considering the current situation regarding accounting for GHG emissions associated with harvested wood and forest bioenergy, particularly those referred to in international commitments and EU regulations. However, most of the discussion in the paper appears to be more concerned with how to correctly assess the potential GHG emissions associated with increased production and use of bioenergy. It is important to clarify that methodologies to account for GHG emissions within international commitments and regulatory frameworks generally need to be designed differently to methodologies for assessing potential GHG emissions associated with future scenarios for forest bioenergy consumption.

Table 5.8 Analysis of GCB Bioenergy invited editorial: Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral (Schulze *et al.*, 2012)

Objectives and Scope
The objective is to assess the potential impacts of a significant increase in global consumption of bioenergy on GHG emissions and the integrity of terrestrial ecosystems. The focus is strongly on carbon stocks in terrestrial vegetation systems, most specifically associated with forests. There is limited consideration of full life cycle assessment of bioenergy consumption. The analysis is restricted to assessing the impacts of potential increases in bioenergy consumption, rather than scenarios involving more general mobilisation of forest resources for co-production of solid wood products and bioenergy.
Key findings, insights and conclusions
The discussion emphasises that a significant increase in harvesting of biomass, particularly forest biomass, for use as bioenergy, will lead to significant increases in GHG emissions. It is also argued that subsidies for forest bioenergy will cause diversion of woody biomass from use for solid wood products, for consumption as bioenergy instead. The view is expressed that there will also be significant negative consequences for biodiversity and other ecosystem services if production of woody biomass from forests is intensified. An important trade-off is emphasised between maximising biomass productivity and maximising carbon stocks of land-based vegetation.

Table 5.8 (continued) Analysis of GCB Bioenergy invited editorial: Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral (Schulze *et al.*, 2012)

Points requiring clarification
It should be clarified that the assessment is from a narrow 'natural science' perspective with principal focus on potential negative impacts on terrestrial vegetation systems. This is emphasised by the statement included in the paper, also given high profile in the abstract, that, "humans would *appropriate* ca. 60% of the global increment of woody biomass if forest biomass were to produce 20% of current global primary energy supply" (emphasis in italics added). The assessment would benefit from more comprehensive treatment, particularly with regard to consideration of LCA studies of forest management and wood production. The paper appears to support the view that a 'no use' scenario should be referred to as a baseline when assessing the contribution of forest carbon stock changes to GHG emissions of forest bioenergy. As discussed in Section 4.10 of this current report, the use of a 'no use' baseline is sometimes, but certainly not always, appropriate, depending on the goal and research question being addressed by an assessment, and the details of the system being studied.

Table 5.9 Analysis of Journal of forestry article: Carbon cycle effects of different strategies of utilisation of forest resources – a review (Trømberg *et al.*, 2011)

Objectives and Scope
This paper sets out to review a number of studies with relevance to Norwegian forestry to assess the global warming impacts of the use of forest biomass to substitute for fossil fuels and fossil fuel intensive products, and the impacts of a number of forest management options. This study specifically addresses forest management and usage of forest resources in Norway. It attempts to assess those factors that will impact the carbon cycle and also the non-GHG effects. It also mentions non-climate impacts such as economic and environmental impacts and attempts to identify in what areas more knowledge is required. The report reviews studies into carbon flows in forestry systems, the impacts of forest management on these flows, and the impacts of product and commodity substitution by forest products.

Table 5.9 (continued) Analysis of Journal of forestry article: Carbon cycle effects of different strategies of utilisation of forest resources – a review (Trømberg *et al.*, 2011)

Key findings, insights and conclusions
Use of forest harvesting residues can give GHG benefits in the short, medium and long term. However increased demand for biomass to replace fossil fuel will give increased GHG emissions in the short to medium term, but benefits in the long term based on current Norwegian forest management practice and increased harvesting. For maximum GHG benefits it is important that wood is used to replace the most GHG intensive commodities. This will influence the timescale on which GHG benefits become positive. It is concluded that it is inappropriate to consider just one country in isolation as increased usage and/or harvesting in one country will impact harvesting levels in other countries and imports/exports. It is also necessary to consider total global climate effects, not just GHG emissions. Consideration of changes in factors such as albedo could have implications on optimum forestry strategy. Although changes in forestry practice can have an impact on carbon sequestration, most of these effects are only felt in the medium to long term with the exception of forest fertilizer application and use of forestry residues and allocation of harvest which can have relatively rapid benefits. It is pointed out that the current age structure of the Norwegian forest means that gross growth will gradually decline and that understanding of the carbon impacts of old forest stands is incomplete.
Points requiring clarification
This is essentially a qualitative, rather than quantitative analysis. Although there are a number of references to numerical results and specific timescales, e.g. for recovery of forest carbon stocks following harvesting, and for different wood products, there is no attempt to combine carbon stocks in the forest with those in timber products. All final discussion and conclusions are therefore of necessity qualitative rather than quantitative. Without including wood products in the analysis of carbon stocks, it is difficult to see how some of the conclusions can be justified. A few individual, more minor points that require clarification: In discussing soil carbon stocks following forest harvesting, results are highlighted which suggest initial reductions in soil carbon. It is acknowledged that the overall effect is uncertain, but there appears to be no comment on particular, longer term results which show soil carbon stocks significantly higher than before harvesting. There are a number of places in the discussion of carbon stock changes and flows where statements are made without it being clear whether they are based on the review of papers or their own modelling or analysis. Table 3 refers to CO_2 savings by substitution of steel (and concrete) by wood products of 250 tonnes CO_2-eq m^{-3} of wood, whereas the text refers to (more realistic) figures of a few hundred kg CO_2-eq m^{-3}.

Points requiring clarification (continued)
Although the use of pulpwood for paper and board manufacture is mentioned at a number of points in the report, owing to the assumed short lifetime of these products there appears to be no attempt to incorporate them into consideration of carbon stocks, and no mention is made of the impact of recycling. This report makes it clear that there are a number of uncertainties which still require clarification and further analysis, including albedo effects associated with different levels of harvesting, the effects of ageing forests on carbon sequestration and the substitution effects of wood products.

5.4.1. Conclusions on other existing reviews and commentaries

In large part, the reviews and commentaries considered in Tables 5.4 to 5.9 present a consistent story and frequently echo points raised in the JRC technical report (see Section 5.3). Some apparent diversity in viewpoints may arise from particular perspectives or scopes taken in individual reviews, e.g. a focus on natural science (see for example Table 5.8). Some useful additional insights may be drawn from the various reviews. Notably, several reviews stress the importance of assessing GHG emissions in the context of socio-economic and techno-economic developments and trends that are already taking place (see for example Table 5.7). The critical link between the goal and research question to be addressed and the detailed methodology to be applied in an LCA study of forest bioenergy is also strongly emphasised (see for example Tables 5.5 and 5.7). The observation that variations between studies are not necessarily shortcomings or substantive methodological conflicts, but reflect the large range of possible scenarios for forest bioenergy use that can be studied (see Table 5.7), is particularly pertinent to any attempt to review and interpret the diverse results presented in the literature. However, this may imply that results of existing studies may be of relatively little value if the goal and research question they address are not relevant to the objectives of a new study.

Particularly noteworthy points commonly expressed in the reviews, including the JRC review report include:

- It is necessary to include biogenic carbon when assessing the GHG emissions due to the consumption of forest bioenergy. This point, although already evident from the discussion in this report, is unanimously expressed by existing reviews. Furthermore, all but one of the reviews comment on the risks of potentially detrimental impacts on forest carbon stocks, if high pressure were to be placed on forest resources.
- The majority of studies observe that an increase in levels of harvesting in forest areas to produce bioenergy will involve a permanent, one-off reduction in forest carbon stocks.
- Three studies also note the possibility of actions being taken in the forest sector in response to increased demand for forest bioenergy that could potentially also sustain

or enhance forest carbon stocks, e.g. regeneration or planting of stands at high tree densities, afforestation. The importance of avoiding iLUC in the case of afforestation is also commented on.

- Two studies stress the importance of assessing the impacts of forest bioenergy on climate comprehensively, i.e. including non-GHG effects on climate such as albedo.

In discussing the methodologies needed to assess the climate effects of changes in consumption of forest bioenergy:

- All of the studies particularly concerned with commenting on methodology state that LCA is the appropriate tool for making such an assessment, but also stress that results are very sensitive to variations in LCA methods.
- The majority of the reviews note that a major source of variation in reported results of LCA studies of forest bioenergy is due to the particular bioenergy feedstocks being assessed in the different studies.
- In terms of sensitivity of results to LCA methodology and assumptions, the reviews identify many factors as important. Assumptions about bioenergy conversion technology, counterfactual land use and counterfactual energy source are particularly prominent. In this context, one review emphasises the distinction between systematic variation and sources of uncertainty (Table 5.5).

The reviews also present a fairly consistent view on the GHG emissions associated with the consumption of different types of bioenergy feedstocks and associated forest management changes:

- The majority emphasise that, typically, additional consumption of forest bioenergy involves increased GHG emissions for an initial period, followed by reduced GHG emissions compared with fossil energy sources. Two studies identify a potential exception in the case where additional harvesting involves co-production of bioenergy alongside material/fire wood products, for which GHG emissions can be reduced very quickly. However, it is also stressed that the outcome is extremely sensitive to the counterfactuals for the material/fibre products. In this context, one study emphasises the importance of ensuring that wood replaces the most GHG-intensive commodities (Table 5.9).
- Those reviews which present their own analysis and/or meta-analyses arrive at conclusions broadly consistent with the JRC review (Tables 5.4 and 5.7).
- The majority of reviews also highlight the extraction of harvest residues as a ‘moderate risk’ case for production of additional forest bioenergy.
- Two studies identify the utilisation of waste wood and/or sawmill co-products as potentially ‘low risk’, particularly in the case of ‘biomass cascading’.
- Two studies emphasise the case of diverting wood feedstock from the manufacture of material/fibre products to use as bioenergy as ‘very high risk’.
- The growth rate of forest areas is highlighted by three reviews as important in determining outcome for GHG emissions of additional harvesting of forest bioenergy, although the details are very context-specific.

In considering all of the above points, potentially very important specific conclusions reported by two reviews should also be highlighted. On the one hand, the review of EEA (2013) concludes that varying the environmental constraints on bioenergy consumption should not significantly affect the potential for total bioenergy supply. However, it is likely to have a strong effect on the mix of bioenergy feedstocks involved in meeting the total supply (see Table 5.7). This suggests that, in principle, consumption of forest bioenergy from 'low risk' sources could be prioritised, without limiting the potential for overall supply of bioenergy. However, on the other hand, Lamers and Junginger (2013, see Table 5.7) warn that it would be inappropriate to adopt measures aimed simply at including or excluding different types of forest biomass feedstock for use as bioenergy, because it would be too simplistic to identify specific types of feedstocks and/or associated forest management systems as a 'silver bullet' (see Table 5.7).

5.5. Case studies of GHG emissions associated with forest bioenergy

The consideration of individual published case studies of GHG emissions associated with forest bioenergy builds on the existing discussions presented in Sections 2 to 4 of this report and on the extensive reviews of case studies already carried out as discussed in Sections 5.3 and 5.4, notably as reported by Marelli *et al.* (2013) and Lamers and Junginger (2013). Against this background, a further exhaustive treatment of relevant literature would be duplicative and unlikely to provide new insights. This current review of case studies therefore focuses on three issues, directly following from the research questions posed in the introduction to this report.

A first step in carrying out the review of individual case studies involved identifying and bringing together an essential collection of contemporary scientific research papers and technical reports on the subject. A total of 31 published studies were identified[19]. It should be noted that some of these papers have already received attention in the discussion of existing reviews and commentaries. In addition, results presented in the review of Ros *et al.* (2013) were included.

A meta-analysis of the case studies was then carried out, consisting of a set of assessments (Appendices 5 to 11). The purpose of the meta-analysis is to review and interpret the methods and results in the various case studies. The emphasis in the meta-analysis is on eliciting information and insights that add to those already arrived at earlier in this report and by previous reviews. To begin with, brief summary descriptions are provided in Appendix 5 for all 31 published case studies (avoiding duplicate entries for papers which are very similar). A detailed meta-analysis of the published case

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[19] Mitchell *et al.* (2009); Walker *et al.* (2010); Werner *et al.* (2010); Cherubini *et al.* (2011ab); Hudiburg *et al.* (2011); Kilpeläinen *et al.* (2011); Lecocq *et al.* (2011); McKechnie *et al.* (2011); Repo *et al.* (2011, 2012); Ter-Mikaelian *et al.* (2011); UN-ECE (2011); Zanchi *et al.* (2011); Böttcher *et al.* (2012); Colnes *et al.* (2012); Galik and Abt (2012); Holtsmark (2012a); Krug *et al.* (2012); Mitchell *et al.* (2012); Nepal *et al.* (2012); Poudel *et al.* (2012); Routa *et al.* (2012); Stewart and Nakamura (2012); Bernier and Paré (2013); Eliasson *et al.* (2013); Fiorese and Guariso (2013); Jonker *et al.* (2013); Kallio *et al.* (2013); Lamers *et al.* (2014); Matthews *et al.* (2014).

studies, against a large set of criteria was also carried out and a summary for the most relevant criteria can be found in Appendix 6.

It is notable that the various case studies use a variety of metrics and functional units for reporting GHG emissions and seemingly adopt every conceivable approach to the presentation of results, in graphical or tabular form. This lack of standardisation significantly frustrates attempts to review and compare the results of the various studies.

5.5.1. Transparency of case studies

An assessment in Appendix 7 is concerned with the specific issue of the transparency of published case studies. This is regarded as an important point that must be considered when working with previously published results and comparing different case studies. Adequate transparency is needed to be able to understand what results for GHG emissions associated with forest bioenergy actually represent, to understand how they were calculated, and to ensure correct interpretation and use. The assessment of transparency is based on seven tests:

1. A broad description is given of calculation methods, and of data, results and parameters used in calculations.
2. Citations are given for all data, results and parameters used in calculations.
3. All data results and parameters used in calculations are presented, with original sources and references cited where appropriate.
4. Citations are given for published statements of methods, models and approaches which set out the general principles adopted in calculations.
5. In addition to Test 4, it is stated that the published statements describe in detail the methods, models and calculation steps used.
6. Aspects of the detailed calculation methods and data, results and parameters used in calculations are described.
7. The calculation methods employed and the data, results and parameters referred to in calculations are fully described, so that it is possible to replicate the calculations and results.

Ideally, all published case studies, indeed all published scientific reports should pass Test 7, since this represents a fundamental principle of the scientific method. However, it is fully accepted that there are significant practical constraints on the description of methods that can be supplied within the framework of a published journal article, particularly for the analysis and modelling of complex systems. The seven transparency tests listed above are thus intended to provide an indication of the extent to which the description of systems and calculations in published case studies approach the ideal.

All studies have been found to adequately present a broad description of calculation methods and of data, results and parameters used in calculations (Test 1). The majority of published studies also *give citations* for all data, results and parameters used in calculations, and for published statements of methods, models and approaches which set out the general principles adopted in calculations (Tests 2 and 4). Often, they also *describe in detail* calculation methods, and data, results and parameters (Test 6). It is perhaps surprising that a small number of published studies actually fail these tests. A minority of studies present *all* data, results and parameters used in calculations, with original sources and references cited where appropriate (Test 3), and state that they refer to published statements that describe in detail the methods, models and calculation steps used. Only two papers fully describe the calculation methods employed and the data, results and parameters referred to in calculations, so that it is possible to replicate the calculations and results. However, this reflects the fact that these papers are actually intended as methodology statements (Cherubini *et al.*, 2011ab), and must be regarded as exceptions that are less relevant to the current exercise.

The efforts of the authors of published case studies towards achieving adequate transparency in methodologies used for assessment of GHG emissions must be applauded. At the same time, it must be acknowledged that published studies generally lack complete transparency. This can sometimes be a barrier to the interpretation and use of the results of studies, for example when attempting to establish the sensitivity of GHG emissions of forest bioenergy in terms of specific feedstocks and associated forest management. It also limits the use of existing literature for informing the development of appropriate and robust methodologies for the assessment of GHG emissions associated with forest bioenergy, e.g. for the purposes of establishing a methodology for policy evaluation with regard to forest bioenergy or accounting of the GHG emissions of forest bioenergy within a regulatory framework.

5.5.2. Methodologies applied in case studies

An assessment in Appendix 8 builds on the meta-analysis presented in Lamers and Junginger (2013), which compares the methodological choices, scenario assumptions and model parameterisations adopted in individual case studies (see Table 1 in Lamers and Junginger, 2013). Most of the criteria referred to in Appendix 8 derive directly from Lamers and Junginger, where they are described and discussed. In addition, Table A8.1 in Appendix 8 lists the time horizons adopted in individual case studies.

The results in Appendix 8 confirm the previous meta-analysis of Lamers and Junginger (2013). There is considerable variation in methodological choices, which practically reflect the scoping of individual analyses and the scenario assumptions. Holtsmark (2012b, 2013b) has demonstrated that detailed variations in calculation methods can be the prime cause of significant differences in results for GHG emissions of forest bioenergy reported by different published studies. As noted previously, these variations do not necessarily imply shortcomings or substantive methodological differences. Rather, these may reflect variations in the goal and research question addressed by specific case studies, as well as the details of the particular bioenergy system being studied. Whilst these variations in methodologies can create problems for comparing or combining the results of different studies, this is something that has to be accepted, so that meta-analyses, as attempted in previous reviews and in this review, must be undertaken with appropriate caution.

Further insights concerning variation in published results of case studies can be drawn from the detailed meta-analysis against criteria undertaken as part of this review (see Appendix 6). Key points are summarised in Table 5.10. These consider details of the particular forest bioenergy systems studied as well as associated calculation methods.

Table 5.10 reveals considerable variation in the forest bioenergy systems being studied and the calculation methods used for assessment. These will cause significant variations in reported results for GHG emissions. Based on the summary assessments in Table 5.10 and Appendix 8, important sources of variations in results can be identified in a tentative descending order of significance:

- Forest bioenergy feedstock and forest management scenario.
- Bioenergy conversion system.
- Counterfactual land use and counterfactual energy source(s).
- LCA approach.
- Spatial scale.

It is notable that the main sources of variation in results for GHG emissions of forest bioenergy seem to be related to variations in the type of forest management, feedstock and conversion system considered in different studies. Assumptions about counterfactual land use and counterfactual energy sources are clearly also very influential, and arguably are also part of the definition of the systems being studied. Important and influential details of calculation methodology include the approach to LCA and the spatial scale with which forest systems are represented. Earlier cautionary observations concerning the sensitivity of results for GHG emissions to detailed calculation methods must be recalled.

Table 5.10 Summary of key points from analysis of published case studies of forest bioenergy against criteria (see Appendix 6)

Criterion	Summary assessment
Geographical location	Roughly half of the case studies consider forestry systems located in Europe whilst the rest consider locations in North America. One case study is theoretical and does not represent a specific geographic location.
Scale (spatial)	The majority of studies adopt a spatial scale of a forest holding or landscape, a region of a country or larger scale. This should be adequate to represent carbon stock dynamics across the population of stands of trees forming forests. However, eight studies use a spatial scale of an individual stand.
Forest bioenergy feedstock	A diverse range of feedstocks is represented in the case studies but the majority consider cases in which all additional harvested forest biomass is used for bioenergy, or there is additional extraction of harvest residues. Small numbers of studies consider other types of feedstock such as raw sawlogs, sawlog co-products and small roundwood. Recycled and waste wood are not represented in the case studies. For a few studies, the type of feedstock considered is not entirely clear.
Bioenergy conversion system	The majority of studies consider power only generation or district heating based on combustion. Six studies consider combined heat and power, only three studies consider small scale heating, and there is just one study of co-firing of biomass with coal for power generation. Quite a large number of studies do not specify a clearly defined conversion system.
Forest management scenario	The majority of the studies are concerned with assessments of additional extraction of biomass on harvesting or additional harvesting in general. However, a great diversity of scenarios are represented to a lesser extent including business as usual harvesting of bioenergy, shortened rotations, conversion of semi-natural forest to plantations, enrichment of growing stock and afforestation. For a few studies, the forest management scenario considered is not entirely clear.
Wood utilisation scenario	Many studies are concerned with the utilisation of 'low value wood' for bioenergy. However, in general, studies consider a diversity of possible wood utilisation scenarios. For example, large-scale scenario assessments may consider complex changes in patterns of wood use across the wood processing sector.
Counterfactual land use	Most studies assume a counterfactual land use of business as usual, whilst a significant number assume 'no harvest'. It should be noted that a 'no harvest' counterfactual land use will be equivalent to business as usual for some case studies. Studies of afforestation assume a 'no forest' counterfactual. Three studies do not represent a counterfactual land use. For one study, the counterfactual land use is not entirely clear.
Counterfactual energy source(s)	Most studies assume a counterfactual energy source of coal. However, a number consider oil or natural gas. Some studies refer to a generic fossil energy displacement factor or (in the case of some large scale assessments) detailed changes in energy use. Six studies do not represent a counterfactual energy source.
LCA approach	The vast majority of studies fail to clearly state the LCA approach and some might strictly be regarded as not LCA studies. However, 22 of the studies can be interpreted as applying a consequential LCA approach. Just four studies apply attributional LCA methods, whilst three should be regarded as employing other methods.

5.5.3. Meta-analysis of reported results of case studies

In Appendix 9, results relating to the GHG emissions associated with the production and consumption of forest bioenergy are collated and listed along with essential information about the type of forest management, production scenario, conversion technology and details of any baseline scenario referred to in an individual case study. The format in Appendix 9 is based on the approach adopted in Tables 1 and 3 of the JRC technical report (Marelli *et al.*, 2013), with certain elaborations, e.g. to accommodate results for GHG emissions expressed in different units. An attempt has also been made to clarify details of forest management, production and baseline scenarios where this may assist with interpretation. Wherever possible, results included in Appendix 9 are expressed as GHG emissions payback times (see Section 5.2.1). This has involved some interpretation and manipulation of results actually presented in some individual case studies.

It is very important to understand that results for GHG emissions payback times reported in Appendix 9 have not always been calculated consistently. Rather, the details of calculation may be context-specific. For examples where harvesting is introduced in forests that were not previously in management for production, the payback time most likely relates to the period required to recoup the loss of forest carbon stocks as a result of the introduction of harvesting. For examples where forests are already in management for production (i.e. this is the business as usual scenario), but changes are made to existing management, the payback time is likely to represent the period required to achieve net GHG emissions reductions, compared to a business as usual reference case.

The results in Appendix 9 display the same wide variation, as seen in Tables 1 and 3 of the original meta-analysis of the JRC technical report (Marelli *et al.*, 2013). Quite a large number of results are available from the various published case studies considered. However, as already noted, these are reported using a range of metrics, functional units and time horizons. For most of the studies, it has been possible to translate the reported results into GHG emissions payback times. Some studies must be eliminated from further assessment at this stage because, for example, results may not be expressed in a suitable form or calculation methods used in the study are inappropriate. This is particularly the case for studies which have applied attributional LCA.

Selected results from Appendix 9 can be further interpreted, as already presented above based on the results covered by the JRC technical report, to look for structure with respect to the types of forest bioenergy system being assessed. The results of this tentative investigation are given in Appendix 10. The assessment is generally limited to consideration of results for bioenergy systems concerned with power or heat, as there are too few values reported for transport fuels. (It should be noted, however, that the results reported for transport fuels derived from forest bioenergy appear unpromising in terms of associated GHG emissions.)

The results in Appendix 10 largely confirm but also expand on the previous analysis based on the results reviewed in the JRC technical report. As with this earlier analysis, the results suggest a classification of forest management and bioenergy production scenarios as typically 'low risk', 'moderate risk', 'high risk' and 'very high risk', as shown in Table 5.11. The analysis in Table 5.11 is consistent with and slightly elaborates on the version already presented in Table 5.3, Section 5.3.2. Table 5.11 also includes a provisional qualitative assessment of the relevance of various forest management and bioenergy production scenarios in contributing towards increased bioenergy consumption in the EU (see Appendix 11 for more information).

Two scenarios in Table 5.11 are very similar, but are assessed differently as 'very high risk' and 'low to moderate risk'. These scenarios represent two extremes of a case involving co-production of bioenergy in combination with wood material/fibre products (otherwise referred to as solid-wood products), through additional thinning and felling in forest areas. The outcomes of such scenarios in terms of risk of adverse effects on GHG emissions are very sensitive to the types of material/fibre products manufactured along with the bioenergy, and on the counterfactual materials that would be consumed in the absence of additional wood supply. Depending on these details, the outcomes can range from increased GHG emissions to very significant decreases in GHG emissions, as illustrated in the study of Matthews *et al.* (2014). It follows that scenarios involving increased harvesting of wood for co-production of bioenergy and material/fibre products can potentially be very important for contributing towards reduced GHG emissions, but could also have adverse effects, depending on the details of particular scenarios.

Although it is possible to identify and distinguish forest bioenergy sources in terms of associated risk of adverse outcomes for GHG emissions, it is accepted that the diversity of possible outcomes presents significant challenges for the development of policies providing incentives for the use of forest bioenergy. It is important to determine the types of bioenergy system, forest bioenergy feedstock and forest management that are more or less likely to occur in response to incentives for increased consumption of forest bioenergy. A full answer to this question is beyond the scope of this report and may be addressed by subsequent tasks in this project. However, a provisional qualitative assessment would appear to suggest that:

- A range of possible energy conversion systems, forest bioenergy feedstocks and associated changes in forest management could potentially be involved in meeting EU targets for consumption of bioenergy in 2020. Some cases are more relevant as activities that may occur in the EU, whilst others are more relevant for other regions likely to be involved in supplying forest bioenergy to the EU (the Russian Federation, Eastern Europe, Canada and the USA).
- This range encompasses some of the cases described and assessed in Table 5.11, and includes cases involving 'low', 'moderate', 'high' and 'very high' risks of adverse outcomes for GHG emissions (as defined in Section 5.2.1 and Table 5.2).
- The risks for certain cases are highly sensitive to details, such as conversion systems, the involvement of particular material/fibre co-products, and counterfactuals.

- The above observations also apply for consumption of bioenergy above the levels of 2020 targets, but potentially involving a wider range of energy conversion systems, forest bioenergy feedstocks and associated changes in forest management. There is increased possibility of cases involving high and very high risks of adverse outcomes for GHG emissions.
- Some cases in Table 5.11 are assessed as 'less relevant' to meeting EU targets for consumption of bioenergy in 2020 (or greater levels of consumption). Some of these cases are potentially important as involving low risk, but are likely to require complementary incentives, e.g. in support of forest practices.

The qualitative assessment presented above seems to be broadly supported by the discussion in Section 2.5 of the JRC review report (Marelli *et al.*, 2013), which suggests that increased biomass supply to meet EU 2020 targets is likely to be achieved through forest management activities involving, "additional fellings, harvest residues, complementary fellings, salvage loggings etc." However, it should also be noted that, following wide consultation with forest sector researchers and experts, the JRC review concluded that, "most of the forest feedstocks used for bioenergy, as of today, are industrial residues, waste wood, residual wood (thinnings, harvest residues, salvage loggings, landscape care wood etc.) for which, in the short to medium term, GHG savings may be achieved". This may be considered in conjunction with the findings of the EUwood study (Mantau *et al.*, 2010) and the EFSOS II study, as already reviewed in Section 2.6. These studies conclude that very high efforts would be required to mobilise wood resources in the EU in order to meet 2020 targets for bioenergy consumption and projected levels of consumption in 2030, *if all the additional wood supply were to be met from within the EU forest sector.* The EFSOS II study also indicated that increased demand for bioenergy in the EU would involve a rise in imported wood and increased prices for wood raw materials, suggesting some pressure on potential for wood supply. It is therefore difficult to clarify whether increased consumption of forest bioenergy in the EU is likely to be achieved through 'low risk' and 'moderate risk' scenarios for forest management and bioenergy production, such as increased extraction of harvest residues, or whether a wider range of scenarios with varying risk may be involved.

Table 5.11 Classification of forest management/bioenergy production scenarios in terms of risk based on Appendix 10

Risk[1]	Forest management/bioenergy production scenario[2]	Comments
Scenarios potentially relevant to 2020 targets for bioenergy consumption		
'Very high' and 'high'	Co-production of solid wood products and bioenergy through additional thinning and/or felling in forest areas with low potential for displacement of GHG emissions associated with solid wood products[3].	Very sensitive to counterfactuals for forest bioenergy and material/fibre products[3].
	Salvage logging and restoration of forests on rotational management for production of bioenergy only.	
	Diversion of harvested wood from solid wood products to bioenergy, leaving harvesting intensity unchanged.	Very sensitive to counterfactuals for forest bioenergy and solid wood products.
'Moderate'	Salvage logging for co-production of solid wood products and bioenergy followed by restoration of forest areas with moderate harvesting intensity, also for co-production.	
	Extraction of harvest residues[4].	Sensitive to harvesting of stumps, and to fossil energy counterfactual.
	Extraction of pre-commercial thinnings.	Sensitive to fossil energy counterfactual.
'Moderate' to 'low'	Co-production of solid wood products and bioenergy through additional thinning and/or felling in forest areas with high potential to displace GHG emissions associated with solid wood products[5].	Very sensitive to counterfactuals for forest bioenergy and material/fibre products[5].

Notes to Table 5.11:

1. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1 and levels of risk are defined in Table 5.2.
2. Scenarios for forest management and bioenergy production have been classified using background shading in the table to indicate their potential relevance to increased consumption of bioenergy in the EU. See Appendix 11 for details.
3. The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals.
4. Moderate risk has been assigned on the assumption that harvesting of stumps would not increase significantly. A high risk would be assigned in the case of stump harvesting.
5. The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals.

Table 5.11 (continued) Classification of forest management/bioenergy production scenarios in terms of risk based on Appendix 10

Risk[6]	Forest management/bioenergy production scenario[7]	Comments
Additional scenarios potentially relevant to bioenergy consumption above 2020 targets		
'Very high' and 'high'	Additional harvesting of stemwood and 'residual wood' for bioenergy only in forest stands for fire prevention.	
	Additional harvesting of stemwood in forest areas already under management for production, for bioenergy only.	Sensitive to fossil energy counterfactual.
Scenarios less relevant to increased bioenergy consumption		
'Very high' and 'high'	Harvesting of forest with high carbon stocks and replacement with rotational forest management for production of bioenergy only.	
	Harvesting forests with high carbon stocks for bioenergy only, followed by restoration of forest areas with low productivity plantation for bioenergy only.	
'Moderate'	Harvesting of forest with high carbon stocks and replacement with high-productivity short rotation plantations for production of bioenergy only.	Sensitive to the assumption that short rotation plantations have much faster growth rates than previous forest
'Moderate' to 'low'	Diversion of harvested wood from solid wood products to bioenergy, combined with reduced harvesting intensity.	Requires reduced harvesting intensity to fully compensate for possible impacts of diverting wood
'Low'	Enrichment of growing stock in existing forest areas as part of enhancement of bioenergy production.	Important to avoid negative impacts on soil carbon stocks, where these could occur
	Creation of new forests for bioenergy only on marginal agricultural land with low initial carbon stock[8].	Sensitive to risks of iLUC.

Notes to Table 5.11:

6. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1 and levels of risk are defined in Table 5.2.
7. Scenarios for forest management and bioenergy production have been classified using background shading in the table to indicate their potential relevance to increased consumption of bioenergy in the EU. See Appendix 11 for details.
8. It must be stressed that these activities have been classified as low risk on the assumption that risks of iLUC would be mitigated, e.g. by restricting the activities to marginal/low productivity agricultural land.

It is very important to stress that the identification of a scenario in Table 5.11 as 'relevant' indicates the possibility that the scenario 'could be' involved in contributing towards increased bioenergy consumption in the EU. A full systematic analytical assessment is required to determine whether scenarios are more or less likely to actually be involved in meeting increased demands for bioenergy, which is a subject for further research.

As already stressed, further research is required to clarify the detailed responses which may occur in the forest and energy sectors, depending on future levels of bioenergy consumption in the EU. This forms the basis for subsequent tasks in this project.

5.6. Conclusions on assessment of literature on GHG emissions of bioenergy

Existing literature on GHG emissions associated with forest bioenergy and their assessment consists of a number of significant review reports and articles, numerous published case studies presenting actual assessments, and a range of published statements on aspects of methodology. This rich literature exhibits considerable diversity and, superficially, may be seen as supporting a quite widely held view that GHG emissions of forest bioenergy are complex and uncertain.

A meta-analysis of case studies has revealed considerable diversity in methods applied for the estimation of GHG emissions associated with forest bioenergy. As noted earlier, variations in methodology do not necessarily imply shortcomings or substantive methodological differences, but can reflect variations in the goal and research question addressed by specific case studies. However, this can present difficulties for the interpretation and application of results from published studies, whilst a general lack of transparency limits the usefulness of previous studies for informing methodological choices and for other purposes.

A conclusion emerges from contemporary literature that the 'closed cycle' of carbon flows suggested by Figure 1.1 (Section 1.2) is accurate in some situations, but strictly only applies in other situations if long timescales are considered, and it is accepted that carbon sequestration in the living vegetation of trees, and the emission of carbon resulting in the burning of wood, do not occur simultaneously. If emissions from the burning of biomass and related sequestration of carbon take place with significant delay involved, the GHG emissions the atmosphere actually 'sees' will resemble those implied by the biogenic carbon content of wood and will be comparable to or greater than GHG emissions of fossil energy sources (Table 1.1, Section 1.2). Consequently, contemporary literature on GHG emissions of forest bioenergy places considerable emphasis on what Lamers and Junginger (2013) have referred to as, 'the temporal imbalance between the release and sequestration of forest carbon'. It is for this reason that a large number of case studies focus on the estimation of GHG emissions payback times associated with different types of forest bioenergy feedstock, the forest management involved in producing the bioenergy, and the energy conversion systems involved in utilising the forest biomass.

The analysis of published case studies presented in Section 5.5.3 indicates that forest bioenergy sources potentially contributing towards levels of consumption in 2030 and beyond may involve widely varying risks of adverse outcomes for GHG emissions. However, it is very important to stress that this variability does not imply that outcomes are uncertain. Rather, these analyses of published research strongly indicate that there is systematic variation with respect to identifiable factors, as illustrated in Table 5.11. This implies that, potentially, increased consumption of forest bioenergy in the EU could make a contribution towards achieving reductions in GHG emissions, if 'low risk' and 'moderate risk' sources are used (see Table 5.11). Conversely, if 'high risk' or 'very high risk' sources are used, increased consumption of forest bioenergy could make a negligible contribution or could seriously frustrate the achievement of GHG emissions reductions.

Whilst the analysis of scientific literature suggests it is possible to identify 'low risk' and 'high risk' sources of forest bioenergy, encouraging the consumption of 'low risk' sources and discouraging 'high risk' sources could be complicated for a number of reasons. For example, as shown in Table 5.11, the same feedstocks can be involved in 'low risk' and 'high risk' scenarios. As a consequence, it is not possible to limit or remove risk of adverse GHG emissions due to consumption of forest bioenergy by favouring particular feedstocks and discouraging the use of others.

The most obvious approach to supporting positive outcomes for GHG emissions when consuming forest bioenergy would involve commitments by large consumers in the EU to demonstrate that genuine and significant GHG emissions reductions are being achieved, when GHG emissions due to biogenic carbon are considered. It is important to clarify that what needs to be demonstrated is that significant reductions in GHG emissions are achieved as the *overall result* of the management of forest areas, to supply bioenergy *and potentially to meet other objectives*. This means, for example, that where additional forest bioenergy is being produced as a co-product along with material/fibre products, it is the overall impact of these activities on GHG emissions that is of interest. The specific contribution of the forest bioenergy to the overall result is of less concern. Similarly, it is more relevant to focus on the overall impacts of forest bioenergy consumption on forest carbon stocks for the complete area of forests involved in supply. This is because the atmosphere will 'see' net changes in forest carbon stocks across the whole forest area due to the harvesting of biomass. Outcomes for individual stands are thus of less relevance for overall impact, although may be important to consider when making operational decisions about forest management at the stand scale.

The possibilities could be considered for complementary approaches (i.e. 'flanking measures') to support positive management of carbon stocks in forests, or more generally in terrestrial vegetation and soil. In principle, if the extraction of additional biomass in forest areas involves reductions in forest carbon stocks, this could be compensated for by enhancement of vegetation and soil carbon stocks in other parts of the landscape, with the aim of achieving an overall positive impact on carbon stocks at the landscape and/or regional scale. (Note that as such, individual stands of trees would be managed to contribute towards the overall result, rather than to achieve fixed outcomes for carbon stocks of individual stands or small forest holdings. At the same time, it would be very important to ensure that any such measures do not lead to unintended adverse impacts on forest or vegetation carbon stocks as a result of iLUC, for example, if the reservation of land areas for conservation and enhancement of carbon stocks were to result in greater importation of biomass or other resources.) Such action would indirectly support a positive contribution by forest bioenergy to achieving reductions in GHG emissions, but would not be explicitly linked to bioenergy consumption. In this context, it should be noted that existing EU Decisions and Regulations on monitoring and accounting for GHG emissions in the Land Use, Land-Use Change and Forestry sector (EU, 2013ab) effectively provide an appropriate accounting framework at national scale within the EU.

A thorough consideration of the policy implications of the preceding discussion could be considered as an area for further research.

5.6.1. Key messages from review of literature

Careful examination of existing scientific literature suggests a consistent story

To sum up the assessment presented in this section, a superficial consideration of the scientific literature on GHG emissions associated with forest bioenergy would most likely arrive at the impression that the outcomes and conclusions of different publications are highly variable and that the overall picture of forest bioenergy is confused and sometimes contradictory. However, on closer examination, it becomes evident that there is a certain level of fundamental agreement or at least consensus on some basic phenomena.

Biogenic carbon needs to be included in *strategic assessments* of GHG emissions arising from consumption of forest bioenergy

Fundamentally, it is undeniable that the status of forest bioenergy as an energy source with either low or high associated GHG emissions is inextricably linked to the property of wood as a reservoir of biogenic carbon and, crucially, how the source of that biogenic carbon, i.e. the carbon stocks in forests, is managed to produce bioenergy.

It is particularly important to allow for biogenic carbon when making *strategic assessments* of GHG emissions due to policies, plans or decisions involving changes in activities that will lead to increased consumption of forest bioenergy. It is important to clarify that what needs to be demonstrated is the achievement of significant reductions in GHG emissions, as the ‘global consequence’ of any changes to the management of forest areas involved in the supply of forest bioenergy, implying the application of consequential LCA for the purposes of assessment.

GHG emissions of forest bioenergy display systematic variation more than uncertainty

An analysis of published case studies indicates that forest bioenergy sources may involve widely varying outcomes in terms of impacts on GHG emissions. However, it is very important to stress that this variability does not imply that outcomes are uncertain. Rather, much of the variation is systematic and can be related to clearly identifiable factors.

Many factors can influence the GHG emissions of forest bioenergy

The variability in reported results for GHG emissions of forest bioenergy reflects many factors related to the forest bioenergy systems being studied and the methodologies applied in calculations. However, a meta-analysis of published studies would appear to indicate that a major reason why different studies have arrived at different results and conclusions is simply down to the fact that they have looked at different types of forest bioenergy source.

Forest bioenergy systems can vary considerably with respect to a number of factors including:

- Geographical location and spatial scale.
- Characteristics of pre-existing growing stock of forest areas.
- Productive potential of forests.
- Types of forest management intervention involved in producing additional forest bioenergy, e.g. any or all of additional thinning, additional felling, increased extraction of harvest residues, enrichment of growing stock for increased production.
- Whether additional harvesting in forest areas is for forest bioenergy as the sole product or as a co-product alongside material/fibre products.
- The types of feedstocks used for forest bioenergy, e.g. any or all of harvest residues, poor quality trees, small roundwood, stemwood, sawlog co-products, recovered waste wood.
- Energy conversion systems, e.g. small-scale heat, district heat or combined heat and power, power-only, co-firing with coal for power generation, and associated efficiencies of conversion systems.
- Counterfactuals for forest bioenergy sources, e.g. fossil energy sources such as natural gas, oil or coal, and for any material/fibre co-products.
- Counterfactuals for forest management, i.e. how forest areas would have been managed if bioenergy consumption had not been increased, and what this would mean for the development of forest carbon stocks.

The impacts on GHG emissions due to the increased consumption of forest bioenergy depend very strongly on variations in these factors. It follows that forest bioenergy cannot be regarded as an energy source with ‘homogenous properties’ such as a characteristic value or range for a GHG emissions factor. Rather, such properties need to be assessed for specific types of forest bioenergy sources.

Results for GHG emissions also depend on the methodology applied for assessment

Results reported by published studies for GHG emissions of forest bioenergy also vary because different studies have used different methodologies, often because studies have different goals and address different research questions. For example, most studies apply methods consistent with consequential LCA, with the aim of assessing the impacts of decisions to increase consumption of certain types of forest bioenergy sources. However, a few studies apply attributional LCA as part of the 'operational' assessment of (typically absolute) GHG emissions of specific forest bioenergy sources. These two types of study will, inevitably, arrive at very different results for the GHG emissions of forest bioenergy sources. Clearly, only the former type of study is relevant to the assessment of the potential impacts of policies encouraging the consumption of forest bioenergy. At the same time, it should be stressed that such variations between studies are not necessarily shortcomings or substantive methodological conflicts. Rather, these variations reflect the large range of possible scenarios for forest bioenergy use that can be studied, and the diversity in the specific objectives and questions addressed by different studies.

Increased harvesting typically involves reductions in forest carbon stocks

There is widespread recognition in the research literature that increasing the levels of wood harvesting in existing forest areas will, in most cases, lead to reductions in the overall levels of forest carbon stocks compared with the carbon stocks in the forests under previous levels of harvesting. Where the additional harvesting is used to supply bioenergy as the sole product, then such forest bioenergy will typically involve high associated GHG emissions (i.e. compared with fossil energy sources) for many decades.

Increased biomass production sometimes involves increased forest carbon stocks

There is also recognition that there exist some specific cases where forest management interventions to increase biomass production may involve increased forest carbon stocks. These include situations in which rotations applied to forest stands are extended as part of optimising biomass productivity, or the growing stock of existing degraded or relatively unproductive forests is enriched to enhance productive potential. It is also possible to create new forest areas with the specific purpose of managing them for wood production, provided that forest carbon stocks on the land are increased as part of the conversion of non-forest land to forest stands, and that there are no associated detrimental indirect land-use changes.

There is reasonable consistency in outcomes for particular forest bioenergy sources

There is reasonable consistency in the research literature on outcomes for particular forest bioenergy sources with regard to impacts on GHG emissions. The meta-analyses of published studies by the JRC review, Lamers and Junginger (2013) and in this report, list a number of specific examples of forest bioenergy sources, which can be categorised in terms of associated impacts on GHG emissions, as summarised in Table 5.11.

GHG emissions of forest bioenergy very sensitive to assumptions

The outcomes of GHG assessment of forest bioenergy are very sensitive to the counterfactual scenario for land use. The development of forest carbon stocks in the counterfactual land-use scenario, which considers the case in which increased consumption of forest bioenergy does not occur, requires assumptions to be made which can be highly uncertain. The projected development of forest carbon stocks under the counterfactual scenario will depend on the assumed forest management, the potential of the growing stock forming forest areas (tree species, age distribution, climatic conditions, soil quality, nutrient regime etc.), and on the likelihood of natural disturbances.

Similarly, outcomes are very sensitive to the counterfactual scenario for energy systems, which also involve assumptions which may be very uncertain, e.g. because of unforeseen market-mediated effects or future policy developments.

Uncertainties in counterfactual scenarios are inherent due to the fact that the counterfactual scenario is, by definition, a path that characteristically is not followed. It is thus never possible to verify what would have actually happened. Long time horizons related to forest carbon cycles and lifetimes of energy systems increase the inherent uncertainty.

GHG emissions of forest bioenergy sources vary over time

The GHG emissions due to the use of forest bioenergy generally vary over time. As a consequence, different results are obtained for GHG emissions when calculated over different periods (or 'time horizons'), e.g. 1 year, 10 years or 100 years. This complicates the characterisation of forest bioenergy sources, particularly with regard to their potential to contribute to reductions in GHG emissions. There are many examples involving an initial period of increased GHG emissions, compared to the alternative of using fossil energy sources, followed eventually by reductions in GHG emissions. The initial period of increased GHG emissions can vary from less than one year to hundreds of years, depending on the type of forest bioenergy.

There is no obvious scientific basis for selecting a standard time horizon – essentially this is a politically-related decision. The choice of time horizon is thus a critical issue in the assessment of GHG emissions associated with the use of forest bioenergy.

Forest bioenergy sources can be assessed in terms of risk

It is possible to categorise different forest bioenergy sources according to their suitability for achieving overall GHG emissions reductions over a time horizon up to a specified target year. In this report, a target year of 2050 was identified as a policy-relevant time horizon (see Section 5.2.1), and forest bioenergy sources were characterised as 'low risk', 'moderate risk', 'high risk' or 'very high risk', according to the likelihood of adverse impacts on GHG emissions reductions over the period to 2050 (see Table 5.11, Section 5.5.3).

Forest bioenergy sources likely to contribute to levels of consumption in 2030 vary in risk

A provisional qualitative assessment was made of the likelihood of particular forest bioenergy sources being involved in meeting levels of consumption in 2030. These various forest bioenergy sources varied from 'low risk' to 'very high risk', according to the likelihood of adverse impacts on GHG emissions reductions over the period to 2050.

This implies that, potentially, increased consumption of forest bioenergy in the EU could make a significant contribution towards achieving reductions in GHG emissions, if 'low risk' and 'moderate risk' sources are used. Conversely, if 'high risk' or 'very high risk' sources are used, increased consumption of forest bioenergy could make a negligible contribution or could seriously frustrate the achievement of GHG emissions reductions.

As part of this qualitative assessment, it is difficult to clarify whether increased consumption of forest bioenergy in the EU is likely to be achieved through 'low risk' and 'moderate risk' scenarios for forest management and bioenergy production, such as increased extraction of harvest residues, or whether a wider range of scenarios with varying risk may be involved. A full systematic analytical assessment is required to determine whether scenarios are more or less likely to actually be involved in meeting increased demands for bioenergy, which is a subject for further research.

Low/high-risk cannot be determined simply in terms of feedstocks

The analysis of scientific literature suggests it is possible to identify 'low risk' and 'high risk' sources of forest bioenergy. However, the same feedstocks can be involved in 'low risk' and 'high risk' scenarios. As a consequence, it is not possible to limit or remove risk of adverse GHG emissions due to consumption of forest bioenergy by favouring particular feedstocks and discouraging the use of others.

In this context, it is also important to recognise that, as part of sustainable forest management and wood utilisation (Sections 2.3 and 2.5):

- Different types and sizes of trees and quantities of wood are harvested at different points in the cycle of forest management. Trees harvested at different ages (and hence of particular dimensions and physical characteristics) will be suitable for different applications and end uses.

- At any one time across a whole forest, a broad mix of trees will be harvested which will be variously suitable for a range of end uses, even though particular types of trees may be harvested from individual stands for specific uses, depending on their stage of development. Collectively, the broad mix of trees harvested from a forest meets a range of demands.

- The wood processing sector is complex, with outputs from the forest providing feedstocks for the manufacture of structural sawn timber, plywood, pallets and fence posts, particleboard and fibreboard, paper and other products including bioenergy.

- The complexity of the wood processing sector can present challenges when attempting to track flows of wood from the forest through to ultimate end use.

For these reasons, there are likely to be very serious obstacles to regulating the consumption of forest bioenergy based on individual consignments of forest bioenergy or based on specific types of forest bioenergy feedstock.

Significant initiatives involving increased consumption of forest bioenergy could be subjected to strategic assessment for impacts on GHG emissions

One possible step towards managing risk associated with increased consumption of forest bioenergy could involve commitments by proponents of significant new forest bioenergy projects in the EU to demonstrate that genuine and significant GHG emissions reductions should be achieved, when GHG emissions due to biogenic carbon are considered. This would require *strategic assessment*, as already identified earlier in this discussion as appropriate for assessment of GHG emissions due to policies, plans or decisions involving changes in activities that will lead to increased consumption of forest bioenergy.

It must be stressed that such assessment of new activities involving consumption of forest bioenergy would be undertaken before a decision is taken to proceed with the activities. Such an approach is not suggested for ongoing monitoring of GHG emissions, for example at bioenergy installations to demonstrate compliance with regulations, such as targets for net GHG emissions savings. Further research is needed to assess the implications of the findings of this report for the development of robust methodologies for monitoring of GHG emissions for such regulatory purposes.

Increased use of forest bioenergy might be integrated with wider measures to support forest carbon stock management

The possibilities could be considered for complementary approaches (i.e. ‘flanking measures’) to support positive management of carbon stocks in forests, or more generally in terrestrial vegetation and soil. In principle, if the extraction of additional biomass in forest areas involves reductions in forest carbon stocks, this could be compensated for by enhancement of vegetation and soil carbon stocks in other parts of the landscape, with the aim of achieving an overall positive impact on carbon stocks at the landscape and/or regional scale. (Note that as such, individual stands of trees would be managed to contribute towards the overall result, rather than to achieve fixed outcomes for carbon stocks of individual stands or small forest holdings. At the same time, it would be very important to ensure that any such measures do not lead to unintended adverse impacts on forest or vegetation carbon stocks as a result of iLUC, for example, if the reservation of land areas for conservation and enhancement of carbon stocks were to result in greater importation of biomass or other resources.) Such action would indirectly support a positive contribution by forest bioenergy to achieving reductions in GHG emissions but would not be explicitly linked to bioenergy consumption. In this context, it should be noted that existing EU Decisions and Regulations on monitoring and accounting for GHG emissions in the Land Use, Land-Use Change and

Forestry sector (EU, 2013ab) effectively provide an appropriate accounting framework at national scale within the EU.

The suitability of metrics for assessing GHG emissions depends on the question

Metrics used for assessing the potential of forest bioenergy need to be relevant to the goal, scope and policy or research question being addressed. For example, if there is interest in achieving a significant level of GHG emissions reductions, say 50% to 95%, by a target year such as 2020 or 2050, then results expressed as GHG emissions payback times may be useful for initially sifting out high risk scenarios for forest bioenergy consumption, but are not appropriate for assessing whether target levels of emissions reductions are likely to be met. In this context, a metric such as cumulative reduction in GHG emissions is more appropriate. Furthermore, if there is interest in understanding the effects of various scenarios for forest bioenergy consumption on cumulative radiative (climate) forcing, then a metric should be used which directly expresses such effects.

References

Adams, P., Bows, A., Gilbert, P., Hammond, J., Howard, D., Lee, R., McNamara, N., Thornley, P., Whittaker, C. and Whitaker, J. (2013) *Understanding greenhouse gas balances of bioenergy systems*. SUPERGEN Bionergy Hub Report. University of Manchester: Manchester, UK.

Al-Riffai, P., Dimaranan, B. and Laborde, D. (2010) *Global Trade and Environmental Impact Study of the EU Biofuels Mandate*. Final Report for the Directorate General for Trade of the European Commission. International Food Policy Research Institute. (See http://trade.ec.europa.eu/doclib/docs/2010/march/tradoc_145954.pdf.)

Allen, M.R., Frame, D.J., Huntingford, C., Jones, C.D., Lowe, J.A., Meinshausen, M. and Meinshausen, N. (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458**, 1163-1166.

Amiro, B.D., Orchansky, A.L., Barr, A.G., Black, T.A, Chambers, S.D., Chapin-III, F.S., Goulden, M.L., Litvak, M., Liu, H.P., McCaughey, J.H., McMillan, A. and Randerson, J.T. (2006) The effect of post-fire stand age on the boreal forest energy balance. *Agricultural and Forest Meteorology*, **140**, 41–50.

Anderson, R.G., Canadell, J.G., Randerson, J.T., Jackson, R.B., Hungate, B.A., Baldocchi, D.D., Ban-Weiss, G.A., Bonan, G.B., K. Caldeira, K., Cao, L., Diffenbaugh, N.S., Gurney, K.R., Kueppers, L.M., Law, B.E., Luyssaert, S. and O'Halloran, T. L. (2010) Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment*, **9**, 174-182.

Aquino Ximenes, F., Goeroge, B.H., Cowie, A., Williams, J. and Kelly, G. (2012) Greenhouse gas balance of native forests in New South Wales, Australia. *Forests*, **3**, 653-683.

Bala, G., Caldeira, K., Wickett, M., Phillips, T.J., Lobell, D.B., Delire, C. and Mirin, A. (2007) Combined climate and carbon-cycle effects of large-scale deforestation. *PNAS*, **104**, 6550–6555.

Bernier, P. and Paré, D. (2013) Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. *GCB Bioenergy*, **5**, 67-72.

Betts, R.A. (2000) Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature*, **408**, 187–190.

Beurskens, L.W.M., Hekkenberg, M. and Vethman, P. (2011). *Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States*. Covering all 27 EU Member States with updates for 20 Member States. ECN report ECN-E--10-069. Energy Research Centre of the Netherlands: Petten, NL. (See http://www.ecn.nl/docs/library/report/2010/e10069.pdf.)

Bird, D.N., Pena, N., Schwaiger, H. and Zanchi, G. (2010) *Review of existing methods for carbon accounting*. Occasional paper 54. CIFOR: Indonesia.

Bird, D.N., Pena, N., Frieden, D. and Zanchi, G. (2012) Zero, one or in between: evaluation of alternative national and entity-level accounting for bioenergy. *GCB Bioenergy*, **4**, 576-587.

Bonan, G.B. and Pollard, D. (1992) Effects of boreal forest vegetation on global climate. *Nature*, **359**, 716–718.

Bonan, G.B. (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, **320**, 1444–1449.

Böttcher, H., Verkerk, P.J., Gusti, M., HavlÍk, P. and Grassi, G. (2011) Projection of the future EU forest CO_2 sink as affected by recent bioenergy policies using two advanced forest management models. *GCB Bioenergy*, **4**, 773-783.

Boustead, I. and Hancock, G.F. (1979) *Handbook of industrial energy analysis*. Ellis Horwood: Chichester, UK.

Brandão, M., Levasseur, A., Kirschbaum, M.U.F., Weidema, B.P., Cowie, A.L., Jørgensen, S.V., Hauschild, M.Z., Pennington, D.W. and Chomkhamsri, K. (2013) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *International Journal of Life Cycle Assessment*, **18**, 230-240.

Brander, M., Tipper, R., Hutchison, C. and Davis, G. (2009) *Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels*. Technical Paper TP-090403-A. Ecometrica Press. (See http://ecometrica.com/white-papers/consequential-and-attributional-approaches-to-lca-a-guide-to-policy-makers-with-specific-reference-to-greenhouse-gas-lca-of-biofuels/.)

Bright, R., Strømman, A. and Peters, G. (2011) Radiative forcing impacts of boreal forest biofuels: a scenario study for Norway in light of albedo. *Environmental Science and Technology*, **45**, 7570-7580.

Bright, R., Cherubini, F., Astrup, R., Bird, N., Cowie, A., Ducey, M.J., Marland, G., Pingoud, K., Savolainen, I. and Strømman, A. (2012) A comment to "Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral": Important insights beyond greenhouse gas accounting. *GCB Bioenergy*, **4**, 617-619.

Bringezu, S., Fischer-Kowalski, M., Klein, R. and Palm, V. (1997). Regional and National Material Flow Accounting: From Paradigm to Practice of Sustainability. Proceedings of the ConAccount Workshop, 21-23 January. Leiden, Netherlands. (See http://conaccount.net/pdf/Part%20I.pdf.)

Chapman, P. (1975) *Fuels paradise: energy options for Britain*. Penguin books: Harmondsworth, UK.

Chen X. and Khanna M. (2012) Food vs. fuel: the effect of biofuel policies. *American Journal of Agronomical Economics*, **95**, 289-295

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B. and Woess-Gallasch, S. (2009) Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. *Resources, Conservation and Recycling*, **53**, 439-447.

Cherubini, F. (2010) GHG balances of bioenergy systems – overview of key steps in the production chain and methodological concerns. *Renewable Energy*, **35**, 1565-1573.

Cherubini, F., Peters, G.P., Berntsen, Strømman, A.H. and Hertwich, E. (2011a) CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy*, **3**, 413-426.

Cherubini, F., Strømman, A.H. and E. Hertwich, E. (2011b) Effects of boreal forest management practices on the climate impact of CO_2 emissions from bioenergy. *Ecological Modelling*, **223**, 59-66.

Cherubini, F., Guest, G., Strømman, A.H. (2012) Application of probability distributions to the modeling of biogenic CO_2 fluxes in life cycle assessment. *GCB Bioenergy*, **4**, 784–798.

Cherubini, F., Guest, G. and Strømman, A.H. (2013) Bioenergy from forestry and changes in atmospheric CO_2: reconciling single stand and landscape level approaches. *Journal of Environmental Management*, **129**, 292-301.

Christie, J.M. and Lines, R. (1979) A comparison of forest productivity in Britain and Europe in relation to climatic factors. *Forest Ecology and Management*. **2**, 75-102.

Claussen, M., Brovkin, V. and Ganopolski, A. (2001) Biogeophysical versus biogeochemical feedbacks of large-scale land cover change. *Geophysical Research Letters*, **28**, 1011–1014.

Cocchi M., Nikolaisen L., Junginger, M., Goh, C.S., Heinimö, J., Bradley, D., Hess, R., Jacobson, J., Ovard, L.P., Thrän, D., Hennig, C., Deutmeyer, M., Schouwenberg, P.P. and Marchal, D. (2011) *Global wood pellet industry market and trade study*. IEA Bioenergy Task 40. (See http://www.bioenergytrade.org/downloads/t40-global-wood-pellet-market-study_final.pdf.)

Colnes, A., Doshi, K., Emick, H., Evans, A., Perschel, R., Robards, T., Saah, D. and Sherman, A. (2012). Biomass supply and carbon accounting for southeastern forests. Biomass Energy Resource Center (BERC), Forest Guild, Spatial Informatics Group: Santa Fe, USA (See www.forestguild.org/publications/research/2012/FG_Biomass_Guidelines_SE.pdf.)

Curran, M.A., Mann, M. and Norris, G. (2005) The international workshop on electricity data for life cycle inventories. *Journal of Cleaner Production*, **13**, 853–862.

Delucchi. M.A. (2011) *Beyond lifecycle analysis: developing a better tool for simulating policy impacts*. In: Ogden, J. and Anderson, L. (eds.) Sustainable Transportation Energy Pathways. Institute of Transportation Studies: University of California, Davis, USA.

Delucchi, M.A. (2013) *Estimating the climate impact of transportation fuels: moving beyond conventional lifecycle analysis toward integrated modeling systems scenario analysis*. Article in preparation.

Dehue, B. (2013) Implications of a 'carbon debt' on bioenergy's potential to mitigate climate change. *Biofuels, Bioproducts and Biorefining*, **7**, 228-234.

den Hond, F. (2000) Industrial ecology: A review. *Regional Environmental Change*, **1**, 60-69.

Drabik D. and de Gorter, H. (2011) Biofuel policies and carbon leakage. *AgBioForum*, **14**, 104-110.

Druckman A., Chitnis M., Sorrell S. and Jackson T. (2011) Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy*, **39**, 3572-3581.

EEA (2011) *Opinion of the EEA Scientific Committee on greenhouse gas accounting in relation to bioenergy*. (See http://www.eea.europa.eu/about-us/governance/scientific-committee/sc-opinions/opinions-on-scientific-issues/sc-opinion-on-greenhouse-gas/view.)

EEA (2013) EU bioenergy potential from a resource efficiency perspective. EEA Report 6/2013. European Environment Agency, Publications of the European Union: Luxembourg.

Eliasson, P., Svensson, M., Olsson, M. and Ågren, G.I. (2013) Forest carbon balances at the landscape scale investigated with the Q model and the CoupModel - responses to intensified harvests. *Forest Ecology and Management*, **290**, 67-78.

EU (2013a) Decison No 529/2013/EU of the European Parliament and of the Council on accounting rules on greenhouse gas emissions and removals resulting from activities relating to land use, land-use change and forestry and on information concerning actions relating to those activities. (See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:165:0080:0097:EN:PDF.)

EU (2013b) Regulation (EU) No 525/2013 of the European Parliament and of the Council of 21 May 2013 on a mechanism for monitoring and reporting greenhouse gas emissions and for reporting other information at national and Union level relevant to climate change. (See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:165:0013:0040:EN:PDF.)

Evans, J. and Turnbull, J. (2004). *Plantation Forestry in the Tropics*. Third edition. Oxford University Press: Oxford, UK.

FAO (2010) *Global Forest Resources Assessment 2010: Main report*. FAO Forestry paper 163. Food and Agriculture Organization of the United Nations: Rome. (Report and data sets can be found at http://www.fao.org/forestry/fra/fra2010/en.)

Fargione, J., Hill, J., Tilman, D., Polasky, S. and Hawthorne, P. (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 1235–1238.

FICGB (1998) *The Forest Industry Handbook 1998: a reference for the forestry industry*. Forest Industry Council of Great Britain: Stirling, UK.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guin_Ee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S. (2009) Recent developments in life cycle assessment. *Journal of Environmental Management*, **91**, 1-21.

Fiorese, G. and Guariso, G. (2013) Modeling the role of forests in a regional carbon mitigation plan. *Renewable Energy*, **52**, 175–182.

Forestry Commission (2011) *Forestry Statistics 2011: A compendium of statistics about woodland, forestry and primary wood processing in the United Kingdom*. Forestry Commission: Edinburgh, UK. (See information at www.forestry.gov.uk/forestry/infd-7aqdgc.)

Forestry Commission (2012) *Forestry Statistics 2012: A compendium of statistics about woodland, forestry and primary wood processing in the United Kingdom*. Forestry Commission: Edinburgh, UK. (See information at www.forestry.gov.uk/forestry/infd-7aqdgc.)

Forestry Commission (2013) *Forestry Statistics 2013: A compendium of statistics about woodland, forestry and primary wood processing in the United Kingdom*. Forestry Commission: Edinburgh, UK. (See information at www.forestry.gov.uk/forestry/infd-7aqdgc.)

Forsström, J., Pingoud, K., Pohjola, J., Vilén, T., Valsta, L. and Verkerk, H. (2012) *Wood-based biodiesel in Finland. Market-mediated impacts on emissions and costs*. VTT Technology Report 7. VTT Technical Research Centre of Finland: Espoo, Helsinki, Finland. (See http://www.vtt.fi/inf/pdf/technology/2012/T7.pdf.)

Galik, C.S. and Abt, R.C. (2012) The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass. *Biomass and Bioenergy*, **44**, 1-7.

Greening L.A., Greene D.L. and Difiglio C. (2000) Energy efficiency and consumption – the rebound effect – a survey. *Energy Policy*, **28**, 389-401.

Guest, G., Cherubini, F. and Strømman, A.H. (2012a) Global warming potential of carbon dioxide emissions from biomass stored in the anthroposphere and used for bioenergy at end of life. *Journal of Industrial Ecology*, **17**, 20-30.

Guest, G., Cherubini, F. and Strømman, A.H. (2012b) The role of forest residues in the accounting for the global warming potential of bioenergy. *GCB Bioenergy*, **5**, 459–466.

Guest, G., Cherubini, F. and Strømman, A.H. (2012c) Climate impact potential of utilizing forest residues for bioenergy in Norway. *Mitigation and Adaptation Strategies for Global Change*, **18**, 1089-1108.

Gustavsson, L. and Sathre, R. (2006) Variability in energy and carbon dioxide balances of wood and concrete building materials. *Building and Environment*, **41**, 940-851.

Gustavsson, L., Pingoud, K. and Sathre, R. (2006) Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings. *Mitigation and Adaptation Strategies for Global Change*, **11**, 667-691.

Haberl, H., Schulze, E.-D., Körner, C., Law, B.E., Holtsmark, B. and Luyssaert, S. (2013) Response: complexities of sustainable forest use, *GCB Bioenergy*, **5**, 1-2.

Harmon, M.E. and Marks, B. (2002) Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model. *Canadian Journal of Forest Research*, **32**, 863-877.

Helin, T., Sokka, L., Soimakallio, S., Pingoud, K., and Pajula, T. (2013) Approaches for inclusion of forest carbon cycle in life cycle assessment - a review. *GCB Bioenergy*, **5**, 475-486.

Henderson-Sellers, A. and Wilson, M.F. (1983) Albedo observations of the Earth's surface for climate research. *Philosophical Transactions of the Royal Society of London*, **309A/1508**, 285-294.

HMRC (2012) Statistics on woodfuel trade in the UK collected and reported by UK HM Revenue and Customs, accessed through the UKTradeInfo website (www.uktradeinfo.com).

Hochman G., Rajagopal D. and Zilberman, D. (2010) The effect of biofuels on crude oil markets. *AgBioForum*, **13**, 112-118.

Hogan, G.P. (2013) *UK trade in woodfuel – an overview*. Forest Research Report to Forestry Commission Plant Health. Forestry Commission: Edinburgh. (See www.forestry.gov.uk/pdf/WoodfuelTradeReport.pdf/$FILE/WoodfuelTradeReport.pdf.)

Holtsmark, B. (2012a) Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, **112**, 415-428.

Holtsmark, B. (2012b) The outcome is in the assumptions: analyzing the effects on atmospheric CO_2 levels of increased use of bioenergy from forest biomass. *GCB Bioenergy*, 5, 467-473.

Holtsmark, B. (2013a) Boreal forest management and its effect on atmospheric CO_2. *Ecological Modelling*, **248**, 130-134.

Holtsmark, B. (2013b) Calculating the global warming potential of CO_2 emissions from wood fuels. *GCB Bioenergy* (in press, early view published online September 2013).

Hudiberg, T.W., Law, B.E., Wirth, C. and Luyssaert, S. (2011) Regional carbon dioxide implications of forest bioenergy. *Nature Climate Change*, **1**, 219-423.

IPCC (2011) *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S. and von Stechow, C. (eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, Y., Xia, Y., Bex, V., and Midgely, P.M (eds.)]. Cambridge University Press: Cambridge, UK and New York, USA. (See www.ipcc.ch/report/ar5/wg1.)

ISO 2006:14040. *Environmental management – Life cycle assessment – Principles and framework*. International Organization for Standardization (ISO), 2006. International Standards organisation: Geneva, Switzerland.

ISO 2006:14044. *Environmental management – Life cycle assessment – Requirements and guidelines*. International Organization for Standardization (ISO), 2006. International Standards organisation: Geneva, Switzerland.

Jackson, R.B., Randerson, J.T., Canadell, J.G., Anderson, R.G., Avissar, R., Baldocchi, D.D., Bonan, G.B., Caldeira, K., Diffenbaugh, N.S., Field, C.B., Hungate, B.A., Jobbágy, E.G., Kueppers, L.M., Nosetto, M.D. and Pataki, D.E. (2008) Protecting climate with forests. *Environmental Research Letters*, **3**, 044006.

Johnson, E. and Tschudi, D. (2012) Baseline effects on carbon footprints of biofuels: the case of wood. *Environmental Impact Assessment Review*, **37**, 12-17.

Jonker, J.G.G., Junginger, H.M. and Faaij, A. (2013) Carbon payback period and carbon offset parity point of wood pellet production in the Southeastern USA. *GCB Bioenergy* (in press, early view published online 11 April 2013).

JRC (2010) *International Reference Life Cycle Data System (ILCD) Handbook*. Joint Research Centre - Institute for Environment and Sustainability. JRC-IES: Ispra. Italy.

Kaipainen, T., Liski, J., Pussinen, A. and Karjalainen, T. (2004) Managing carbon sinks by changing rotation length in European forests. *Environmental Science and Policy*, **7**, 205-219.

Kallio, A.M.I. and Salminen, O. (2012) Impacts of the increased production of wood based bioenergy on the carbon balance projections for Finland. 20th Biomass conference and exhibition proceedings: presentation 5BO.9.4.

Kallio, A.M.I., Salminen, O. and Sievänen, R. (2013) Sequester or substitute — consequences of increased production of wood based energy on the carbon balance in Finland. *Journal of Forest Economics*, **19**, 402-415.

Kendall, A., Chang, B. and Sharpe, B. (2009) Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. *Environmental Science and Technology*, **43**, 7142–7147.

Kilpeläinen, A., Alam, A., Strandman, H. and Kellomäki, S. (2011) Life cycle assessment tool for estimating net CO_2 exchange of forest production. *GCB Bioenergy*, **3**, 461-471.

Kim, S. and Dale, B.E. (2011) Indirect land use change for biofuels: testing predictions and improving analytical methodologies. *Biomass and Bioenergy*, **35**, 3235-4240.

Kirkinen J, Palosuo T, Holmgren K and Savolainen I (2008) Impact due to the use of combustible fuels: life cycle viewpoint and relative radiative forcing commitment. *Environmental Management*, **42**, 458–469.

Kirkinen, J., Soimakallio, S., Mäkinen, T., Savolainen, I. (2010). Greenhouse impact assessment of peat-based Fischer-Tropsch diesel life-cycle. *Energy Policy*, **38**, 301–311.

Koellner, T., de Baan, L., Beck,T., Brandão, M., Civit, B., Margni, M., Milà i Canals, L., Saad,R., de Souza, D.M. and Müller-Wenk, R. (2013) UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. *International Journal of Life Cycle Assessment*, **18**, 1188-1202.

Köster, K., Püttsepp, Ü. and Pumpanen, J. (2011) Comparison of soil CO_2 flux between uncleared and cleared windthrow areas in Estonia and Latvia. *Forest Ecology and Management*, **262**, 65–70.

Krug, J., Koehl, M. and Kownatzki, D. (2012) Revaluing unmanaged forests for climate change mitigation. *Carbon Balance and Management*, **7**(11), 1-8.

Kujanpää, M., Eggers, J., Verkerk, H., Helin, T., Lindner, M. and Wessman, H. (2010) Carbon balance of forest residue collection and combustion in Southern-Finland. Proceedings of the 18th European Biomass Conference and Exhibition, Lyon, 1575-1579.

Kulmala, M., Suni, T., Lehtinen, K.E.J., Dal Maso, M., Boy, M., Reissell, A., Rannik, Ü., Aalto, P., Keronen, P., Hakola, H. Bäck, J., Hoffmann, T. Vesala, T. and Hari, P. (2004) A new feedback mechanism linking forests, aerosols, and climate. *Atmospheric Chemistry and Physics*, **4**, 557-562.

Lamers, P. and Junginer, M. (2013) The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels, Bioproducts, and Biorefining*, **7**, 373-385.

Lamers, P., Junginger, M., Dymond, C.C. and Faaij, A. (2014) Damaged forests provide an opportunity to mitigate climate change. *GCB Bioenergy*, 6, 44-60.

Lecocq, F., Caurla, S., Delacote, P., Barkaoui, A. and Sauquet, A. (2011) Paying for forest carbon or stimulating fuelwood demand? Insights from the French Forest Sector Model. *Journal of Forest Economics*, **17**, 157–168.

LIIB (2012) *Low Indirect Impact Biofuel methodology – version zero.* Ecophys, EPFL and WWF International. (See http://www.ecofys.com/files/files/12-09-03-liib-methodology-version-0-july-2012.pdf.)

Lindeijer, E., Müller-Wenk, R. and Steen, B. (eds.) (2002) Impact assessment of resources and land use. In: Udo de Haes, H.A., Finnveden, G., Goedkoop, M., Hauschild, M., Hertwich, E.G., Hofstetter, P., Jolliet, O., Klöpffer, W., Krewitt, W., Lindeijer, E.W., Müller-Wenk, R., Olsen, S.I., Pennington, D.W., Potting, J. and Steen, B (eds) Life cycle impact assessment: striving towards best practice. SETAC: Pensacola, USA, 11–64.

Lindroth, A., Lagergren, F., Grelle, A., Klemedtsson, L., Langvall, O., Weslien, P. And Tuulik, J. (2009) Storms can cause Europe-wide reduction in forest carbon sink. *Global Change Biology*, **15**, 346-355.

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

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

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

Mantau, U., Saal, U., Prins, K., Steierer, F., Lindner, M., Verkerk, H., Eggers, J., Leek, N., Oldenburger, J., Asikainen, A. and Anttila, P. (2010) *EUwood - Real potential for changes in growth and use of EU forests.* Final report. University of Hamburg: Hamburg, Germany.

Marelli, L. (ed.), Agostini, A., Giuntoli, J. and Boulamanti, A. (2013) *Carbon accounting of forest bioenergy: conclusions and recommendations from a critical literature review*. JRC Technical Report JRC70633 (EUR 25354 EN). Joint Research Centre: Ispra, Italy.

Marland, G. and Marland, S. (1992) Should We Store Carbon in Trees? *Water, Air, and Soil Pollution*, **64**, 181-195.

Marland, G., and Schlamadinger, B. (1997) Forests for Carbon Sequestration or Fossil Fuel Substitution? A Sensitivity Analysis. *Biomass and Bioenergy*, **13**, 389-397.

Matthews, G.A.R. (1993) *The carbon content of trees*. Forestry Commission Technical Paper 4. Forestry Commission: Edinburgh.

Matthews, R.W., Robinson, R.L., Abbott, S.R. and Fearis, N. (1994). *Modelling of carbon and energy budgets of wood fuel coppice systems*. Contract report ETSU B/W5/00337/REP. ETSU: Harwell, UK.

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

Matthews, R.W., Robertson, K.A., Marland, G. and Marland, E. (2007) *Carbon in wood products and product substitution*. In: Freer-Smith, P.H., Broadmeadow, M.S.J. and Lynch, J.M. (eds.). Forestry and Climate Change. CAB International: Wallingford, UK, 91-104.

Matthews, R.W., Mortimer, N.D., Mackie, E.D., Hatto, C., Evans, A., Mwabonje, O. Randle, T.J., Rolls, W., Sayce. M. and Tubby, I. (2014) *Carbon impacts of using biomass in bioenergy and other sectors: forests*. Revised and updated final report parts a and b for UK Department of Energy and Climate Change project TRN 242/08/2011. DECC: London, UK.

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

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J. and Allen, M.R. (2009) Greenhouse gas emissions targets for limiting atmospheric warming to 2 °C. *Nature*, **458**, 1158-1163.

Michelsen, O., Cherubini, F. and Strømman, A.H. (2011) Impact assessment of biodiversity and carbon pools from land use and land use changes in life cycle assessment, exemplified with forestry operations in Norway. *Journal of industrial ecology*, **16**, 231–242.

Milà i Canals, L., Romanya, J. and Cowell, S.J. (2007a) Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in life cycle assessment (LCA). *Journal of Cleaner Production*, **15**, 1426–1440.

Milà i Canals L., Bauer, C., Depestele, J., Dubreuil, A., Freiermuth-Knuchel, R., Gaillard G, Michelsen, O., Müller-Wenk, R. and Rydgren, B. (2007b) Key elements in a framework for land use impact assessment in LCA. *Internaltional Journal of Life Cycle Assessment*, **12**, 5–15.

Mitchell, S.R., Harmon, M.E. and O'Connell, K.E.B. (2009) Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. *Ecological Applications*, **19**, 643-655.

Mitchell, S.R., Harmon, M.E. and O'Connell, K.E.B. (2012) Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy*, **4**, 818-827.

Moiseyev, A., Solberg, B., Kallio, A.M.I. and Linder, M. (2011) An Economic Analysis of the Potential Contribution of Forest Biomass to the EU RES Target and Its Implications for the EU Forest Industries. *Journal of Forest Economics*, **17**, 192-213.

Morison, J.I.L., Matthews, R., Miller, G., Perks, M., Randle, T., Vanguelova, E., White, M. and Yamulki, S. (2012) *Understanding the carbon and greenhouse gas balance of UK forests*. Forestry Commission Research Report. Forestry Commission: Edinburgh. (See http://www.forestry.gov.uk/pdf/FCRP018.pdf/$file/FCRP018.pdf.)

Müller-Wenk R and M Brandão (2010): Climatic impact of land use in LCA—carbon transfers between vegetation/soil and air. *International Journal of LCA*, **15**, 172-182.

Muys, B. (2002) *Reference system*. In: Schweinie, J. (ed.) The assessment of environmental impacts caused by land use in the life cycle assessment of forestry and forest products. Final Report of Working Group 2, Land Use, of COST Action E9..

Nabuurs, G.J., Thürig, E., Heidema, N., Armolaitis, K., Biber, P., Cienciala, E., Kaufmann, E., Mäkipää, R., Nilsen, P., Petritsch, R., Pristova, T., Rock, J., Schelhaas, M.J., Sievanen, R., Somogyi, Z. and Vallet, P. (2008) Hotspots of the European forests carbon cycle. *Forest Ecology and Management*, **256**, 194-200.

Nabuurs, G-J., Lindner, M., Verkerk, P.J., Gunia, K., Deda, P., Michalak, R., and Grassi, G. (2013) First signs of carbon sink saturation in European forest biomass. *Nature Climate Change*, **3**, 792-796.

Nelson, M.D., Liknes, G.C. and Butler, B.J. (2010) *Forest Ownership in the Conterminous United States*. Res. Map NRS-2. Department of Agriculture, Forest Service, Northern Research Station: Newtown Square, PA, USA. (See http://www.nrs.fs.fed.us/pubs/rmap/rmap_nrs2.pdf.)

Nepal, P., Ince, P.J., Skog, K.E. and Chang, S.J. (2012) Projection of U.S. forest sector carbon sequestration under U.S. and global timber market and wood energy consumption scenarios, 2010–2060. *Biomass and Bioenergy*, **45**, 251–264.

Ni, W. and Woodcock, C.E. (1999) *Surface Albedo of Boreal Conifer Forests: Modeling and Measurements*. Geoscience and Remote Sensing Symposium, Hamburg, 1999. IGARSS '99 Proceedings. IEEE.

Ofgem (2012) *Ofgem annual sustainability report 2011-12*. (The report and data set can be found at www.ofgem.gov.uk/publications-and-updates/annual-sustainability-report-2011-12.)

O'Halloran, T.L., Law, B.E., Goulden, M.L., Wang, Z., Barr, J.G., Schaaf, C., Brown, M., Fuentes, J.D., Göckede, M., Black, A. and Engel, V. (2012) *Radiative forcing of natural forest disturbances*, *Global Change Biology*, **18**, 555–565.

Paasonen, P., Asmi, A., Petäjä, T., Kajos, M.K., Äijälä, M., Junninen, H., Holst, T., Abbatt, J.P.D., Arneth, A., Birmili, W., van der Gon, H.D., Hamed, A., Hoffer, A., Laakso, L., Laaksonen, A., Leaitch, W.R., Plass-Dülmer, C., Pryor, S.C., Räisänen, P., Swietlicki, E., Wiedensohler, A., Worsnop, D.R., Kerminen, V-M. and Kulmala, M. (2013) Warming-induced increase in aerosol number concentration likely to moderate climate change. *Nature Geoscience*, **6**, 438-442.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S. and Hayes, D. (2011) A large and Persistent Carbon Sink in the World’s Forests. *Science*, **333**, 998-993.

Pena, N., Bird, D.N. and Zanchi, G. (2011) *Improved methods for carbon accounting for bioenergy: descriptions and evaluations*. Occasional paper 64. CIFOR: Bogor, Indonesia.

Perez-Garzia, J., Lippke, B., Comnick, J. and Manriquez, C. (2005) An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. *Wood and Fiber Science*, **37**, 140-148.

Peyerson, A.K. and Solberg, B. (2005) Environmental and economic impacts of substitution between wood produces and alternative materials: a review of micro-level analyses from Norway and Sweden. *Forest Policy and Economics*, **7**, 249-259.

Pingoud, K., Ekholm, T. and Savolainen, I. (2012) Global warming potential factors and warming payback time as climate indicators of forest biomass use. *Mitigation and Adaptation Strategies for Global Change*, **17**, 369-386.

Plevin, R.J., O'Hare, M., Jones, A.D., Torn, M.S. and Gibbs, H.K. (2010) The greenhouse gas emissions from market-mediated land use change are uncertain, but potentially much greater than previously estimated. *Environmental Science and Technology*, **44**, 8015-8021.

Plevin, R.J., Delucchi, M.A. and Creutzig, F. (2013) Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. *Journal of Industrial Ecology* (in press, early view published online on 8 November 2013).

Poudel, B.C., Sathre, R., Bergh, J., Gustavsson, L., Lundström, A.& Hyvönen, R. (2012) Potential effects of intensive forestry on biomass production and total carbon balance of in north-central Sweden. *Environmental Science and Policy*, **15**, 106–124.

Pulla, P., Schuck, A., Verkerk, J., Lasserre, B., Marchetti, M. and Green, T. (2013) *Mapping the distribution of forest ownership in Europe*. EFI Technical Report 88. European Forestry Institute: Joensuu, Finland.

Rajagopal D., Hochman G. and Zilberman, D. (2011) Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. *Energy Policy*, **39**, 228-233.

Randerson, J.T., Liu, H., Flanner, M.G., Chambers, S.D., Jin, Y., Hess, P.G., Pfister, G., Mack, M.C., Treseder, K.K., Welp, L.R., Chapin, F.S., Harden, J.W., Goulden, M.L., Lyons, E., Neff,, J.C., Schuur, E.A.G. and Zender, C.S. (2006) The Impact of Boreal Forest Fire on Climate Warming. *Science*, **314**, 1130–1132.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W-P., Suh, S., Weidema, B.P. and Pennington, D.W. (2004) Life cycle assessment: Part 1: framework, goal and scope definition, inventory analysis, and applications. *Environment International*, **30**, 701-720.

Repo, A., Tuomi, M. and Liski, J. (2011) Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *GCB Bioenergy*, **3**, 107–115.

Repo, A., Känkänen, R., Tuovinen, J-P., Antikainen, R., Tuomi, M., Vanhala, P. and Liski, J. (2012) Forest bioenergy climate impact can be improved by allocating forest residue removal. *GCB Bioenergy*, **4**, 202–212.

Ros, J.P.M., van Minnen, J.G. and Arets, E.J.M.M. (2013) *Climate effects of wood used for bioenergy*. PBL/Alterra Note PBL 1182/Alterra 2455. PBL Netherlands Environmental Assessment Agency: The Hague/Bilthoven, Netherlands.

Routa, J., Kellomäki, S. and Peltola, H. (2012) Impacts of intensive management and landscape structure on timber and energy wood production and net CO_2 emissions from energy wood use of Norway spruce. *Bioenergy Research*, **5**, 106–123.

Sathre, R. and O'Connor, R. (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitiution. *Environmental Science and Policy*, **13**, 104-114.

Schelhaas, M.J., Nabuurs, G.J. and Schuck, A. (2003) Natural disturbances im the European forests in the 19th and 20th centuries. *Global Change Biology*, **9**, 1620-1633.

Schlamadinger, B., Spitzer, J., Kohlmaier, G.H., and Lüdeke, M. (1995) Carbon balance of bioenergy from logging residues. *Biomass and Bioenergy*, **8**, 221-234.

Schlamadinger, B. and Marland, G. (1996) *Carbon implications of forest management strategies*. In: Apps, M.J. and Price, D.T. (eds.) Forest ecosystems, forest management and the global carbon cycle. NATO ASI Series, **I 40**, 217-232.

Schulze, E.-D., Körner, C., Law, B.E., Haberl, H. and Luyssaert, S. (2012) Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy*, **4**, 611-616.

Schwaiger, H. and Bird, N. (2010) Integration of albedo effects caused by land use change into the climate balance: should we still account in greenhouse gas units? *Forest Ecology and Management*, **260**, 278-286.

Schwarzbauer, P. and Stern, T. (2010) Energy vs. material: economic impacts of a "wood-for-energy scenario" on the forest-based sector in Austria – a simulation approach. *Forest Policy and Economics*, **12**, 31-38.

SDC (2005) *Wood Fuel for Warmth: A Report on the Issues Surrounding the Use of Woodfuel for Heat in Scotland*. Report of the Sustainable Development Commission (Scotland). Sustainable Development Commission (Scotland): Edinburgh, UK.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu, T.-H. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. *Science*, **319**, 1238–1240.

Searchinger, T. (2012) *Sound principles and an important inconsistency in the 2012 UK Bioenergy Strategy*. Non-peer reviewed commentary for RSPB. (See www.rspb.org.uk/Images/Searchinger_comments_on_bioenergy_strategy_SEPT_2012_tcm9-329780.pdf.)

Sedjo, R. and Tian, X. (2012) Does wood bioenergy increase carbon stocks in forests? *Journal of Forestry*, **110**, 304-311.

Socolow, R., Andrews, C., Berkhout, F. and Thomas, V. (eds.) (1994) *Industrial Ecology and Global Change*. Cambridge University Press: Cambridge, UK.

Sorrell S. (2007) *The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. UK Energy Research Centre: London, UK.

Spracklen, D.V., Bonn, B. and Carslaw, K.S. (2008) Boreal forests, aerosols and the impacts on clouds and climate. *Philosophical Transactions of the Royal Society Series A: Mathematical, Physical and Engineering Sciences*, **366**, 4613-4626.

Stewart, W.C. and Nakamura, G.M. (2012) Documenting the full climate benefits of harvested wood products in Northern California: linking harvests to the US Greenhouse Gas Inventory. *Forest Products Journal*, **62**, 340-353.

Ter-Mikaelian, M.T., McKechnie, J., Colombo, S.J. Jiaxin Chen and MacLean, H.L. (2011) The carbon neutrality assumption for forest bioenergy: a case study for northwestern Ontario. *Forestry Chronicle*, **87**, 644-652.

Thompson W., Whistance J. and Meyer, S. (2011) Effects of US biofuel policies on US and world petroleum product markets with consequences for greenhouse gas emissions. *Energy Policy*, **39**, 5509-5518.

Topping, D., Connolly, P. and McFiggans, G. (2013) Cloud droplet number enhanced by co-condensation of organic vapours. *Nature Geoscience*, **6**, 443-446.

Thürig, E., Palusao, T., Bucher, J. and Kaufmann, E. (2005) The impact of windthrow on carbon sequestration in Switzerland: a model-based assessment. *Forest Ecology and Management*, **210**, 337-350.

Trømborg, E., Sjølie, H.K., Bergseng, E., Bolkesjø, T.F., Hofstad, O., Rørstad, P.K., Solberg, B. and Sunde, K. (2011) *Carbon cycle effects of different strategies for utilisation of forest resources – a review*. INA fagrapport 19, Norwegian University of Life Sciences: Ås, Norway.

UN-ECE [and FAO] (2011). *The European Forest Sector Outlook Study II* (EFSOS II). UN-ECE and FAO, United Nations: Geneva (See http://www.fao.org/docrep/016/ap406e/ap406e00.pdf).

UN-ECE (2012) Data on prices and volumes of wood imports and exports in EU Member States (extract). (Data sets can be found at www.unece.org/forests/output/prices.html.)

UNFCCC (1992) *United Nations Framework Convention on Climate Change*. (See http://unfccc.int.)

van der Werf, G.R., Randerson, J.T., Giglio, L., ,Collatz, G.J. Mu, M., Kasibhatia, P.S. Morton, D.C., DeFries, R.S., Jin, Y., and van Leeuwen, T.T. (2010) Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmospheric Chemistry and Physics*, **10**, 11707-11735.

Vilén, T., Gunia, K., Verkerk. P.J., Seidl, R., Schelhaas, M.J., Lindner, M. and Bellassen, V. (2012) Reconstructed forest age structure in Europe 1950-2010. *Forest Ecology and Management*, **286**, 203-218.

Walker, T., Cardellichio, P., Colnes, A., Gunn, J., Kittler, B., Perschel, B., Recchia, C. and Saah, D. (2010) *Massachussets biomass sustainability and carbon policy study*. Manomet Center for Conservation Sciences: Brunswick, Maine. USA.

Werner, F., Taverna, R., Hofer, P., Thurig, E. and Kaufmann, E. (2010) National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. *Environmental Science and Policy*, **13**, 72–85.

Wunder, S., Kaphengst, T., K. Timeus, K. and Berzins, K. (2012) *Impact of EU bioenergy policy on developing countries*. Briefing Paper EP/EXPO/B/DEVE/2011/FWC/2009-01/LOT 5/21. Directorate-General for External Policies of the Union. Directorate B. Policy Department: Brussels, Belgium.

York, R. (2012) Do alternative energy sources displace fossil fuels? *Nature Climate Change*, **2**, 441–443.

Zamagni, A., Guinee, J., Heijungs, R., Masoni, P. and Raggi, A. (2012) Lights and shadows in consequential LCA. *International Journal of Life Cycle Assessment*, **17**, 904–918.

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

Zanchi, G., Pena, N. and Bird, N. (2011) Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, **4**, 761-772.

Appendix 1. Glossary of terms and units

There are many terms used in the evaluation and reporting of greenhouse gas emissions associated with the production and utilisation of forestry products that have apparently specialised meanings. In some instances, these terms have strict definitions that are broadly accepted and used. However, in other instances, there are terms which are less well-defined and often have ambiguous or unclear meanings. This situation has considerable potential for creating confusion for those engaged in this area of work and in subsequent debates over the interpretation of the results of such work. This is particularly relevant in reviewing existing reports and studies. It is not the purpose of this glossary to impose strict definitions on such literature retrospectively or to re-interpret the meaning of such literature. Instead, the glossary is intended to reasonably establish precise terms as used in this project and, where necessary, to point out discrepancies in their former, less defined usage. Given the context of this project, all terms are explained here in the context of the evaluation of the global consequences of policies for the greenhouse gas dynamics of utilising biomass in general, and in forests, in particular, by means of life cycle assessment. The glossary of terms is presented in Section A1.2 whilst units of measurement are also defined in Section A1.2.

A1.1 Glossary of terms

Absolute GHG emissions	In the context of this report absolute GHG emissions can be defined as the total GHG emissions occurring in association with a clearly defined activity. Absolute GHG emissions are calculated as the sum of all GHG emissions crossing a system boundary, as described in Section 4.4. It must be stressed that, strictly, calculations of absolute GHG emissions are not made in comparison with some other possible activity and do not involve calculating GHG emissions compared with any sort of reference/baseline value or reference/baseline projection for GHG emissions. See Section 4.5.2.
Additionality	Additionality refers to the positive net benefits in terms of climate change mitigation directly attributable to a mitigation activity or project. The concept generally refers to net greenhouse gas emissions reductions over and above that which would have occurred anyway in the absence of a given mitigation activity or project.
Afforestation	The direct human-induced conversion of land that has not been forested in the recent past to forested land through planting, seeding and/or the human-induced promotion of natural seed sources.
Albedo	Albedo refers to the reflectivity or reflection coefficient of the Earth's surface, which is measured as the ratio between solar radiation reflected back from the surface, and the original solar radiation incident upon it.
Anthropogenic climate change	Climate change attributable to human activity.

Attributed GHG emissions	In the context of this report attributed GHG emissions are defined as GHG emissions calculated and reported as part of an attributional LCA study. Results for GHG emissions may be 'attributed' to a single product or service, or may be allocated amongst two or more co-products or services (depending on the details of the system being studied). Attributional GHG emissions are defined to distinguish them from absolute GHG emissions and consequential GHG emissions (see Sections 4.5.2 and 4.5.4).
Attributional life cycle assessment	An approach to life cycle assessment in which natural resource and environmental impacts, such as greenhouse gas emissions, are assigned to functional units under consideration. The purpose intended, the approach adopted and the results obtained are different from those of consequential life cycle assessment. This subject is discussed in detail in Section 4.3.
Baseline	In order to estimate the benefits of a climate change mitigation activity in terms of 'additional' greenhouse gas emissions reductions, it is necessary to compare the levels of emissions and removals estimated for the mitigation activity with those estimated assuming the mitigation activity is not carried out. The reference estimate or trajectory referred to in such a comparison is known as a baseline.
Bioenergy feedstock	Biomass which is used to generate energy, in the context of this report, generally in the form of heat or power.
Biofuel	These are liquid and gaseous fuels obtained from feedstocks sourced from organic material. It is a term used by the European Commission specifically to refer to biomass-derived fuels that are predominantly used in transport. This term is sometimes used interchangeably and confusingly with bioenergy (see above) which the European Commission specify as heating, cooling and electricity generated from biomass.
Biogenic carbon	Carbon contained in or derived from recently living organic material, as distinct from fossil carbon. This includes carbon in the living and dead biomass of vegetation, including the woody biomass of trees.
Biologically mature forest	Areas of forest where the trees have reached an age where net growth in volume has effectively ceased and further growth, without some form of environmental change or regeneration, will not occur. Such forest may or may not have high carbon stocks, depending in certain factors, e.g. the extent of natural disturbances.
Biomass	Biological material derived from living, or recently living organisms. In the context of this report, this is taken to mean the biomass of vegetation.
Biomass cascading	The active management of harvested wood through a sequence of uses, with ultimate disposal through burning with energy recovery. A 'classic' example might involve the use of wood in sawn timber products, then re-use or recycling as a feedstock for wood-based panels, and burning as a source of energy only ultimately after repeated use in solid products.
Boreal forests	Broadly defines forests found to the south of the Arctic, but north of the temperate regions, including Taiga in northern Russia.
Branchwood	Generally considered to be the portion of above ground woody biomass of a tree which is not defined as stemwood. May contain branches and stem tops below a certain diameter.

'Business as usual' scenario	A scenario describing specified activities, services and processes, and associated flows, e.g. of energy and GHG emissions, intended to represent the current and future situation in the absence of policy interventions other than those already being implemented.
Calorific value, net calorific value	The quantity of heat produced by the complete combustion of a given amount (i.e. mass) of a substance. Calorific values are typically expressed in units of joules per gram or megajoules per kilogram (MJ kg^{-1}). The net calorific value of an energy source is sometimes also referred to as the lower heating value. Net calorific value represents the quantity of heat produced by the complete combustion of a given amount of a substance, allowing for any moisture content, such as in the case of air-dry wood.
Carbon content	The proportion of the dry mass of a material composed of carbon.
Carbon debt	This term is not favoured in this report and generally is not referred to. The term is used with different meanings by different authors. Broadly speaking, it refers to reductions in carbon stocks or loss of potential carbon sequestration in forest areas, which occur as a result of management interventions such as harvesting.
Carbon neutrality	This term is not favoured in this report and generally is not referred to. Broadly speaking, the concept is concerned with the achievement of zero net carbon emissions by compensating for GHG emissions with an equivalent amount of sequestration or offsetting.
Carbon sequestration	In the context of forestry and forest bioenergy, this is the process by which carbon dioxide is removed from the atmosphere by the growth of trees and carbon is retained in the living and dead biomass of trees, litter and soil organic matter. For sequestration to be said to have occurred, there must have been a reservoir which has increased in carbon stocks. For example, suppose a stand of trees grows by X tonnes of carbon per year, through removal of atmospheric carbon dioxide, but this is balanced by reductions in carbon stocks due to harvesting in another stand, so that the total quantity of carbon stocks in the forest stands does not change. Sequestration is not occurring because there is no increase in carbon stocks. In order to focus on changes of lasting consequence, most commentators would ignore sequestration that takes place on a daily, seasonal or even annual basis, and consider only activities that show a trend over longer time intervals.
Carbon sink	Any process, activity or mechanism which removes carbon dioxide from the atmosphere and retains the carbon in a reservoir. See carbon sequestration.
Carbon stock	In the context of forestry and forest bioenergy, a carbon stock is an amount of carbon sequestered in the living and dead biomass of trees, litter and soil organic matter comprising a forest stand of whole forest.
Carbon dioxide equivalent (CO_2 equivalent)	A unit used to express GHG emissions in terms of the equivalent amount of CO_2. Since each non-CO_2 GHG gas has a different warming effect on the atmosphere, the weightings, also called Global Warmng Potentials (GWPs) reflect this. The latest GWP values published by the IPCC in 2007, based on a 100 year time horizon, are 25 for methane and 298 for nitrous oxide. For example, this means that 1 tonne of methane would be expressed as 25 tonnes CO_2-equivalent.

Complementary felling	In the context of this report, complementary felling is a term used by some commentators to refer to a type of additional tree harvesting in forest areas in order to increase the supply of forest bioenergy. Specifically, when certain types of forest stand are clear felled for timber production, some trees unsuitable for use as timber may be retained on site. Complementary felling involves the additional felling of some or all of the otherwise unsuitable trees for utilisation as bioenergy.
Consequential GHG emissions	In the context of this report consequential GHG emissions can be defined as the total change in GHG emissions that occurs (or would occur) as a consequence of a change (or possible/proposed change) to an existing activity. As such, consequential GHG emissions are typically calculated and reported as part of a consequential LCA study. See Section 4.5.4.
Consequential life cycle assessment	This is a form of life cycle assessment in which the complete natural resource and environmental impacts, such as greenhouse gas emissions, are determined for a given proposed action, decision or policy. The purpose intended, the approach adopted and the results obtained are different from those of “attributional life cycle assessment”. This subject is discussed in detail in Section 4.3.
Counterfactual	For assessments of GHG emissions of forest bioenergy involving changes to the management of forests and/or changes to patterns in the use of harvested wood, it is essential to characterise realistic and justifiable ‘counterfactuals’. For land use (generally involving forest management in this context), the counterfactual describes how forest areas would be managed if the forest management were not to be changed (typically, a ‘business as usual’ scenario). For harvested wood products, counterfactuals involve the ‘business as usual’ patterns for wood use, and also a set of assumptions about what energy sources and materials might be used instead of forest bioenergy and harvested wood products. When defining such counterfactuals, it is important to recognise that the use of wood for material and fibre products, and as a feedstock for chemicals, may be as or more important as forest bioenergy in the future.
Direct GHG emissions	The term ‘direct GHG emissions’ is not of central importance to this project. However, ‘direct GHG emissions’ is a term which has been used variously to refer to: • GHG emissions directly due to the use (i.e. combustion) of an energy source, e.g. coal, oil, natural gas or biomass. • GHG emissions that occur in a specific part of an activity or process that is under consideration, e.g. when considering a specific forest operation, the GHG emissions due to consumption of fossil fuels in machinery carrying out the forest operation. • Possibly, the sum of the quantities described in the previous two points (where relevant). See Section 4.5.1.
Edaphic factors	Factors related to the physical and chemical properties of the site on which plants or trees are growing, particularly associated with the soil. In the context of this report, edaphic factors include the soil quality and characteristics limiting tree growth, as opposed to climatic factors.

End of Life	This is the final phase in the life of a product which may consist of disposal or recycling.
EU Effort Sharing Decision (ESD)	Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. This Decision is sometimes referred to as the Effort Sharing Decision or ESD. Under the Decision, EU Member States are committed to limiting GHG emissions from certain economic sectors (e.g. transport, agriculture) to specified target levels over the period 2013 to 2020.
EU Member States	States that are party to treaties of the European Union (EU). The member states are thereby subject to obligations and privileges of EU membership. As of 1 July 2013, there are 28 member states: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, The Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.
EU Renewable Energy Directive (RED)	The EU Renewables Directive (2009/28/EC) mandates levels of renewable energy use within the European Union. The directive requires Member States to produce 20% of energy consumption (across the EU) from renewable sources by 2020.
EU15	The 15 Member States of the European Union consisting of: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain, Sweden and the United Kingdom. Collectively the EU15 as a body is a signatory to the Kyoto Protocol.
EU27	The 27 Member States of the European Union consisting of: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, The Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.
Feedstocks	In the context of this report, feedstocks are fuel inputs to energy generation processes, for example, coal, oil or woody biomass. In the case of woody biomass, it is possible to distinguish different types of feedstock depending on how they are derived from harvested trees, e.g. branchwood, stemwood, small roundwood, off cuts and co-products from production of sawn timber, and waste wood at end of life. Wood energy feedstocks may also take processed form such as wood chips, pellets and briquettes. This subject is discussed in detail in Sections 2.3 and 2.5. It should be noted that the term 'feedstock' is sometimes used to refer to inputs of materials or chemicals to industrial manufacturing processes.
Finished wood products	The products made from wood as a result of processing of raw harvested wood. Examples include sawn wood and wood-based panels.

Forest bioenergy	Any biomass extracted from forests that is used to produce energy in the form of heat and power (i.e. not including liquid transport fuels). The biomass may be harvested directly from forests, or may be supplied as a by-product of the manufacture of solid wood products (e.g. offcuts from sawmilling) or may be derived from waste wood sources (e.g. solid wood products disposed of at end of life).
Forest biomass	Biomass contained in, or extracted from, forests, typically in the form of woody material.
Forest carbon	A general term referring to carbon stocks and carbon dynamics associated with forest systems.
Forest carbon dynamics	The flows of carbon within a forestry system due to processes such as growth and decay and effects due to management operations, e.g. planting, thinning and felling.
Forest designation	A classification referred to in FAO (2010), which indicates the primary function or management objective assigned to areas of forest, examples being 'Production' and 'Protection of soil and water'. It must be stressed that the primary function designated for a forest area may not be a sufficient indicator of forest management for reasons explained in Section 2.3.
Forest ecosystem	In a forest, the communities of different organisms in conjunction with the wider environment when interacting as a system.
Forest growing stock	The population of trees forming an area of forest. Growing stock is sometimes expressed as the number of trees per hectare or standing stem volume per hectare of different tree species forming a forest area. Standing biomass and carbon stocks may also be referred to when considering growing stock.
Forest harvesting	Any activity involving the felling of trees for the purposes of extraction of timber and/or biomass. Harvesting is often differentiated into thinning and clear felling (or clear cutting). Thinning involves felling small proportions of the trees in an area during the growth of the stand to give the remaining trees more resources. Clear-felling or clear-cutting involves felling an entire stand when the trees have reached a particular target, e.g. maximum average volume growth or mean diameter. This subject is discussed in detail in Section 2.3.
Forest management	The process of managing a forest, usually to a plan detailing the areas and programmes for tree establishment, tending and prescribed forest harvesting events, along with wider management of the biodiversity and social aspects of a forest.
Forest scrub	The term scrub does not have a standardised meaning. In the context of this report, scrub refers to areas of land with some bush and shrub cover but limited or no tree cover, or including small trees with limited productivity. In some cases such land may derive from the degradation of forest areas.
Forestry systems	A general term used to refer to the range of possible land based vegetation systems involving trees and their associated management. Such systems would include high forest, short rotation forestry and coppice systems.
Fossil carbon	Carbon contained in mineral sources, such as fossil fuels, in which it has been stored for geologically-long periods of time, as distinct from biogenic carbon (see separate definition).

Fossil energy	Energy derived from the combustion of mineral sources (fossil fuels such as oil, natural gas and coal).
Gasification and pyrolysis conversion technologies	Processes which convert carbon-based material into synthetic combustable products. Pyrolysis is a process, which uses heat to thermally decompose carbon-based material in the absence of air or oxygen (ie. not combustion). It produces volatile gases including synthetic combustible gas (syngas), together with a carbon-rich solid residue, for example char. Gasification is a process by which the majority of carbon in solid fuel is converted into carbon monoxide and hydrogen in the presence of oxygen. The synthesised gases produced by pyrolysis or gasification can be used in electricity or heat generation, or as a feedstock in the production of transport fuels or other chemicals.
Geological carbon	See fossil carbon.
GHG, greenhouse gas	All gases which absorb infra-red radiation in the atmosphere of any planet, thereby inducing a so-called greenhouse effect which results in trapping heat which would otherwise escape into space. Due to their ubiquity and magnitude, the prominent greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Other minor gases are included such as ozone and CFCs (Chlorofluorocarbons), however the latter two are often not included as usually production is small, and the effect of these gases in small quantities has little perceived effect on climate change.
GHG emissions, greenhouse gas emissions	The production of greenhouse gases as part of natural, domestic, commercial or industrial processes and, usually, their release to the atmosphere. See also absolute GHG emissions, attributed GHG emissions, consequential GHG emissions, direct GHG emissions and indirect GHG emissions.
GHG emissions payback time	A metric for the performance of a bioenergy source, often based on forest bioenergy. The concept of GHG emissions payback time is derived from the observation that, for a number of possible sources of additional forest bioenergy, there must be an initial period during which associated GHG emissions are increased, relative to the alternative of using fossil energy, after which there is a 'switch-over' to net decreases in GHG emissions. In broad terms, the GHG emissions payback time represents the period to the switch-over in GHG emissions. It should also be noted that the term 'GHG emissions payback time' is not particularly favoured by the authors of this report, since it is related to the term 'carbon debt' and presents similar problems for understanding and interpreting results.
Growth rate (forest)	In the context of this report, the growth rate of forests is usually defined in terms of the potential production of stem volume expressed in terms of cubic metres of volume per hectare, i.e. $m^3\ ha^{-1}\ yr^{-1}$. It is sometimes expressed in terms of potential biomass production. This subject is discussed in detail in Section 2.4.2 and Appendix 2. See also Section 3.6.1.

Harvest residues, harvesting residues (or felling or forest residues)	The biomass material remaining in forests that have been harvested for timber. Because only timber of a certain quality can be used by sawmills, boardmills and other processing facilities, components of woody biomass material – harvesting residues – are often left in forests during harvesting operations. Harvesting residues can include very poorly formed trees, stem tips of small diameter, branches and offcuts from the butts of stems of large trees, or from other parts of the stems of trees where there are defects. Harvesting residues may also include dead trees and rough or rotten dead wood. Often, such residues are left to decay in the forest or burned on site as part of forest management and, in particular, as part of preparation for the establishment of new trees. Harvesting residues could be collected as part of harvesting operations and used as a feedstock for forest bioenergy, and currently there is growing interest in this option.
High forest	A very common forest type where the individual trees are allowed to grow as single stems over the life of the stand, often becoming very tall and mature. This may be contrasted with coppice systems where individual trees may be cut at close to ground level on short rotations to encourage regrowth in the form of multiple shoots for the same stump/stool in suitable species.
iLUC (indirect Land Use Change)	Land use change that occurs generally as a result of market mediated responses to changes in existing patterns of land use or land management. For example, if a large area of existing agricultural land is converted to the production of bioenergy, this may limit the potential to produce food, resulting in other land areas being converted to agricultural production to meet the requirements for food. iLUC may operate locally, nationally, or trans-nationally.
Indirect GHG emissions	The term 'indirect GHG emissions' is not of central importance to this project. However, 'Indirect GHG emissions' is a term that has been used variously (but not exhaustively) to refer to: • GHG emissions that occur as part of the provisioning and processing of an energy source, such as coal, oil, natural gas, biomass or electricity (i.e. the construction, maintenance and operation of the infrastructure and associated activities and processes involved in the supply and use of an energy source). • GHG emissions from wider activities or processes, 'connected to' a specific part of an activity or process that is under consideration, e.g. when considering a specific forest operation, the GHG emissions associated with the construction and maintenance of the machinery carrying out the forest operation. • GHG emissions that are not themselves GHGs, but which may be precursors of atmospheric GHGs, e.g. carbon monoxide, which can be a precursor of carbon dioxide. • GHG emissions associated with bioenergy use due to the effects of indirect land use change. See Section 4.5.1.
Industrial roundwood	This report refers to statistics on production of industrial roundwood, as originally reported by the FAO and interpreted by the GB Forestry Commission (2012). In this context, the FAO defines industrial roundwood literally 'by exception', i.e. as 'all roundwood except woodfuel'.

Land occupation	A term used by some commentators to refer to any act by humankind involving moving into an area of land and interfering with natural ecosystem processes, e.g. for the purposes of settlement, industry, agricultural production or timber production. Some commentators argue that, unperturbed, vegetation would adapt so as to optimise the ecological capacity of land (e.g. to support vegetation growth and stocks of biomass and carbon). It is argued that human interventions generally result in the sub-optimal utilisation of the ecological capacity of the land.
Land Use, Land-Use Change and Forestry (LULUCF)	Under the United Nations Framework Convention on Climate Change (UNFCCC, 1992), countries are required to report inventories of GHG emissions to (and removals from) the atmosphere due to human activity. These national GHG inventories are broken down into a number of sectors, each dealing with a distinct aspect of human activity as defined by the IPCC, consisting of Energy (which includes transport), Industrial processes, Solvent and other product use, Agriculture, Waste and 'Land use, land use-change and forestry'. Land use, land-use change and forestry (LULUCF) is an inventory sector defined by the Intergovernmental Panel on Climate Change (IPCC) that covers anthropogenic emissions and removals of GHGs resulting from changes in terrestrial carbon stocks. It covers the carbon pools of living biomass (above and below ground), dead organic matter (dead wood and litter) and organic soil carbon for specified land categories (forest land, cropland, grassland, wetland, urban land and other land).
Land transformation	A term used by some commentators to refer to any act by humankind involving changes to the existing management of land, involving land-use change, such as when an area of pasture is converted to a managed forest by planting trees. See also 'land occupation'.
LCA, life cycle assessment	The evaluation of the total environmental and natural resource impacts of a product or service over its complete life cycle of creation, use and disposal. However, evaluation can be restricted to certain environmental impacts, such as greenhouse gas emissions and to certain parts of the life cycle depending on the goal and scope of the assessment.
Life cycle impact assessment (LCIA)	LCIA is the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system" (ISO 14044:2006).
Life cycle inventory (LCI)	LCI is the phase of the life cycle assessment involving the compilation and quantification of inputs and outputs. It comprises data collection and data calculation. Data collection consists of the identification and quantification of the relevant input and output flows for the whole life cycle of a product.
Mobilising the wood resource	A term used by some commentators to describe a set of possible policies and actions which may be taken to increase the supply of harvested timber and biomass. This may involve more intensive management and harvesting of forest areas and also more efficient use and recycling of wood products. See for example Section 2.7.

National Renewable Energy Action Plans (NREAPs)	Plans published by all EU Member States in 2010. The plans provide details of how each Member State expects to reach the legally binding target for the share of renewable energy in their total energy consumption, as determined by the EU Renewable Energy Directive. The plans include targets, the technology mix they expect to use, and the measures and reforms they will undertake to overcome the barriers to developing renewable energy.
Policy scenario	A scenario detailing how a policy or set of related policies will be implemented and developed. The scenario includes specified activities, services and processes relevant to the policy or policies, and associated flows, e.g. of energy and GHG emissions, intended to represent the future situation following enactment of the policy or policies. See also 'business as usual scenario'.
Primary forest	FAO (2010) defines 'primary forest' as 'naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed'.
Primary wood	In the context of this report, primary wood refers to any wood harvested from a forest, either in raw state or processed into a finished product or forming a by-product of a finished product. Specifically, it does not include wood in the form of a finished product that has come to the end of its useful life and which may either be recycled or enter the waste wood stream.
Pulpwood	A type of small roundwood often (but not exclusively) used for pulp and paper production. It can also include wood chips made directly (i.e. in the forest) from small roundwood. Pulp wood may also be used in the manufacture of wood-based panels or for bioenergy. See 'small roundwood'.
Recycled wood	The term recycled wood is used to refer to any wood in the form of a finished product that has come to the end of its useful life and which is recycled into a new wood product (e.g. recovered sawn timber, paper, particleboard etc.).
Removals	The volume of all trees, living or dead, that are felled and removed from a forest. It includes natural losses that are recovered (i.e. harvested), removals during the year of wood felled during an earlier period, removals of non-stem wood such as stumps and branches (where these are harvested) and removal of trees killed or damaged by natural causes (i.e. natural losses), e.g. fire, windblown, insects and diseases. It excludes bark and other non-woody biomass and any wood that is not removed, e.g. stumps, branches and tree tops (where these are not harvested) and other unutilised harvesting residues.
Roundwood	In the context of this report, the term roundwood is based on the FAO definition, as all roundwood felled or otherwise harvested and removed. It includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form, e.g. branches, roots, stumps and burls (where these are harvested).
Salvage logging	Removal and harvesting of dead, weaker or damaged trees, usually following a natural disturbance (eg. fire, disease, storm).

Sawlog	In the context of this report, the definition of the term sawlog is based on the FAO definition as roundwood that will be sawn (or chipped) lengthways for the manufacture of sawnwood or railway sleepers (ties) or used for the production of veneer (mainly by peeling or slicing). It includes roundwood (whether or not it is roughly squared) that will be used for these purposes and other special types of roundwood (e.g. burls and roots, etc.) used for veneer production.
Secondary wood	In the context of this report, secondary wood refers to any wood in the form of a finished product that has come to the end of its useful life and which may either be recycled or enter the waste wood stream.
Small roundwood	In the context of this report the term small roundwood refers to stemwood of small diameter that does not fall into the sawlog category (see above in this glossary). Small roundwood may typically be used to make fencing, or chipped to make wood-based panels or pulped to make paper. It may also be used for woodfuel.
Stemwood or 'main stem'	There is no international standard definition for stemwood but, in practice, definitions used in different countries and for different types of trees are generally very similar. For example, in the UK (Forestry Commission, 2011), the definition of stemwood is given as, 'The woody material forming the above ground main growing shoot(s) of a tree or stand of trees. The stem includes all woody volume above ground with a diameter greater than 7 cm over bark. Stem wood includes wood in major branches where there is at least 3 m of 'straight' length to 7 cm top diameter'.
Stoichiometric	In the context of this report, the result of a calculation for a process (e.g. a manufacturing process) is stoichiometric if the inputs and outputs of substances follow exact proportions, such as in a balanced chemical reaction.
Sustainable forest management	The concept of managing forests in a way which does not reduce the ecological, social or economic capacity of the forest for future generations. Sustainable forest management is often codified into national and international standards for management. Examples include the UK Forestry Standard and the FSC certification standard.
Sustainable yield management	The concept of managing forests in a way which does not reduce the long-term capacity of the forest to sustain a particular (volume) yield.
Top diameter	The diameter at the narrowest end of a log or length of stemwood or roundwood. Top diameter is used in the specification of different types of primary wood product such as sawlogs and small roundwood. For example, a sawlog is normally specified as having a minimum value of top diameter. Top diameter may be specified over bark or under bark.
Total tree biomass	The mass of the tree parts, both above and below-ground (stem, bark, branches, twigs, stump and roots) of live and dead trees. May also include foliage, flowers and seeds.
Tropical forests	Forests in the countries situated between the Tropic of Cancer and the Tropic of Capricorn. The majority of tropical forests are broadleaved, i.e. not coniferous.

Waste wood	In the context of this report, waste wood refers to any wood in the form of a finished product that has come to the end of its useful life and which would become waste, unless recovered for recycling or use as fuel.
Woody biomass	The mass of the woody parts (stem, bark, branches and twigs) of live and dead trees, excluding foliage, flowers and seeds.
Woodfuel	In the context of this report, the term woodfuel may be used to refer to a commodity or to reported statistics. When referred to in the sense of a commodity, wood fuel means any wood (of primary or secondary origin) which is burned to generate heat or power. When referring to statistics on production of woodfuel, these were originally reported by the FAO and interpreted by the GB Forestry Commission (2012). In this context, the FAO defines woodfuel as, 'Roundwood that will be used as fuel for purposes such as cooking, heating or power production. It includes wood harvested from main stems, branches and other parts of trees (where these are harvested for fuel) … It also includes wood chips to be used for fuel that are made directly (i.e. in the forest) from roundwood. It excludes wood charcoal'.
Woodfuel briquettes	Wood chips, sawdust, and waste and scrap wood, possibly bark, compressed at high temperature to form a homogenised mass of wood with uniform dimensions. Most frequently used for domestic heating, some for food smoking.
Woodfuel chips	Solid wood, with or without bark, comminuted to make small to moderate size pieces of wood. Often wood chips are made to specified dimensions. Used for a range of applications including (relatively) small-scale power generation, domestic and small-scale commercial heating, food smoking. Wood chips may also be used for non-fuel uses, notably animal bedding.
Woodfuel logs	Almost unprocessed raw harvested wood, possibly small stemwood, parts of large stemwood, often parts of branches, with or without bark. Most frequently used for domestic heating, some for food smoking.
Woodfuel pellets	Wood which has been ground to sawdust and then compressed to form pellets of a size, shape and consistency. Used in large quantities for large-scale power generation, including co-firing with coal, also used for domestic and commercial heating systems, particularly automated systems.

A1.2 Units of measurement

gC	1 gC = 1 gram carbon or carbon equivalent.
gCO_2	1 gCO_2 = 1 gram carbon dioxide or carbon dioxide equivalent.
kgC	1 kgC = 1 kilogram (1000 grams) carbon or carbon equivalent.
$kgCO_2$	1 $kgCO_2$ = 1 kilogram (1000 grams) carbon dioxide or carbon dioxide equivalent.
tC	1 tC = 1 tonne carbon or carbon equivalent.
tCO_2	1 tCO_2 = 1 tonne carbon dioxide or carbon dioxide equivalent.
GtC	1 GtC = 1 gigatonne (1 thousand million metric tonnes) carbon or carbon equivalent.
$GtCO_2$	1 $GtCO_2$ = 1 gigatonne (1 thousand million metric tonnes) carbon dioxide or carbon dioxide equivalent.
ha	1 ha = 1 hectare = 10,000 m^2.
Gha	1 giga-hectare (10^9 ha) = 1 thousand million hectares.
m^2	1 m^2 = 1 square metre.
m^3	1 m^3 = 1 cubic metre.
MJ	1 megajoule = 1million (10^6) joules.
odt	1 odt = 1 oven dry tonne. In the case of wood, this is the mass of wood not allowing for any moisture content.
tonne (t)	1 tonne = 1 thousand kilograms.
kilotonne (kt)	1 kilotonne = 1 thousand (10^6) tonnes.
megatonne (Mt)	1 megatonne = 1 million tonnes.
odt	1 odt = 1 oven dry tonne. In the case of wood, this is the mass of wood not allowing for any moisture content.
MWh	1 megawatt hour = 1 million (10^6) watt hours.

Appendix 2. Measurement of forest growth and productive potential

Typically in commercial forestry, the productive potential of forest stands is assessed in terms of potential stem volume productivity and, in particular, cumulative volume production and the related parameter of maximum mean annual increment (MAI_{max}). In particular, maximum mean annual increment represents one of the most important parameters for making decisions about forest management. This section describes these measures of stand productivity and how they are calculated.

A2.1 Cumulative volume production

An important measure of volume productivity in forestry is cumulative volume production. Cumulative timber volume production is the standing stem volume per hectare attained by a forest stand in a given year plus the sum of per hectare stem volumes removed as thinnings up to that year. Cumulative volume production represents the total production of timber volume from a stand up to a given year in the stand's development.

An example of cumulative volume production as measured in a permanent sample plot of even-aged Sitka spruce is given in Table A2.1. As an illustration of how cumulative volume production is calculated, in Table A2.1 cumulative production up to age 44 years is:

369 + 34 + 33 + 49 + 24 + 35 + 61 + 53 = 658 cubic metres per hectare.

Table A2.1 Standing volume and production in an even-aged stand of Sitka spruce in Britain (Forestry Commission permanent mensuration sample plot 1222, Brendon, Somerset, established 1948, felled 1986 at age 57).

Year	Stand age (years)	Top height (m)	Volume per hectare ($m^3\ ha^{-1}$)			Mean annual increment ($m^3\ ha^{-1}\ yr^{-1}$)
			Volume standing after thinning	Volume removed as thinnings	Cumulative volume	
1948	19	8.6	103	34	137	7.2
1951	22	10.0	-	33	-	-
1953	24	11.1	121	49	237	9.9
1958	29	14.5	-	24	-	-
1963	34	16.0	262	35	437	12.9
1967	38	17.8	272	61	508	13.3
1973	44	21.3	369	53	658	15.0
1978	49	23.4	396	59	744	15.2
1986	57	-	531	-	879	15.4

Strictly speaking, cumulative volume production is not a meaningful physical or biological variable. The main applications of cumulative volume production are in economic analysis and in support of practical forest management. In essence, cumulative volume production represents the out-turn of commercial stem volume from a stand up to a given year in the stand's development.

A2.2 Current annual increment

Current annual increment (CAI) is strictly the rate of cumulative volume production for a given year. For example, suppose the cumulative volume production of a 35 year old stand of trees is 500 cubic metres per hectare, and that by the time the stand is 36 years old the cumulative volume production has risen to 520 cubic metres per hectare. The CAI of the stand at age 36 is then calculated as 520 – 500 = 20 cubic metres per hectare per year.

For ease of calculation and for practical reasons, CAI is frequently approximated from two measurements of cumulative volume production taken more than one year apart. For example, the CAI of the Sitka spruce stand in Table A2.1 at age 22 years could be approximated as (237−137 cubic metres) ÷ 5 years = 100 ÷ 5 = 10.0 cubic metres per hectare per year. It is important to note that, because of the way it is calculated, strictly, this example of an estimate of current annual increment applies 'on average' for the stand between the ages of 19 and 24 years.

A2.3 Mean annual increment

Mean annual increment (MAI) is the average rate of cumulative volume production up to a given year. In even-aged stands, MAI is calculated by dividing cumulative volume production by age. For example, for the Sitka spruce stand in Table A2.1, the mean annual increment up to age 44 years is 658 ÷ 44 = 15.0 cubic metres per hectare per year.

A2.4 Development of MAI and CAI over time

For an even-aged stand of trees, both MAI and CAI follow a characteristic pattern of development with respect to stand age, as shown in Figure A2.1. In the early years of stand development, both CAI and MAI rise steadily from zero to reach maximum values before declining again. The annual volume increment (CAI) reaches a peak earlier, and always achieves a higher maximum value, than MAI. Maximum MAI is reached at the age (t_{max}) where the descending CAI curve crosses the MAI curve (see Figure A2.1). For typical even-aged conifer stands grown under temperate or boreal conditions, maximum MAI is usually reached after several decades, perhaps more than a century. (The maximum is reached much more quickly in the tropics, perhaps within 15 to 30 years.) From this point on MAI declines steadily, although the rate of decline may be slight in the years immediately following attainment of maximum MAI. The existence of a stand age t_{max} for which MAI takes a maximum value MAI_{max} may be regarded as being of great commercial significance in the management of even-aged stands particularly if the aim is to maximise sustainable volume production. Specifically, if MAI_{max} occurs at a predictable stand age t_{max} then a forest manager may choose to clearfell the stand at this age. The average rate of volume production over the rotation period t_{max}, will then be MAI_{max}. The forest manager can then replant or regenerate a new stand on the clearfelled site and, if this new stand is also grown over a rotation period t_{max} then average rate of volume production of the new stand will again be MAI_{max} provided that the fertility of the site has not been depleted and environmental conditions have not changed. Clearly, managing a stand on this site using any rotation period other than t_{max} will result in a lower average rate of volume production, because the MAI achieved by an even-aged stand on this site must be lower for a stand age other than t_{max}.

It is very important to stress that MAI_{max} represents the maximum rate of stem volume production that can be achieved if the stand is even-aged and managed for production of maximum raw stem volume (i.e. with no consideration of any requirement for stemwood of particular dimensions, form or quality). In practice, it is very rare for forest stands to be managed in this way. It is more common for stands to be managed on rotations significantly longer than t_{max}, with the result that the overall level of volume production achieved over a rotation is significantly less than MAI_{max}. Long rotations are applied to forest stands for a number of reasons, often to meet wider forest management objectives (see Section 2.3 of this report), but also to enable the development of individual trees with large diameters, from which higher value products such as sawlogs can be produced. Nevertheless, even in these circumstances, MAI_{max} remains a principal parameter referred to in determining the management of forest stands, particularly in terms of setting (the longer) rotations and determining levels of thinning during rotations.

Figure A2.1 clearly illustrates that, for a typical even-aged stand of Sitka spruce growing in upland Britain, a rotation length based on the age at which MAI_{max} for total stem volume is reached is not necessarily optimal if seeking to produce high-value, larger diameter timber which can potentially be turned into long-lived products. In the example illustrated in Figure A2.1, the MAI_{max} for sawlogs with a minimum top diameter, under bark, of 16 centimetres occurs at a stand age of 69 years; 15 years later than the equivalent age of MAI_{max} for total stem volume (age t_{max}). The situation is further complicated by the fact that prevailing market and economic factors may also have an influence on the planned rotation length. For example, the application of a discount factor in financial calculations will often have the effect of shortening the length of the rotation from that which would be required to maximise raw volume production.

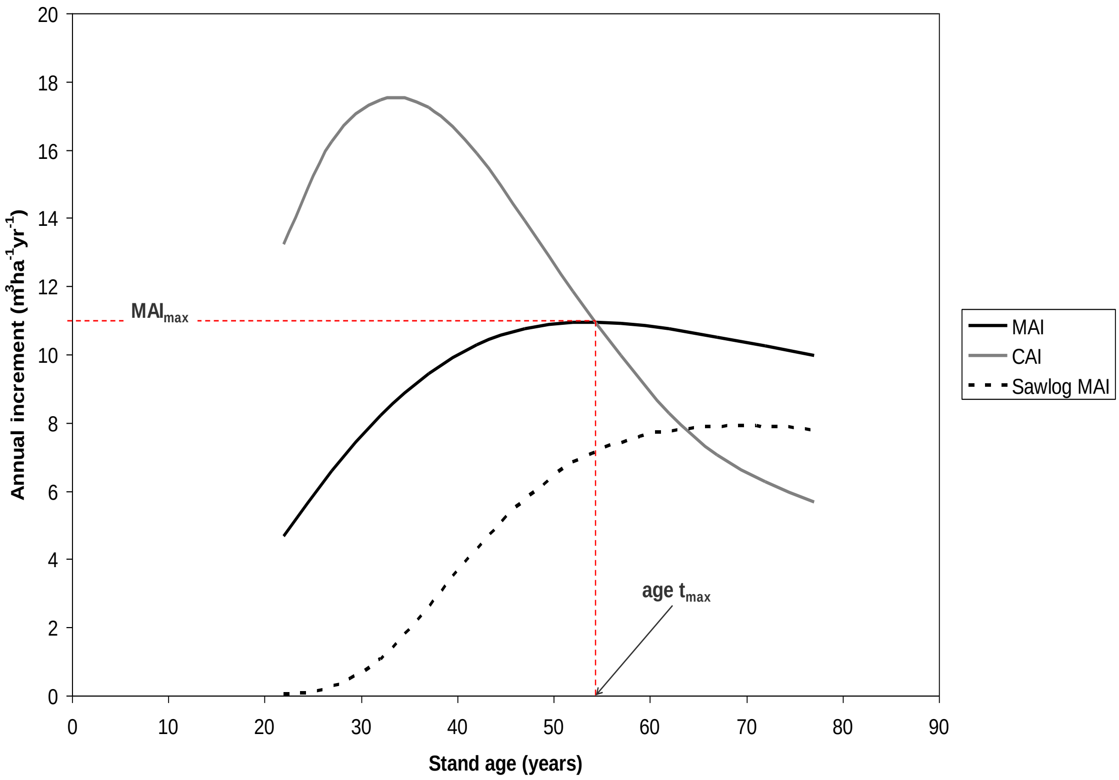

Figure A2.1. Trajectories of mean annual increment (MAI) of cumulative volume production, current annual increment (CAI) and sawlog mean annual increment (Sawlog MAI) for an even-aged stand of unthinned Sitka spruce. In this example, the curves are based on a yield model for Sitka spruce in Great Britain for which MAI$_{max}$ is 11 m^3 ha^{-1} yr^{-1}, occurring at a stand age of 54 years. The above curves clearly illustrate that the MAI$_{max}$ of sawlogs (i.e. roundwood with a minimum top diameter, under bark, of 16 cm) is lower, and occurs later than the equivalent MAI$_{max}$ for total volume production; in this example stand, the MAI$_{max}$ of sawlogs is 7.9 m^3 ha^{-1} yr^{-1} and is reached at a stand age of 69 years.

Appendix 3. Assessment of literature on metrics for quantifying GHG emissions of forest bioenergy

In this Appendix, a brief description is given of a range of metrics referred to in the scientific literature on GHG emissions of forest bioenergy, and an assessment is made of the major strengths and weaknesses of each metric.

A3.1 Annual (absolute) net CO_2 or GHG emission trajectories

The most understandable way to measure GHG emissions is simply to sum the absolute CO_2 emissions from the system to the atmosphere and absolute carbon sequestration from the atmosphere by the system, at the given point in time. In this way the evolution of net emissions over time can be portrayed. The most usual time unit for such purposes is a year, resulting in annual emission trajectories. This kind of indicator has been used for example by Poudel *et al.* (2012); Böttcher *et al.* (2012); Eliasson *et al.* (2013); Nepal *et al.* (2012); Fiorese and Guariso (2013). The major advantage of this indicator is that no predefined assumptions of impacts of the emissions on global warming are required. Thus the indicator is transparent and easy to understand. On the other hand, the indicator handles emissions and sequestration with similar weight regardless of the timing. Thus, the indicator is unable to measure global warming potential or any other impact of the emissions. These are the major disadvantages related to the use of this particular indicator.

The indicator measuring absolute net CO_2 emissions may also be extended to include other GHGs such as methane and nitrous oxide. In such a case non-CO_2 emissions are converted into CO_2-eq by using global warming potential (GWP) factors within a given time horizon. Consequently, predefined assumptions on impacts of the emissions on global warming are to some extent used if such an indicator is applied. However, this kind of indicator is relevant in current international climate policy under the United Nations Framework Convention on Climate Change (UNFCCC), in which emissions are accounted, reported and limited by means of their absolute quantities and considering GWP factors within a 100-year time frame (Bird *et al.,* 2010). This kind of indicator is used for example by Jonker *et al.* (2013).

A3.2 Annual (relative) CO_2 or GHG emission trajectories

Instead of determining emissions in absolute terms, CO_2 or CO_2-eq emission trajectories may also be calculated in comparison with a predefined reference scenario over the studied time horizon. For example, Zanchi *et al.* (2011) and Werner *et al.* (2010) have used this kind of relative indicator in which the emissions and sequestration of a bioenergy system is compared to a predefined reference land use scenario. In contrast to absolute emission trajectories, this indicator reflects the land use change emissions of a bioenergy system in comparison with a given baseline in which the studied bioenergy system does not take place. As the land use related GHG emissions tend not to be constant but dynamic, this particular indicator is more appropriate to be applied in life cycle assessment of bioenergy systems compared to absolute emission trajectories. On the other hand, predefined assumptions of a baseline are required which make the indicator less easy to understand. Also, this indicator is unable to measure global warming potential or any other impact of the emissions.

A3.3 Cumulative or average (absolute) CO_2 or GHG emissions

Absolute net emissions may also be accounted for in cumulative terms over a longer time horizon (e.g. 20 or 100 years) instead of one year (Johnson & Tschudi 2012). This kind of indicator has been applied for example by Jonker *et al.* (2013), Perez-Garzia *et al.* (2005) and Kilpeläinen *et al.* (2011). This indicator has the advantage over annual emission trajectories in that it describes the net emissions over the given time horizon and not only the situation in a single year. Cumulative emissions may also be easily converted into average annual emissions. This indicator also handles emissions and sequestration with similar weight regardless of their timing.

A3.4 Cumulative or average (relative) CO_2 or GHG emissions

Cumulative CO_2 or CO_2-eq emissions may also be determined in comparison with a predefined reference scenario over a time horizon studied, instead of in absolute terms (Holtsmark 2012a). For example, McKechnie *et al.* (2011), Walker *et al.* 2010, Lecocq. *et al.* (2011), Eliasson *et al.* (2013); Jonker *et al.* (2013); Repo *et al.* (2011) have used this kind of relative indicator in which the cumulative emissions and sequestration of a bioenergy system over a given time horizon are compared to a predefined reference land use scenario. This indicator integrates the advantages of a relative indicator to describe the difference between the studied system and the baseline, and also the advantages of a cumulative indicator to describe the net emissions over the given time horizon and not only the situation in a single year. The other pros and cons are similar to the absolute cumulative emission indicator.

A3.5 (Relative) cumulative radiative forcing (CRF)

In order to show the timing and dynamics of emissions, sinks and slow removal of GHGs from the atmosphere, explicitly the changes in the atmospheric GHG concentrations due to the activities under consideration should be calculated (Helin *et al.* 2012; Cherubini *et al.* 2012). The total greenhouse effect of various gases can be shown if the changes in concentrations are converted to radiative forcing (RF) values, which can be seen to be additive in the case of well-mixed gases (IPCC, 2013). Positive RF leads to a global mean surface warming, and negative RF to a global mean surface cooling. In order to calculate the RF for the studied activity, the correlation between the atmospheric GHG concentrations and RF has to be determined. As emitted GHGs cause a RF which accumulates over time, a cumulative radiative forcing (CRF) integrated over a given time describes RF over that time period, instead of instantaneous RF.

A3.6 Relative radiative forcing commitment (RRFC)

Relative radiative forcing commitment (RRFC) is a ratio that accounts for the energy absorbed in the Earth system due to changes in greenhouse gas concentrations in comparison to the energy released in the burning of fuel within a given time horizon (Kirkinen *et al.* 2008). The indicator makes comparisons with GHG emissions from fossil fuels relatively easy. Moreover, it takes into account the reference land-use emissions (i.e. emissions in the absence of the studied bioenergy system). However, it requires predefined assumptions of the GWP of the emissions. The indicator makes it possible to study different time horizons separately in order to, for example, study the impact of climate policy on different time horizons (Kirkinen *et al.* 2008).

A3.7 (Absolute) time correction factors (TCF)

Time correction factor (TCF, Kendall *et al.* 2009) is calculated on the basis of the relative climate change impact of an emission occurring at the beginning of biofuel feedstock cultivation. Typically these emissions are amortized equally over an assumed time horizon in order to divide the burdens of land use change over several generations of crops. However, this approach overlooks the fact that the effect of greenhouse gas emissions increases with the time they stay in the atmosphere. TCF can be used to account for the relative effect of emissions occurring at different times. The downside of the indicator is that it does not consider the land use emissions in relation to a reference system in which the bioenergy system does not exist. Moreover, it requires predefined assumptions as to the global warming potential of the emissions studied.

A3.8 (Absolute) GWPbio factor

GWPbio factor (e.g. Cherubini *et al.* 2011ab; Cherubini *et al.* 2013) is calculated by approximating the atmospheric decay of carbon from long-rotation biomass with a forest growth equation. GWPbio factors are assessed for situations where the carbon in stemwood is released into the atmosphere within one year after harvest. As the indicator is analogous to the global warming factors derived for non-CO_2 GHGs, it makes comparisons to fossil CO_2 easy (Pingoud *et al.* 2012). However, it does not describe the land use related impacts in comparison to a reference land use scenario.

A3.9 (Relative) GWPbio factor

The relative GWPbio factor measures the cumulative radiative forcing of biomass carbon emission at time t0 in comparison to an equivalent carbon emission at time t0 (Pingoud *et al.* 2012). Furthermore, the emissions/sequestration in the biomass system is calculated in comparison to a predefined reference land-use scenario. The assessment can be conducted in the same way on both landscape and stand level. The indicator is based on a presumed development of the terrestrial C stock and it is therefore subject to uncertainties.

A3.10 (Relative) GWPnetbio factor

In the GWPnetbio factor cumulative displaced fossil GHG emissions due to biomass use are added to the biomass carbon balance in time, thus forming an indicator of the total carbon benefits of the studied biomass in relation to a fossil alternative (Pingoud *et al.* 2012). The indicator enables comparison to the warming impacts of fossil CO_2 emissions.

Moreover, it takes into account the impact of timing of emissions on their warming potential. In addition, a reference scenario in the absence of the studied bioenergy system is included in the assessment. A down side of the indicator is that it necessitates predefined assumptions on the displaced fossil fuels and can therefore be hard to understand and communicate.

A3.11 (Relative) carbon neutrality factor

Carbon neutrality (CN) factor can be used to take into account the time needed to re-absorb the CO_2 emitted into the atmosphere by the bioenergy used. The CN is defined as ”the ratio between the net reduction/increase of carbon emissions in the bioenergy system and carbon emissions from the substituted reference energy system, over a certain period of time” (Zanchi *et al.* 2010). The indicator thus includes a built-in comparison with the emissions from the fossil fuel system. Moreover, it takes into account land use emissions in the absence of the bioenergy system studied, i.e. in comparison to a reference scenario (Holtsmark 2012a). However, unlike e.g. the GWPbio factors, this indicator does not consider the impact of timing of emissions on their warming potential. In addition, it includes assumptions of fossil fuel displacement and can therefore be problematic to understand or communicate.

A3.12 (Relative) fossil combustion equivalent

In this method, the mean lifetime of 1 tonne of carbon from fossil fuel combustion in the atmosphere is taken as the basis for converting 1 tonne of carbon emitted from biomass combustion to a ‘fossil fuel combustion equivalent’. A predefined land use reference scenario is also applied. The indicator enables comparisons with fossil carbon emissions fairly easily. However, the method does not take into account the effect of timing on the warming potential of the emission.

A3.13 (Relative) warming payback time

Warming payback time refers to the time needed for the biomass option to become greater than its functionally-equivalent fossil-based alternative (Pingoud *et al.* 2012). In the method presented by Pingoud *et al.* (2012), warming payback time is based on the cumulative radiative forcing. Thus, it takes into account the impact of timing of the emissions on the warming potential. A land use reference scenario in the absence of the studied bioenergy system is also considered in the indicator. However, predefined assumptions of fossil fuels displacement are needed, which can again make communication of the results difficult.

A3.14 Assessment of metrics

Table A3.1 summarises the various metrics used for GHG emissions or related global warming impacts of bioenergy. The metrics are categorised as ‘absolute’ or ‘relative’, depending on whether a predefined land use reference scenario has been applied (relative) or has not been allowed for (absolute).

Table A3.1 Summary description and assessment of metrics applied to GHG emissions of forest bioenergy

Type of indicator	Short description	Examples of use	Major advantages	Major disadvantages
Annual (absolute) CO_2 or CO_2-eq emission trajectories	Measures the development of annual CO_2 or CO_2-eq emissions of a bioenergy system in absolute terms over a specified time horizon	Poudel *et al.* (2012); Böttcher *et al.* (2012); Eliasson *et al.* (2013); Nepal *et al.* (2012); Fiorese & Guariso (2013)	- Does not require predefined assumptions on impacts of the emissions - Easily understandable - Relevant for current climate policy	- Emissions have similar weight regardless of the timing of the emissions - Does not measure global warming potential, or any other climate impact, of the emissions - Does not as such consider the land use change emissions or related impacts in the absence of the studied bioenergy system (in comparison with a predefined reference scenario)
Annual (relative) CO_2 or CO_2-eq emission trajectories	Measures the development of annual CO_2 or CO_2-eq emissions of a bioenergy system in comparison to a predefined land use reference scenario over a specified time horizon	Zanchi *et al.* (2011), Werner *et al.* 2010	- Does not require predefined assumptions on impacts of the emissions - Considers the land use emissions in the absence of the studied bioenergy system (in relation to a predefined reference scenario)	- Emissions have similar weight regardless of the timing of the emissions - Does not measure global warming potential, or any other climate impact, of the emissions
Cumulative or average (absolute) CO_2 or CO_2-eq emissions	Measures the cumulative or average CO_2 or CO_2-eq emissions of a bioenergy system over a given time horizon in absolute terms	Jonker *et al.* (2013); Perez-Garzia *et al.* 2005; Kilpeläinen *et al.* (2011)	- Does not require predefined assumptions on impacts of the emissions - Easily understandable - Describes the sum of the emissions within the studied period, and thus also the importance of variation in emissions in single years better than the annual emission trajectories	- Emissions have similar weight regardless of the timing of the emissions - Does not measure global warming potential, or any other climate impact, of the emissions - Does not as such consider the land use emissions or related impacts in the absence of the studied bioenergy system (in comparison with a predefined reference scenario)

Table A3.1 (continued) Summary description and assessment of metrics applied to GHG emissions of forest bioenergy

Type of indicator	Short description	Examples of use	Major advantages	Major disadvantages
Cumulative or average (relative) CO_2 or CO_2-eq emissions	Measures the cumulative or average CO_2 or CO_2-eq emissions of a bioenergy system over a given time horizon in comparison with a predefined land use reference scenario	McKechnie *et al.* (2011), Walker *et al.* (2010), Lecocq. *et al.* (2011), Eliasson *et al.* (2013); Jonker *et al.* (2013); Repo *et al.* (2011)	- Does not require predefined assumptions on impacts of the emissions - Considers the land use change emissions in the absence of the studied bioenergy system (in comparison with a predefined reference scenario) - Describes the sum of the emissions within the studied period, and thus also the importance of variation in emissions in individual years better than the annual emission trajectories	- Emissions have similar weight regardless of the timing of the emissions - Does not measure global warming potential of the emissions or any other climate impacts
(Relative) cumulative radiative forcing (CRF)	Measures cumulative radiative forcing of a bioenergy system over a given time horizon in comparison with a predefined land use reference scenario	Repo *et al.* (2012)	- Considers the impact of timing of emissions on the warming potential - Considers the land use related warming potential in the absence of the studied bioenergy system (in comparison to a predefined reference scenario)	- Requires predefined assumptions of global warming potential of the emissions

Table A3.1 (continued) Summary description and assessment of metrics applied to GHG emissions of forest bioenergy

Type of indicator	Short description	Examples of use	Major advantages	Major disadvantages
(Relative) Relative radiative forcing commitment (RRFC)	A ratio that accounts for the energy absorbed in the Earth system due to changes in atmospheric greenhouse gas concentrations (production and combustion of fuel compared to a predefined land use reference scenario) compared to the energy released in the combustion of fuel over a given time horizon	Kirkinen *et al.* (2008, 2010)	- Considers the impact of timing of emissions on the warming potential - Considers the land use related warming potential in the absence of the studied bioenergy system (in comparison to a predefined reference scenario)	- Requires predefined assumptions of global warming potential of the emissions
(Absolute) time correction factors (TCF)	TCF is calculated based on the relative climate change effect of an emission (measured as cumulative radiative forcing) occurring at the outset of biofuel feedstock cultivation. Provides an equivalency factor for the relative impact of the emissions occurring at different times. The amortized (annualised) emissions are then multiplied by the TCF	Kendall *et al.* (2011)	- Considers the impact of timing of emissions on the warming potential	- Does not consider the land use emissions or related impacts in the absence of the studied bioenergy system (in relation to a predefined reference scenario) - Requires predefined assumptions of global warming potential of the emissions - Only suitable for adjustment of annualised pulse emissions
(Absolute) GWP_{bio} factor	Measures the cumulative radiative forcing of a biomass carbon emission at time t_0 with a land use emission/sequestration scenario in comparison with an equivalent fossil carbon emission at time t_0	Cherubini *et al.* (2011ab, 2012); Guest *et al.* (2012abc); Michelsen *et al.* 2011	- Makes comparison with fossil CO_2 emissions relatively easy - Considers the impact of timing of emissions on the warming potential	- Requires predefined assumptions of global warming potential of the emissions - Does not as such describe the land use related impacts in the absence of the studied bioenergy system (in comparison to a predefined reference scenario)

Table A3.1 (continued) Summary description and assessment of metrics applied to GHG emissions of forest bioenergy

Type of indicator	Short description	Examples of use	Major advantages	Major disadvantages
(Relative) GWP_{bio} factor	Measures the cumulative radiative forcing of a biomass carbon emission at time t_0 with a land use emission/sequestration scenario (biomass system) compared to an equivalent fossil carbon emission at time t_0. The emissions/ sequestration in the biomass system are determined in comparison with a predefined land use reference scenario	Pingoud *et al.* (2012)	- Makes comparison with fossil CO_2 emissions relatively easy - Considers the impact of timing of emissions on the warming potential - Considers the land use related warming potential in the absence of the studied bioenergy system (in comparison to a predefined reference scenario)	- Requires predefined assumptions of global warming potential of the emissions
(Relative) GWP_{netbio}	Measures the cumulative radiative forcing of a biomass carbon emission at time t_0 with a land use emission/sequestration scenario (biomass system) and fossil fuel displacement in comparison with an equivalent fossil carbon emission at time t_0. The emissions/sequestration in the biomass system are determined in comparison with a predefined land use reference scenario	Pingoud *et al.* (2012)	- Includes comparison with the warming impacts of fossil CO_2 emissions - Considers the impact of timing of emissions on the warming potential - Considers the land use related warming potential in the absence of the studied bioenergy system (in comparison to a predefined reference scenario)	- Requires predefined assumptions of global warming potential of the emissions - Requires predefined assumptions of fossil fuel displacement, and thus can be difficult to understand and communicate

Table A3.1 (continued) Summary description and assessment of metrics applied to GHG emissions of forest bioenergy

Type of indicator	Short description	Examples of use	Major advantages	Major disadvantages
(Relative) carbon neutrality factor	Quantifies the extent to which use of biomass reduces emissions considering a predefined land use reference scenario and compared to a predefined replaced fossil fuel over a given time in terms of cumulative emissions	Schlamadinger *et al.* (1995); Zanchi *et al.* (2010); Holtsmark (2012a)	- Built-in comparison with the emissions from a fossil fuel system - Considers the land use emissions in the absence of the studied bioenergy system (in comparison to a predefined reference scenario)	- Does not consider the impact of timing of emissions on the warming potential - Requires predefined assumptions of fossil fuel displacement, can be difficult to understand/explain
(Relative) fossil combustion equivalent	The mean lifetime in the atmosphere of 1 tonne of carbon from fossil fuel combustion is taken as a basis for converting 1 tonne of carbon released from biomass compared to a predefined land use reference scenario into 'fossil-combustion-equivalent'	Müller-Wenk & Brandao (2010); Kujanpää *et al.* (2010)	- Makes comparison with the CO_2 emissions from a fossil fuel system relatively easy - Considers the land use emissions in the absence of the studied bioenergy system (in comparison to a predefined reference scenario)	- Does not consider the impact of timing of emissions on the warming potential
(Relative) warming payback time	Describes the time after which forest biomass use is superior to its functionally equivalent fossil fuel-based alternative considering cumulative radiative forcing	Pingoud *et al.* (2012)	- Built-in comparison to the warming impacts of fossil CO_2 emissions - Considers the impact of timing of emissions on the global warming potential - Considers the land use related warming potential in the absence of the studied bioenergy system (in comparison to a reference scenario)	- Requires predefined assumptions of global warming potential of the emissions - Requires predefined assumptions of fossil fuel displacement, and thus can be difficult to understand and communicate

Appendix 4. Analysis of estimates for GHG emissions payback time associated with production of forest bioenergy as reported in Table 1 of the JRC review (Marelli *et al.*, 2013)

Table A4.1 in this appendix presents the results of an investigation of estimates reviewed by Marelli *et al.* (2013) for GHG emissions payback time associated with production of forest bioenergy. An attempt has been made to identify structure, principally whether results can be ranked as high or low GHG emissions, and whether such results are associated with particular types of forest management and/or bioenergy feedstock. Thus, the various estimates of GHG emissions payback time in Table A4 have been classified according to:

- Forest management scenario and bioenergy production scenario (see Sections 3.6 and 3.16).
- Fossil energy scenario (i.e. fossil energy counterfactual, see Sections 3.8 and 3.16).

The results reported in Table A4.1 based on Mitchell *et al.* (2012) are for representative cases involving:

- ‘Moderate’ growth rate
- ‘Moderate’ biomass longevity
- For fossil energy system, a single value of ‘bioenergy conversion factor’ which the authors quote as an estimated average value (0.51).

Table A4.1 Analysis of estimates for GHG emissions payback time associated with production of forest bioenergy as reported in Table 1 of the JRC review (Marelli *et al.*, 2013)

Forest management /production scenario	**Fossil energy counterfactual**[1,2]			**Source**
	Coal	**Oil**	**Natural Gas**	
Harvesting of biologically mature forest with high carbon stocks for bioenergy only, followed by restoration of forest areas with high harvesting intensity for bioenergy only.	~2000			Mitchell *et al.* (2012)
Salvage logging of recently disturbed forest, with all harvested biomass used for bioenergy only, followed by restoration of forest areas with high harvesting intensity for bioenergy only.	~2000			
Diversion of harvested wood from solid wood products to bioenergy, combined with increased harvesting intensity for bioenergy only.	1000			
Harvesting of biologically mature forest with high carbon stocks for bioenergy only, followed by restoration of forest areas with low harvesting intensity for bioenergy only.	~400			Mitchell *et al.* (2012)
Salvage logging of recently disturbed forest, with all harvested biomass used for bioenergy only, restoration of harvested forest areas with low harvesting intensity for bioenergy only.	~100			
Additional harvesting of stemwood and 'residual wood' for bioenergy only in forest stands for fire prevention.	34 to 459			Mitchell *et al.* (2009)

Notes to Table A4.1:

1. Mitchell *et al.* (2012) present results for a continuous range with respect to fossil fuel counterfactual, represented by a 'bioenergy conversion factor', similar to the 'multiplier for efficiencies' defined by Marland and Schlamadinger (1997; see discussion of Figure 1.2, Section 1.2 in this current report). Results from Mitchell *et al.* (2012) are presented in this table for a single value of bioenergy conversion factor which the authors quote as an estimated average value (0.51).
2. Results presented in Mitchell *et al.* (2009) are based on a fossil fuel counterfactual which represents 'average fossil fuel'.

Table A4.1 (continued) Analysis of estimates for GHG emissions payback time associated with production of forest bioenergy as reported in Table 1 of the JRC review (Marelli *et al.*, 2013)

Forest management /production scenario	**Fossil energy counterfactual**[3]			**Source**
	Coal	**Oil**	**Natural Gas**	
Diversion of harvested wood from solid wood products to bioenergy, leaving harvesting intensity unchanged.	1 to 100			Mitchell *et al.* (2012)
Additional harvesting of stemwood in forest areas already under management for production, for bioenergy only.	Min = 11 Med = 38 Max = 230	Min = 25? Med = 87? Max = 295	Min = 59 Med = 200 Max = 400	Walker (2010), Jonker *et al.* (2013)[4], McKechnie (2011), Zanchi *et al.*(2011)
Harvesting of biologically mature forest with high carbon stocks for bioenergy only, followed by restoration of forest areas with high productivity plantation forest for bioenergy only.	17	20	25	Zanchi *et al.* (2011)
Additional harvesting of stumps for bioenergy only.[5]	15?	22	35	Repo *et al.* (2012)
Additional harvesting of pre commercial thinnings for bioenergy only.[5]	5?	12	20	Repo *et al.* (2012)
Additional harvesting of residues for bioenergy only.	0	7	16	Zanchi *et al.* (2011)
Additional harvesting of branch wood for bioenergy only.[5]	0?	5	8	Repo *et al.* (2012)
Harvesting of biologically mature forest with high carbon stocks for 50% bioenergy and 50% additional solid wood products, followed by restoration of forest areas with high productivity plantation forest for 50% bioenergy and 50% additional solid wood products.[6]	0	3?	8	Zanchi *et al.* (2011)

Notes to Table A4.1:

3. See note 1 to Table A4.1.
4. Result from Jonker *et al.* (2013) is for 'medium intensity' forest management and a fossil energy counterfactual involving coal fired power generation with 41% efficiency.
5. Estimate for fossil energy scenario of coal produced by extrapolation from other results.
6. Estimate for fossil energy scenario of oil produced by interpolation from other results.

Table A4.1 (continued) Analysis of estimates for GHG emissions payback time associated with production of forest bioenergy as reported in Table 1 of the JRC review (Marelli *et al.*, 2013)

Forest management /production scenario	**Fossil energy counterfactual**[7]			**Source**
	Coal	**Oil**	**Natural Gas**	
Diversion of harvested wood from solid wood products to bioenergy, combined with reduced harvesting intensity.	0			Mitchell *et al.* (2012)
Creation of new forests for bioenergy only on marginal agricultural land with low initial carbon stock.	0	0	0	Zanchi *et al.* (2011)
	0			Mitchell *et al.* (2012)

Notes to Table A4.1:

7. See note 1 to Table A4.1.

Appendix 5. Summary descriptions

Title and source of the study:
Mitchell, S.R., Harmon, M.E. & O'Connell Kari E.B. 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecological Applications 19(3): 643-655.
Aims and Objectives:
The paper studies the trade-offs between managing forests for fuel reduction and carbon storage. These management options involve a balance between fire restoration and carbon sequestration.
Summary of the study:
The paper looks at the trade-off between fire restoration and carbon sequestration, and its implications for the resulting long-term carbon dynamics in three U.S. Pacific Northwest ecosystems (the east Cascades ponderosa pine forests, the west cascades western hemlock-Douglas-fir forests and the Coast Range western hemlock-Sitka spruce forests). The trade-offs between these two management strategies are studied using a forest ecosystem simulation model, STANDCARB. According to the results, fuel reduction treatments in all of these ecosystems reduced fire severity. However, in order to reduce the fraction by which C is lost in a wildfire, a much greater amount of C is removed because most of the C stored in forest biomass remains untouched even in the most severe wildfires. Thus, in almost all of the areas studied, fuel reduction treatments led to reduced mean stand C storage. It was also analysed whether these losses could be compensated by utilising harvested wood as biofuel. However, the analysis implies that this won't be an effective strategy in the west Cascades or the Coast Range ecosystems over the next 100 years. Thus, the authors conclude that policies aimed solely at reducing CO_2 emissions, should not apply fuel reduction treatments in the studied areas, except for some east Cascade ponderosa pine stands with exceptionally high amount of understory fuel accumulation.
Main strength
Thorough analysis, long time period analysed.
Main weaknesses
Not clear what has been assumed about the fuels substituted with fire wood (reliance on generic emissions displacement factor).
Transparency
Moderate
Reported indicators
Mt C/ha

Title and source of the study: Walker, T., Cardellichio, P., Colnes, A., Gunn, J., Kittler, B., Perschel, B., Rechhia, C. & Saah, D. 2010. Biomass Sustainability and Carbon Policy Study. Natural Capital Initiative at Manomet Report. Massachusetts, USA: Manomet Center for Conservation Studies.
Aims and Objectives: The aim of the report is to assess what are the atmospheric greenhouse gas impacts of shifting energy production from fossil fuels to forest biomass. In addition, the report analyses how much wood is available from forests for bioenergy in Massachusetts and what are the potential ecological impacts of increased biomass and their policy implications.
Summary of the study: The timeframe of the analysis is 2010-2100. The paper looks at the stand-level response of following a single harvest event at time 0 (=2010). The carbon accumulation over time following this harvest is compared to the BAU scenario. The time period of the assessment is 90 years. An average of 88 different stands located in the state of Massachusetts in the USA is used in the assessment. Modelling is conducted with the 4 different energy scenarios assessed: utility scale electric (50 MW electric plant); thermal chips; thermal pellets and a CHP plant. Each of these is compared to different reference fossil fuel system. In the assessment, one-time biomass harvest for bioenergy is compared to the BAU where wood is only harvested for timber and no harvesting for energy wood takes place. The carbon pools covered include above-ground biomass, deadwood and litter. Soil carbon is excluded from the assessment. Walker *et al.* introduce the term carbon dividend, which reflects the additional reductions in emissions beyond what would have occurred if only fossil fuel had been used to generate energy. According to the results, technology choices or replacement of fossil fuels play an important role in determining the carbon cycle implications of biofuel use. Replacement of oil-fired thermal systems typically leads to relatively low carbon debts. Carbon debts payoff times for large-scale electricity generation are higher, varying between >90 and 45 years, depending on the replaced fossil fuel. CHP facilities on the other hand have low carbon debts. A further key finding of the study is that the carbon recovery times are also very sensitive to the forest management practices adopted by the landowners. Sensitivity analysis is conducted through a set of scenarios classified as sensitivity analysis harvests. These have been designed to elucidate the C dynamics associated with retaining versus removing tops and limbs in biomass harvests. Also different silvicultural practices are studied.
Main strengths The paper is thorough and fairly transparent in the reporting of the findings. Several different scenarios are used and also the amount of forest plots used as the basis of the assessment is wide.

Summary continued **- Title and source of the study:** Walker, T., Cardellichio, P., Colnes, A., Gunn, J., Kittler, B., Perschel, B., Rechhia, C. & Saah, D. 2010. Biomass Sustainability and Carbon Policy Study. Natural Capital Initiative at Manomet Report. Massachusetts, USA: Manomet Center for Conservation Studies.
Main weaknesses In some aspects the paper perhaps over-simplifies matters. Only carbon accumulated through tree growth is assessed, not the climate impacts of the different scenarios.
Transparency Moderate / good
Reported indicators Carbon accumulated by tree growth over 100 years.

Title and source of the study:

Werner, F., Taverna, R., Hofer, P., Thurig, E., Kaufmann, E. 2010. National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environmental Science and Policy 13: 72-85.

Aims and Objectives:

The stated aim of the paper is to assess all relevant GHG effects of different forest management and wood use scenarios while also distinguishing between national effects and effects occurring abroad. The paper attempts to demonstrate the connections of these GHG effects over a strategically relevant time scale.

Summary of the study:

In the paper, an integral model-based approach is presented and applied to assess the GHG impacts of different forest management and wood use scenarios in Switzerland. The results are intended to provide a basis for demonstrating the possible utility of the forestry and timber industry in relation to reduction of CO_2 emissions in Switzerland over long term.

The carbon pools studied include above-ground and below-ground biomass, deadwood and litter and soil carbon. The time horizon of the assessment is 100 years. Four different scenarios are assessed: Construction (increased use of wood in construction); energy (increased use of bioenergy); Kyoto-optimized (construction use of long-living wood products and subsequent energetic use) and Reduced forest management (significant reduction in wood use for construction and energy). These scenarios are compared to a baseline scenario consisting of ‘business as usual’ (extrapolation of the current, i.e. year 2000, consumption patterns). In the modelling of the forest carbon flows, the study uses the forest model MASSIMO and the YASSO soil model.

On the basis of the results, the scenarios Construction, Energy and Kyoto-optimized present the best global C balance in the long term. However, due to the sink effect, in the short term, the Reduced Forest Maintanence scenario displays the largest CO_2 savings. However, in the long-term this scenario is found to be the worst because the high stand volumes and growing stocks in the forest result in a considerable increase in natural mortality. In addition, there is a reduced substitution effect. The Energy scenario gives clearly poorer results than the Construction and Kyoto-optimized scenarios. Overall, the comparison between the different scenarios shows that the short and long term effects can be very different from one another. The BAU scenario performs worst in the short and medium term and the second worst in the long-term. The authors conclude that in the long-term the best improvement in the CO_2 balance can be achieved by the highest utilisation of the maximum increment, the processing of the resulting wood in long-lived products and end utilization for energy generation in cascade use.

Main strengths

The study also considers impacts taking place abroad. Several different scenarios are compared and also a baseline scenario is included.

Main weaknesses

Only CO_2 emissions over time are assessed, not the actual warming impacts.

Summary continued **- Title and source of the study:** Werner, F., Taverna, R., Hofer, P., Thurig, E., Kaufmann, E. 2010. National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environmental Science and Policy 13: 72-85.
Transparency Moderate
Reported indicators mt CO_2-eq./year

Title and source of the study:

Cherubini, F., Stromman, A.H. & Hertwich, E. 2011b. Effects of boreal forest management practices on the climate impact of CO_2 emissions from bioenergy. Ecological Modelling 223: 59-66.
Note: this summary is also relevant to the related paper by Cherubini, Peters, G.P., Berntsen, Stromman, and Hertwich. Published in GCB Bioenergy 3(5).

Aims and Objectives:

The paper presents a methodology, and characterisation factors to be applied in LCA for assessing the climate impacts of the use of boreal forest biomass as bioenergy.

Summary of the study:

The aim of the paper is to include the dynamic time dimension in unit-based impact analysis, using a boreal forest stand as an example. The forest growth in a typical boreal forest is approximated with the simple 'Schnute' growth equation. The study builds upon a related paper published by the same team (Cherubini *et al.* 2011a). The biomass carbon is released to the atmosphere in one time step through combustion. Thus, the resulting CO_2 emission is modelled as a single pulse. The biomass harvest comes from an even-aged vegetation stand, which is immediately re-vegetated after the harvest (clear-cut). The atmospheric decay of CO_2 is predicted as an Impulse Response Function (IRF).

The paper is not really a case-study but rather a methodological statement. It presents GWP_{bio} factors for the typical boreal forest for three different time horizons and different rotation periods. The GWPbio factors can be used in a regular LCA study as characterisation factors in the life cycle impact assessment phase to estimate the climate impacts of forest bioenergy use.

The assessment shows that the selected time horizon and growth rate play a key role for the resulting GWPbio factors. If the time horizon assessed is only 25 years, the climate impact of biogenic carbon from boreal forest stand is very close to that of fossil carbon. However, with a horizon of 100 years, the GWPbio factors range between 0.28-0.82. For the time horizon of 500 years, the GWPbio factors can be negative, depending on the rotation period and growth rate, indicating a net carbon sink.

Reference:

Cherubini, F., Peters, G.P., Berntsen, Stromman, A.T. and Hertwich, E. 2011. CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy 3(5): 413-426.

Main strengths

Presents characterisation factors that can be easily applied in life cycle impact assessment. Different time horizons (20, 100 and 500 years), growth rates and rotation periods are considered (30-130 years).

Main weaknesses

No baseline scenario is applied. Only the use of above-ground biomass is assessed. Changes in other carbon pools (such as dead-wood and soil carbon) are not included in the assessment. Only clear-cut is considered.

Summary continued **- Title and source of the study:**
Cherubini, F., Stromman, A.H. & Hertwich, E. 2011b. Effects of boreal forest management practices on the climate impact of CO_2 emissions from bioenergy. Ecological Modelling 223: 59-66.
Transparency
Good
Reported indicators
GWP_{bio} factors

Title and source of the study: Hudiburg, T., Law, B.E., Wirth, C. and Luyssaert, S. 2011. Regional carbon dioxide implications of forest bioenergy production. Nature Climate Change.
Aims and Objectives: The aim of the paper was to study the implication of fire prevention measures and large-scale bioenergy harvest on regional carbon dioxide.
Summary of the study: In Northern America there is increasing interest to meeting some of the bioenergy demands through large-scale forest thinning, with the added benefit of preventing catastrophic wildfire and carbon loss. The study aims to show whether such a strategy can satisfy both the aims of preventing wildfire and reducing regional carbon dioxide emissions. Three different scenarios are studied: 'Fire prevention' (forest fire prevention through removal of fuel ladders in fire-prone areas); 'Economically feasible' (making fuel ladder removal economically feasible through focusing on removal of additional marketable wood in fire-prone areas); 'Bioenergy production' (thinning all forestlands regardless of fire risk to support energy production and contribute to fire prevention). These are compared to the business as usual management, which is characterized by current preventive thinning and harvest levels. The timeframe of the study is 20 years. According to the results, large scale bioenergy harvest in the US West Coast forests leads to 2-14% higher emissions compared to the current management practices over the next 20 years. 19 ecoregions were studied and it was found that in 16 of these regions the carbon sink is so strong that it cannot be matched or exceeded through substitution of fossil fuels by forest bioenergy. If the sink drops below its current levels by 30-60 g C m^2/year as a result of insect damage, fire emissions or reduced primary production, management schemes including bioenergy production could become successful in reducing both fire risk and carbon emissions.
Main strength The analysis methods are thoroughly explained in the very long appendix material. The study covers all ecoregions of the area.
Main weaknesses The assessment only covers 20 years.
Transparency Good
Reported indicators Tg C / year

Title and source of the study:

Kilpeläinen, A., Alam, A., Strandman, H., Kellomäki, S., 2011. Life cycle assessment tool for estimating net CO_2 exchange of forest production. GCB Bioenergy 3(6): 461-471.

Aims and Objectives:

Introduction and demonstration of an LCA tool that can be used for studying the carbon exchanges of forest bioenergy production.

Summary of the study:

Describes an LCA tool for studying the net carbon exchange of forest production. The aim is to calculate and allocate the emissions due to changes in biogenic carbon balances for all the raw material streams from forest: energy wood, fibre wood and timber. In addition, both current climate and changed climate (based on the A2 IPCC 2007 scenario) were assessed. The emissions were calculated over the 80 yr rotation and allocated to the amount of energy or timber produced. There was no comparison to a no-use reference. According to the results, the emissions allocated for the energy from biomass were 172 and 188 kg CO_2/MWh in the current climate and in a changed climate, respectively in Southern Finland. In Northern Finland they were 199 and 157 kg CO_2/MWh, respectively. Thus, in Southern Finland the probable increased biomass growth obtained under the changed climate could not compensate for decomposition and biomass combustion related carbon loss.

Main strengths

Different scenarios assessed. The potential impacts of climate change on forest growth are taken into account.

Main weaknesses

There is no comparison to an appropriate baseline forest management/wood use scenario.

Transparency

Moderate

Reported indicators

g $CO_2/m^2/a$

Title and source of the study:

Lecocq, F., S. Caurla, P. Delacote, A. Barkaoui and A. Sauquet 2011. Paying for forest carbon or stimulating fuelwood demand? Insights from the French Forest Sector Model. Journal of Forest Economics 17(2): 157-168.

Aims and Objectives:

The aim of the paper is to compare the environmental (carbon) and economic implications of three different policies (stock, substitution and a combination of these) for the French forest sector. These three policies are compared to the business-as-usual.

Summary of the study:

The paper compares the environmental (carbon) and economic implications of three different policies (stock, substitution and a combination of these) for the French forest sector. These three policies are compared to the business-as-usual. According to the simulations over 2010-2020, the stock policy is the only one that performs better than business-as-usual in terms of carbon. In the substitution policy, cumulative substitution benefits are not high enough to offset carbon losses in standing trees over this biologically fairly short time. However, the authors emphasise that the results are contingent on three factors: the energy-mix of France is much less C-intensive than that of other countries and the substitution benefits therefore are low in terms of carbon; the substitution policy tested only concerns carbon and the assessed time-period is very short. Thus, the ranking would probably change in the long run.

Main strength

Interesting comparison of the economic and carbon implications of different forest policies.

Main weaknesses

The time period assessed is very short, covering only 10 years. The paper is not an LCA study.

Transparency

Moderate

Reported indicators

$MtCO_2$

Title and source of the study:

McKechnie, J.; Colombo, S.; Chen, J.; Mabee, W.& MacLean, H.L. 2011. Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels. Environ.Sci.Technol. 45: 789-795.

Aims and Objectives:

The paper combines LCA with forest carbon analysis in order to assess the total GHG emissions of the use of forest bioenergy over time. The method is applied to case studies in which wood pellets or ethanol are produced from forest biomass.

Summary of the study:

In the paper, LCA is combined with forest carbon analysis in order to assess the total GHG emissions of the use of forest bioenergy over time. The method is applied to case studies where wood pellets or ethanol are produced from forest biomass. The different production pathways considered in the study are: (1) electricity generation: (a) production of electricity from coal at an existing generation station (GS) in Ontario, Canada; (b) Pellet cofiring from harvest residues, production of electricity at 20% cofiring rate at a retrofit coal GS; (c) same as (b) but pellets made from standing trees; (2) Transportation: (a) reference gasoline use in LDV; (b) E85 ethanol/gasoline blended fuel use in LDV, ethanol produced from harvest residues; (c) same as (b) but ethanol produced from standing trees.

The paper takes into account all the carbon flows in the forest, including living trees, soil, standing dead trees, down dead wood, forest floor and understory vegetation pools. Forest carbon flows are calculated using the FORCARB-ON forest model, which is an Ontario specific adaptation of the FORCARB2 model.

Cumulative emissions are compared between different scenarios and a reference scenario. The reference land use scenario is posed by "current harvest baseline" where biomass is not collected for bioenergy production but timber is harvested only for the current demand of (traditional) wood products. The difference in carbon stocks between the reference and "the bioenergy harvest scenario" is allocated to the bioenergy products.

According to the results, harvest-related forest carbon emissions initially exceeded the avoided fossil fuel related emissions, thereby temporarily increasing overall emissions for all the cases studied. In the long run, electricity production from pellets reduced overall emissions relative to coal, although forest carbon losses delayed net GHG mitigation by 16-38 years, depending on the biomass source (harvest residues / standing trees). Ethanol from standing trees increased emissions throughout the 100 years of continuous production, while ethanol from residues achieved reductions after 74 years of production.

A sensitivity analysis of the key sources of uncertainty / variability in the LCI and forest carbon model parameters is conducted.

Main strengths

Attempts to include the forest dynamics in LCA. Contains several different scenarios. A sensitivity analysis is included.

Summary continued **- Title and source of the study:** McKechnie, J.; Colombo, S.; Chen, J.; Mabee, W.& MacLean, H.L. 2011. Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels. Environ.Sci.Technol. 45: 789-795.
Main weaknesses GWP factors used in the calculation of GHG emissions are not explained. Principles of the FORCARB-ON model are not explained transparently. Possible ILUC impacts are not taken into account.
Transparency Moderate / good
Reported indicators Cumulative GHG emissions ($MtCO_2$-eq.); forest carbon stock change over time ($MtCO_2$-eq.)

Title and source of the study:

Repo, A., Tuomi, M., Liski, J., 2011. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. GCB Bioenergy (2011) 3: 107–115. doi: 10.1111/j.1757-1707.2010.01065.x

Aims and Objectives:

The aim of the paper is to estimate the indirect emissions from using logging residues for bioenergy production.

Summary of the study:

The purpose of the paper is to introduce an approach for estimating the indirect CO_2 emissions caused by the use of forest residues for bioenergy production. Moreover, such emissions are estimated in a forested boreal landscape during the first 100 years after beginning of the activity. In the paper, Yasso07 model is used to estimate the indirect emissions from using logging residues for bioenergy production. The total CO_2 emissions per unit of bioenergy produced are compared to the total emissions caused by using other fuels (coal, oil, diesel and natural gas). The Yasso07 is used to estimate the emissions. The indicator presented is kg CO_2 eq./MWh. All changes in carbon emissions due to forest residue collection are allocated to forest residues.

According to the results, the indirect emissions per unit of energy produced decreased with time since starting to collect the harvest residues due to decomposition at older harvest sites. The removal of stumps caused a larger indirect emission per unit of energy produced than the removal of branches. This results from the lower decomposition rate of the stumps. Over the 100 years of conducting the activity, the indirect emissions from average-sized branches decreased from 340 to 70 kg CO_2-eq. / MWh, and those from stumps from 340 to 160 kg CO_2-eq. / MWh. The removal of harvest residues had to be continued for 22 (stumps) or 4 (branches) years before the total emissions were lower than the emissions from natural gas.

Main strength

The paper uses a dynamic approach and includes a comparison to a reference case where the logging residues are not used at all. Both branches and stumps are analysed separately, which gives one an understanding of the differences in the impacts of their utilisation.

Main weaknesses

The paper focuses on logging residues only, and does not look at the complete utilisation of harvested trees. Such a perspective would, however, have been interesting for understanding of the overall climate impacts of wood utilisation.

Transparency

Moderate / good

Reported indicators

kg CO_2 eq./MWh

Title and source of the study:

Ter-Mikaelian, M., McKechnie, J., Colombo, S., Chen, J. and MacLean, H. (2011) The carbon neutrality assumption for forest bioenergy: A case study for northwestern Ontario. Forest Chron 87(05):644-652.

Aims and Objectives:

The paper builds on a previous study by McKechnie *et al.* (2011). It assesses whether the delay in achieving net GHG reductions through forest bioenergy use could be shortened if more intensive post-harvesting silvicultural regimes were applied, or if new forest stands could be used as potential biomass source.

Summary of the study:

The paper builds on a previous study by McKechnie *et al.* (2011). It assesses whether the delay in achieving net GHG reductions through forest bioenergy use could be shortened if more intensive post-harvesting silvicultural regimes were applied, or if new forest stands could be used as potential biomass source. A case study from Ontario, Canada, is studied where coal is displaced with wood pellets in the Atikokan generating station.

Total GHG emissions related to the forest biomass use are assessed with the framework developed by McKechnie *et al.* (2011). In the framework life cycle inventory analysis (assessing the GHG emissions related to bioenergy production) is combined with forest carbon modelling (quantifying the effect of biomass harvest on forest carbon stocks over time).

Break-even and carbon-neutral periods are assessed. Break-even period refers to the time since harvest after which the total greenhouse-gas benefits of displacing coal with wood pellets, and the amount of carbon in the regenerating forest are equal to the amount of carbon in the reference scenario (i.e. the same forest with no harvest for wood pellets). Carbon neutral period refers to the time since harvest after which the amount of carbon in the forest is equal to the amount of carbon in the reference scenario (i.e. the same forest with no harvest for bioenergy). Theoretically achievable minimum carbon neutral and break-even periods were estimated to be 28 and 18 years, respectively. The minimum carbon neutral periods across all the scenarios studied varied between 28-122 years. The minimum break-even periods ranged between 18-89 years. Thus, the authors emphasize that the 28 and 18 years should be treated as optimistic because it was assumed that all forest in the studied areas would be available for wood pellet production, and the best post-harvest silvicultural regimes would be applied.

Main strengths

Several different harvest ages assessed. A no-use reference scenario is applied. All the carbon pools, including soil carbon are taken into account.

Main weaknesses

The actual warming impacts are not assessed, only cumulative carbon flows.

Transparency

Moderate

Reported indicators

t C/ha; break even period for greenhouse gas emissions (years); carbon neutral period (years)

Title and source of the study: UN-ECE and FAO 2011. The European Forest Sector Outlook Study II. United Nations. Geneva, UN-ECE, FAO. http://www.fao.org/docrep/016/ap406e/ap406e00.pdf
Aims and Objectives: The aim of the study is to address and discuss the long-term environmental consequences of possible policy choices related to forest management in Europe.
Summary of the study: In this study, four different policy scenarios and a baseline scenario are presented for the European forest sector. The calculations are carried out by the EFISCEN model. The study has been conducted at the country level but the results are presented as aggregates. To maximise the forest sector's contribution to climate change mitigation, the best strategy is to combine forest management focused on carbon accumulation in the forest (longer rotations and a greater share of thinnings) with a steady flow of wood for products and energy (Maximising biomass carbon scenario). Considering the energy substitution effects, also 'Promoting wood energy' scenario result in higher GHG benefits compared to the reference scenario. However, the impacts of the changed material demand between the particular scenarios were not considered. Furthermore compared to Maximising biomass carbon scenario, Promoting wood energy scenario results in lower GHG benefits indicating that GHG emissions are not reduced (considering the substitution credits) if the energy wood harvesting is increased from the baseline scenario level.
Main strengths Relevant for the EU in that it covers all Europe.
Main weaknesses The results of the study cannot be directly used when analysing the impacts of increasing bioenergy production on forest carbon stocks, as the wood demand for energy (and materials) is equal in all the scenarios except in *Promoting wood energy* scenario, in which the material use is to some extent lower compared to the other scenarios. Relatively short time period considered. Carbon emissions considered only on an annual basis and the results are given only for the year 2030. Parameter uncertainty only discussed qualitatively. Substitution credits only considered through a rough aggregate value.
Transparency Moderate
Reported indicators Tg C / a

Title and source of the study:

Zanchi, G., N. Pena and N. Bird 2011. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. GCB Bioenergy 4(6): 761-772.

Aims and Objectives:

The aim of the study is to compare time-dependent emission benefits from different wood sources and to thereby help identify which bioenergy sources would be more beneficial to achieve near-term emission reduction targets.

Summary of the study:

The paper compares the greenhouse gas emissions of different energy supply options based on either bioenergy or fossil fuels. Selective examples are used to show the greenhouse gas benefits of using wood from residues, additional fellings or new plantations. The study is based on the findings of previous studies, which show that climate impacts of wood bioenergy are time-dependent and can thus be different on a short to medium term compared with a long term. The method applied in the study can be used to identify time-dependent emission reductions for alternative bioenergy sources. Three different forest management scenarios are studied: increased takeoff (removal of residues); increased harvest; establishment of a new plantation (3 sub-scenarios: land with a low C stock and 2 cases of replacing an existing forest with a plantation). In addition, each scenario is compared to a baseline scenario where the forest is not harvested for bioenergy or the land is not converted to a plantation. An individual stand of 90 ha situated in the Austrian Alps is studied. One ha of the stand is cut every year. Bioenergy use is compared to three different sources of fossil fuel: coal, oil and natural gas.

According to the results, in the additional harvest scenario, bioenergy begins to provide carbon benefits after 175-230 (depending on the harvest level) if coal is substituted or after 300-400 if natural gas is substituted. In the scenario where only residues are considered, it takes 0 (coal) to 16 (natural gas) years for the bioenergy to start producing carbon benefits. Establishing bioenergy plantation on lands with low initial C stocks produces clearest C benefits. If the plantation is established on an existing forest, the situation is different. In the cases assessed, it is assumed that either high (case B) or low (case C) productivitity forest is grown on the plantation. In case B, the initial C loss is repaid within 17-25 years. Within case C it takes 114-197 to repay the initial C loss. The study concludes that the GHG benefits achieved by using woody biomass for energy can vary a lot depending on the source of biomass and the considered time-horizon.

Main strength

The paper is clearly and transparently written. Several different scenarios for both bioenergy and fossil fuel use are studied. In addition, each bioenergy scenario is compared to a counterfactual land-use scenario.

Main weaknesses

Only an individual stand is considered. Natural disturbances are not taken into account.

Transparency

Good

Reported indicators

1000 t C, t CO_2

Title and source of the study:

Böttcher H, Verkerk PJ, Gusti M, Havlík P, Grassi G (2012) Projection of the future EU forest CO_2 sink as affected by recent bioenergy policies using two advanced forest management models.

Aims and Objectives:

The aim of the paper is to assess tradeoffs in bioenergy use and carbon sequestration on a large scale covering the whole EU (except for Greece, Cyprus and Malta). In addition, two advanced forest management models are compared.

Summary of the study:

In the paper, tradeoffs of bioenergy use and carbon sequestration in the EU are assessed. Two scenarios are compared: baseline and reference scenario. The modelling is conducted with two different forest models, EFISCEN and G4M, and the results are compared. The time horizon of the study is 20-30 years (ranging from 2000 or 2010 to 2030, the exact time frame is not exactly clear). Two different scenarios are compared: baseline and reference scenarios. The baseline scenario describes the development of the EU energy demand under trends and policies implemented by April 2009. In the reference scenario, i.e. increased harvest (for bioenergy) scenario, everything is otherwise the same as in the baseline scenario, but national targets for renewable energy set in the Renewable Energy Directive and the GHG effort Sharing Decision (2009/406/EC) are assumed to be achieved by 2020.

According to the results, in the baseline scenario the net CO_2 sink of the EU forests is expected to decline by 25-40% by 2030 compared to 2010. The shift arises on the one hand from the increasing demand for wood for material and energy use, and the ageing of the EU forests on the other. The reference scenario results in a further decrease in the forest carbon sink of 4-11% compared to the baseline scenario. The authors point out that this sink is presently not accounted for as the emission reduction target of 2020 excludes land use emissions and removals. Use of the wood and substitution of reduced wood material consumption seem not to have been taken into account. Neither have impacts on forests outside the EU been included in the study.

Main strengths

Relevant for the EU in that it covers all EU. Fairly comprehensive in that it uses two different models. Uncertainty is assessed by a sensitivity analysis.

Main weaknesses

The paper is partly unclear with many of the central assumptions, concerning for example forest rotation time, not being stated. The difference between the two scenarios seems to originate from imported biomass. Considering this, it seems odd that imports and the possible direct or indirect land use change related to them have not been taken into account.

Transparency

Poor / moderate

Reported indicators

Mt CO_2 per year

Title and source of the study:

Colnes, A., K. Doshi, H. Emick, A. Evans, R. Perschel, T. Robards, D. Saah and A. Sherman (2012) Biomass Supply and Carbon Accounting for Southeastern Forests, Biomass Energy Resource Center, Forest Guild, Spatial Informatics Group.

Aims and Objectives:

The report aims to consider the atmospheric GHG impacts of an increase in the use of forest biomass for electric power generation in the South Eastern US.

Summary of the study:

Compares cumulative atmospheric CO_2eq for two different levels of biomass power generation in the south eastern US, including 7 states, and looks at GHG impacts over time. Includes forest carbon. Concludes that (17) existing biomass power stations in the region give better GHG performance than fossil fuel alternative, but that increasing by 22 additional power stations give short term carbon debt with net atmospheric carbon benefits from about 35-50 years, depending on power generation efficiency. Accepts that heat generation would show far better performance. Also considers varying parameters including different proportions of pellets exported to Europe, which shows little effect.

Main strengths

Sensitivity analysis to several criteria is included. Considers biomass switching from pulpwood to fuel and other variables including increased export of pellets to Europe.

Main weaknesses

Almost no details on LCA model.

Transparency

Low

Reported indicators

Cumulative atmospheric GHG emissions (MtCO_2-eq.); forest carbon stock change over time (MtCO_2-eq.)

Title and source of the study:

Galik CS and Abt RC (2012) The effect of assessment scale and metric selection on the greenhouse gas benefits of woody biomass. Biomass and Bioenergy **44,** 1-7

Aims and Objectives:

An attempt to evaluate the extent to which the choice of scale (boundaries) and metrics used to assess net GHG impact in woody biomass energy project analysis impact the results obtained. In particular, consideration whether the inclusion of market effects of increased biomass demand tend to give rise to a more or less favourable GHG balance.

Summary of the study:

This study attempts to investigate whether changing the geographical boundaries when considering the GHG impact of bioenergy has a significant impact on the conclusions reached and the magnitude of the net GHG implications. It also compares four different GHG metrics: Average annual GHG balance; Average annual GHG flux; Net present value of GHG flux; Annual annuity value of GHG flux.

It uses the SubRegional Timber Supply (SRTS) model (developed by one of the authors) of forest inventory, growth, harvesting and timber supply and demand. It then uses the same model of bioenergy demand: maximum co-firing with coal for the state of Virginia, and then compares the calculated GHG impacts in MgC/ha.

It concludes that in general, calculating GHG balances at the scale of state, procurement area, or landowner all give consistent net benefits each year, using cumulative GHG balance, and also initially at the forest scale (though this subsequently falls off); whereas at the plot scale it is slightly negative for the managed plot, but very highly negative for a previously unmanaged plot.

The benefits appear to be less pronounced for Annual annuity GHG flux and Average annual GHG flux, and the authors consider the Annual annuity to be the most appropriate.

Main strengths

Compares the results obtained for the same demand conditions. Shows the importance of choice of geographical scale boundaries and GHG impact metrics to conclusions drawn.

Main weaknesses

Only directly relevant to Virginia and situation modelled. As a comparative study there is little detail on assumptions. Not a full LCA study.

Transparency

Low/moderate. Unclear how readily available the model used (SRTS) is.

Reported indicators

Multiple metrics compared: Average annual GHG balance; Average annual GHG flux; Net present value of GHG flux; Annual annuity value of GHG flux.

Tonnes CO_2eq

Title and source of the study: Holtsmark, B. 2012a. Harvesting in boreal forests and the biofuel carbon debt. Climatic Change 112: 415-428.
Aims and Objectives: Aims to assess the extent to which woody biomass sourced from boreal forest can be regarded as carbon neutral, owing to the time taken for a forest stand to achieve maturity. Studies the effect of a 30% increase in harvesting of Norwegian forest on net CO_2 release to atmosphere. Considers two models: using the biomass as feedstock for wood pellet manufacture for power generation, displacing coal, and as feedstock for manufacture of second generation liquid biofuel.
Summary of the study: This study only considers the situation where woody biomass is sourced from boreal (Norwegian) forest by increasing harvesting, and using the entire harvest for either wood pellet manufacture to replace coal in large scale power generation, or as feedstock for manufacture of second generation liquid biofuel. It explicitly does not consider the use of forest residues alongside the production of sawn timber. It considers carbon stocks in 75,000 individual 1 km^2 parcels of woodland, of uneven age structure, chosen to reflect that of typical Norwegian forest. Both living and dead wood are included, however the impact of harvesting on soil carbon is ignored. Concludes that for a forest with an even aged structure, shortening the rotation cycle from 250 to 90 years reduces the carbon stock by 50%. When the harvested timber is used to manufacture pellets to replace coal in electricity generation he concludes that it takes 190 years to repay the carbon debt, and that if used to manufacture liquid biofuels it would take 340 years, where a reduced harvest rotation is used. Where increased harvest is achieved through extension of the harvest area, these times change to 135-205 years and 205-360 years respectively, depending on the impact of harvesting on subsequent tree density.
Main strengths Considers net atmospheric effect on the total forest scale rather than individual stands. Attempts a detailed model of typical Norwegian forest age structure. Considers effect of multiple harvest cycles.
Main weaknesses Only considers using the entire harvest for energy purposes, not timber products. Limited consideration of carbon dynamics: only forest carbon stock and displaced fossil fuel.
Transparency Low in the main paper, but good in supplementary material.
Reported indicators Tonnes of carbon in the atmosphere.

Title and source of the study: Krug, J., Koehl, M. & Kownatzki, D. 2012. Revaluing managed forests for climate change mitigation. Carbon Balance and Management 7: 11.
Aims and Objectives: The purpose of the paper is to review studies on the potential of unmanaged forests to sequester carbon in Central Europe.
Summary of the study: The paper presents an appraisal of published results on the potential of unmanaged forests for carbon sequestration in Central Europe. It is concluded that some studies have recorded unexpected high growth rates compared to common yield tables. There is evidence that such high growth rates relate to changed environmental conditions, such as increased N deposition and warmer temperatures. However, the authors emphasise that no uniform conclusions can be drawn on the basis of the review. It is highlighted that forests provide other mitigation potential in addition to C sequestration. It is suggested that traditional forest management concepts of "increment optimised maintenance" of relatively high biomass stocks could be revitalized. Thus, the contribution of temperate forests to climate mitigation could be improved by concentrating forest management at mature but not over-aging stands.
Main strengths Review is fairly comprehensive and deals with a relevant topic.
Main weaknesses Does not deal with the climate impacts of forest bioenergy use, only looks at carbon sequestration in unmanaged forests.
Transparency Low/moderate
Reported indicators None

Title and source of the study: Mitchell SR, Harmon ME and O'Connell KEB GCB Bioenergy (2012) **4**, 818-827. Carbon debt and carbon sequestration parity in forest bioenergy production
Aims and Objectives: Uses an ecosystem simulation model to compare the use of forest bioenergy to substitute for fossil fuels, with a counterfactual of not harvesting the wood. An estimate is made of the 'time for carbon sequestration parity', defined as the time for the use of forest bioenergy to substitute for fossil fuels to equal the carbon that would have been sequestered if the forest had been left unharvested. Analyses a range of ecosystem models and harvesting regimes to compare how carbon payback time is affected by different scenarios. Also considers the effect of different bioenergy efficiencies.
Summary of the study: Uses ecosystem simulation model LANDCARB, developed by one of the authors, to simulate the growth and harvest of woody biomass. This includes up to seven live pools of carbon, eight dead pools and three stable pools (including soil), and also charcoal (surface and buried). This is applied to nine different growth rate, mortality and (forest) biomass decomposition scenarios. Two different harvesting intensities (50% and 100%) are applied at three different harvesting frequencies (25, 50 & 100 years) and four different land use histories. These are used to calculate the time for carbon debt repayment and also carbon sequestration parity for each of nine ecosystems types, six harvesting regimes and four land use histories when using the harvest for bioenergy. In addition a range of different bioenergy usage efficiencies/counterfactuals are included corresponding to overall bioenergy conversion factors ranging from 20% to 80%. No attempt appears to have been made to allocate the harvest to a range of different applications. Depending on the previous land use history, carbon debt repayment times range from less than a year (for previously agricultural land) to over 100 years for old growth forest. Times to achieve carbon sequestration parity are significantly longer, greater than 20 years, mainly >100 years.
Main strengths Directly addresses the issue of displaced continued sequestration by the harvesting of forests. Incorporates consideration of the effects of periodic wildfires. Includes live, dead and soil forest carbon stocks. Appears to be a sophisticated model of the forest, including different scenarios with different growth rates and biomass longevities.
Main weaknesses Unsophisticated modelling of harvested timber applications. Although wood products are considered during "spin-up" stage of the model, it appears that the only biomass usage scenario is bioenergy, with no other timber products considered. Does not undertake a full LCA. Bioenergy counterfactual only included as "bioenergy conversion factor".
Transparency The LANDCARB model may be run online for two regions of Oregon. Reasonably comprehensive documentation may be downloaded for this. Otherwise transparency is limited.
Reported indicators Time to achieve carbon sequestration parity: tonnes of carbon.

Title and source of the study:

Nepal, P., P. J. Ince, K. E. Skog and S. J. Chang 2012. Projection of U.S. forest sector carbon sequestration under U.S. and global timber market and wood energy consumption scenarios, 2010–2060. Biomass and Bioenergy 45(0): 251-264.

Aims and Objectives:

The aim of the paper is to examine changes in the U.S. forest sector carbon inventory for alternative projections of U.S. and global timber markets over time.

Summary of the study:

The paper uses a spreadsheet model developed to project growth in timber growing stock inventory by three U.S. regions and two species groups (softwood and hardwood). Change in timberland by U.S. regions and scenarios over time was received from forest land projections for the most recent RPA forest assessment. Timeframe of the assessment is 50 years extending from 2010 to 2060.

Four different scenarios are assessed. The scenarios are based on the IPCC SRES scenarios released in 2000 (A1B, A2, B2 and a variant of the A1B called historical fuelwood scenario). Changes in the forest carbon stock in the different scenarios are compared to year 2010. The carbon pools included in the study are above-ground and below-ground biomass, deadwood of all live and standing dead trees above 2.5 cm diameter. Soil carbon and litter and understory vegetation are excluded as well as foliage biomass.

The results indicated that the sector’s projected capacity for carbon sequestration would be considerably changed by the use of forest resources for energy. Over the studied period, three of the scenarios (A2, B2 and HFW) displayed consistently increasing U.S. tree biomass carbon stocks, while the A1B scenario (with highest wood energy consumption) showed declining biomass carbon stock after 2045. Thus, depending on the future economic scenarios, the U.S. tree biomass carbon stock on timberland could increase by 17-72% over the next 50 years.

On the other hand, although the projected carbon stocks in wood product carbon stock increased in all the scenarios throughout the study period, the stock was projected to be the largest in scenario A1B, followed by HFW, A2 and B2 scenarios. The A2 scenario resulted in the smallest amount of carbon stocks due to lowest lumber production in it. Altogether the results indicated that the A1B scenario with a 16-fold increase in wood energy consumption, would convert U.S. timberlands to an important emission source by 2060. On the other hand, scenario HFW with the same high economic growth as in scenario A1B but with much lower wood energy consumption, would result in a c. 4-fold increase in the average annual additions to the U.S. forest sector carbon by 2060. Nevertheless, the results suggest that the decline in the sink could be partially offset over time by increased forest plantations and more intensive forest management.

Main strengths

The study is fairly comprehensive covering all the timberlands in the USA. It also assesses several different scenarios.

Main weaknesses

The period studied is fairly short, 50 years. Soil carbon has been excluded. The use phase of the wood and the possible substitution impacts have not been included. Moreover, imports are not considered nor the possible indirect land use change impacts related to wood use abroad.

Summary continued **- Title and source of the study:**
Nepal, P., P. J. Ince, K. E. Skog and S. J. Chang 2012. Projection of U.S. forest sector carbon sequestration under U.S. and global timber market and wood energy consumption scenarios, 2010–2060. Biomass and Bioenergy 45(0): 251-264.
Transparency
Moderate
Reported indicators
Tg CO_2-eq./y; Tg CO_2-eq.

Title and source of the study: Poudel, B.C., Sathre, R., Bergh, J., Gustavsson, L., Lundström, A. & Hyvönen, R. 2012. Potential effects of intensive forestry on biomass production and total carbon balance of in north-central Sweden. Environmental Science and Policy 15: 106-124.
Aims and Objectives: The objective of the paper is to assess the potential effects of intensive forest management in North-Central Sweden over the next 100 years.
Summary of the study: In the paper, the potential effects of intensive forest management on forest production in North-Central Sweden over the next 100 years are assessed. Four different scenarios are compared. These include two scenarios with increased harvest, and one scenario with increased environmental ambitions (8% forest set aside for protected reserves, 14% set aside for special environmental care). In addition, a reference scenario, "business as usual" is assessed in which the forests are assumed to be developed with the silvicultural techniques of the Swedish forestry today and with the current environmental policy. Climate change assumed in all scenarios in accordance with the SRES B2 scenario (warmer climate enhances tree growth). The reference energy scenario is formed by coal or fossil gas in stationary power plants with relative conversion efficiencies of 100% and 96%. According to the results, whole tree harvest increases in the reference scenario increases by ca. 50% over the 100 year period. Intensive forestry may increase forest production by up to 26% and annual harvest 19% compared to the Reference scenario. The largest effect on the carbon balance stems from using the increased biomass production for substitution of fossil fuels and construction materials. Total avoided emissions in the Production and Maximum scenarios are 68 Tg and 132 Tg C larger than in the Reference scenario during the 100-year period for whole tree biomass use with coal reference fuel. Environment scenario has 16 Tg less avoided C emissions than reference scenario. It is concluded that with the assumptions made, intensive forest management can significantly increase biomass production in the area over the next 100 years and thereby produce reductions in the carbon emissions.
Main strength The paper includes many different forest management scenarios and also a counterfactual energy scenario
Main weaknesses Does not consider no use of the forest residues.
Transparency Moderate / good
Reported indicators Tg C and Tg C/year

Title and source of the study:

Routa, J., Kellomäki, S. & Peltola, H. 2012. Impacts of intensive management and landscape structure on timber and energy wood production and net CO_2 emissions from energy wood use in Norway spruce. Bioenerg. Res. 5: 106-123.

Aims and Objectives:

The aim of the study is to analyse the effects of intensive management and forest landscape structure on timber and energy wood production on a site level and on a landscape level.

Summary of the study:

The paper aims to compare the impacts of landscape structure and intensive management on timber and energy wood production. Moreover, the study looks at the resulting implications on net CO_2 emissions. The calculations are conducted with the Ecosystem Model SIMA and the emission calculator tool developed by Kilpeläinen *et al.* (2011).

On the site level, for OMT sites, the emissions varied between 89-285 kg CO_2/MWh without fertilisation and 59-280 kg CO_2/MWh with fertilisation. For MT sites the emissions were 80-357 kg CO_2/MWh without fertilisation, and 67-297 kg/MWh with fertilisation. On the site level, the lowest net CO_2 emissions per year were obtained for OMT and MT sites with rotation lengths of 80 and 100 years, respectively. Per energy unit the lowest emissions resulted for OMT sites with a rotation length of 60 years and a late energy-wood thinning with very dense pre-commercial stand and fertilisation (management regime 3f), and for MT sites either with 80 years combined with fertilisation and late energy wood thinning (management regime 3f) or in a dense pre-commercial stand with a rotation length of 100 years without fertilisation but with late energy wood thinning (management regime 2).

On the landscape level, left-skewed age distribution resulted in least emissions (kg CO_2/MWh/a) on the rotation lengths of 60 and 80 yr, regardless of the fertilisation regime. Landscape structure representing normal age-class distribution outputted the least emissions for rotation length of 120 yrs. Moreover, integrated management (combined mananagement regimes 2 and 3) with fertilisation resulted in the least emissions in all cases.

Main strengths

The analysis is fairly thorough with several different scenarios.

Main weaknesses

An appropriate baseline for forest management and use of the forest raw material is not taken into account.

Transparency

Moderate / good

Reported indicators

Accumulated C over 100 years.

Title and source of the study:

Stewart W.C., and G.M. Nakamura (2012). Documenting the Full Climate Benefits of Harvested Wood Products in Northern California: Linking Harvests to the US Greenhouse Gas Inventory. Forest Products Journal 62, 340–353.

Aims and Objectives:

With a sample of partial and clear-cut harvests in Northern California, the financial and climate benefits of the harvested products are assessed. As there are many studies that argue that increased climate benefits of temperate forests could be achieved by reducing harvests below sustainable levels, the study aimed to test whether the divergence in the outcomes of the previous studies is mainly due to assumptions on the allocation of the harvested biomass to different products and waste. The article focuses only on harvested products. The authors justify this with the fact that many studies have been conducted in the USA.

Summary of the study:

The assessment covered 28 recent harvest operations conducted by five different forest owners over 6870 hectares in Northern California. The operations included a combination of partial cut and clear-cut harvests in a region containing both sawmills and wood-fired energy plants. There were no pulp mills or wood based panel plants. All the harvests in the sample were conducted under the sustainable forest practice regulations of the California Forest Practice Rules. High-value saw-logs are the main consideration of the California forest managers. The forest-types in the region are mainly dry-mixed conifer forests. The region has high risks of large-scale crown fires.

It was assumed that 75% of the saw logs ended up in wood products, 24% were used for energy and 0.9% ended up as uncollected waste. It was assumed that harvested forests continued to accumulate carbon at or above current rates. Clear-cut harvest areas are replanted and are not harvested for decades. Partial-cut harvest areas will typically be harvested every 10-20 years. On the basis of literature, a 52-year half-life was calculated for wood products manufactured in California. The use of wood for energy was assumed to be carbon neutral.

On the basis of a meta-analysis published by Sathre and O'Connor (2010) it is assumed that each ton of carbon in wood-buildings avoided an additional 1.1 tons of carbon emissions that would occurred through producing more fossil fuel intensive materials (e.g. cement and steel). 90% of future post-consumer wood is assumed to be deposited in engineered land-fills or wood-fired energy plants.

According to the authors, the difference between the previous conflicting assessments of the potential climate benefits of the temperate US forests is mainly due to using poorly documented historical estimates of wood utilization as a projection instead of current best practices as an estimate of standard practices in the coming decades. The estimates used by Stewart and Nakamura almost doubled the full cycle climate benefits (123 t $\mathrm{CO_2}$eq. per 100 t $\mathrm{CO_2}$eq. of forest biomass, vs. 66) which is a commonly cited coefficient.

Main weaknesses

The new coefficients could be grounded more. The timeframe of the assessment is not given?

Transparency

Good / moderate

Reported indicators

Climate benefits in t$\mathrm{CO_2}$eq / t $\mathrm{CO_2}$eq forest biomass.

Title and source of the study: Bernier, P. & Paré, D. 2013. Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. GCG Bioenergy 5: 67-72.
Aims and Objectives: The aim of the study is to demonstrate the application of whole ecosystem field-measured CO_2 exchanges obtained from eddy covariance flux towers for the assessment of GHG mitigation potential of forest bioenergy projects. The method enables one to integrate all field-level CO_2 fluxes and the inter-annual variability in these fluxes.
Summary of the study: The objective of the study is to demonstrate the application of whole ecosystem field-measured CO_2 exchanges obtained from eddy covariance flux towers for the assessment of GHG mitigation potential of forest bioenergy projects. As an example, a theoretical bioenergy project that uses tree stems as bioenergy feedstock is evaluated. The method enables one to integrate all field-level CO_2 fluxes and the inter-annual variability in these fluxes. According to the results, the time for carbon debt repayment greatly depends on the ecosystem level CO_2 exchanges. Despite the low carbon sequestration due to the mature stand age in the no-harvest scenario, the harvest scenario leads to a CO_2 debt that takes up to 90 years to repay (the point where the cumulative difference in emissions between the two scerios is zero). The analysis also shows that the time for CO_2 debt repayment is very sensitive to the harvesting age. In the example analysed, the harvested stands were assumed to be mature (120 years). If they were harvested earlier, the time for debt repayment is pushed much beyond 90 years. This is because the larger productivity of the younger trees makes the difference between the harvest and no-harvest scenarios greater.
Main strengths The study apparently applies a novel method that has not been used for this purpose previously. Uncertainties are discussed fairly thoroughly. Moreover, a sensitivity analysis is performed.
Main weaknesses Only one bioenergy scenario is assessed. The use of branches, leaves and residues is not assessed. Soil carbon is not included in the study.
Transparency Moderate
Reported indicators kg CO_2/GJ/year

Title and source of the study: Eliasson, P., Svensson, M., Olsson, M. & Ågren, G.I. 2013. Forest carbon balances at the landscape scale investigated with the Q model and the CoupModel – responses to intensified harvests. Forest Ecology and Management 290: 67-78.
Aims and Objectives: The aim of the study was to compare the carbon budgets under changing management regimes both on a single-stand level and on the landscape scale.
Summary of the study: A reference scenario represented the conventional management regime in Sweden: rotation forestry where only stemwood is removed and thinnings are carried out at recommended intervals. It was assumed in the reference scenario that all logging residues, including tops, are left on the site after harvest. Two management scenarios where harvest intensity was increased relative to the reference scenario were simulated: (a) stems, tops and branches (80% of the tops and branches were removed) and (b) stems, tops, branches and stumps (50% of removal of stumps at final felling, otherwise identical to scenario a. According to the results, the aggregated carbon balance over the landscape was less profound than that of a single stand. According to the authors, provided that the environmental factors and management policy stay the same, the aggregated carbon balance remains stable over time in the landscape. Nevertheless, they point out that when removal of logging residues is begun, the carbon gain starts to increase immediately, while the soil carbon responds much slower. The amount of carbon in the harvest is always larger than the amount of soil carbon lost as a result of increased harvests. The authors argue that the difference between their results and those of other papers is caused by the geographic coverage. The present paper studies carbon flows on a landscape level while some have studied only individual stands. However, this does not cause the difference. The landscape level and stand level lead to exactly the same conclusions as long as the system boundary is the same in both the studied scenario and the reference scenario. The main difference between the assessment of Eliasson *et al.* and that of e.g. Repo *et al.* (2011) or Kirkinen *et al.* (2008), is that the emissions from using the harvest residues for energy are not taken into account.
Main strengths Two different models used.
Main weaknesses Emissions from energy use of wood are not taken into account.
Transparency Good
Reported indicators Mg C ha^{-1}

Title and source of the study:

Fiorese, G. & Guariso, G. 2013. Modeling the role of forests in a regional carbon mitigation plan. Renewable Energy 52: 175-182.

Aims and Objectives:

The aim of the paper is to analyse how the management of forest for energy production contributes to the regional carbon budget. Study conducted in the Italian Emilia-Romagna region.

Summary of the study:

In the paper, the management of the forest in the Emilia Romagna region in Northern Italy for energy production is assessed. The influence of alternative management policies on carbon budget and biomass removal is compared using the CO_2FIX model. The aim is to assess how much such activities can contribute to bioenergy production and climate change mitigation on a regional level.

The study region contains many different types of forests. The most widespread species are deciduous, such as oaks, poplars and willows, while conifer forests represent 3% and mixed conifer and deciduous another 3% of the forest area. About 85-90% of the wood is harvested for energy purposes, less than 5% for wood products and the remaining is lost in the harvesting operations. In the study only energy use is assumed. Four different types of forests are considered: conifer, beech, oak and mixed. For each of these forest types, four different management strategies are compared: complete protection (no intervention and no-use); conservation (the annual net growth is removed each year); maximum annual removal (harvest maximised, respecting the 10% constraint on the litter); 5, 10 and 20 years rotation cycle (biomass harvested in regular intervals, every 5, 10 or 20 year respecting the constraint on litter). It is assumed that the amount of litter cannot deviate more than 10% from the current level.

Heat produced from the biomass is assumed to replace heat produced with natural gas. CO_2 emissions from the energy conversion of the biomass are assumed to be 0. Different management scenarios are compared in terms of the CO_2eq. fixed by the forest and CO_2eq. avoided through replacement of fossil fuels.

Within the studied scenarios, the maximum annual removal leads to the highest amount of emissions avoided per hectare in all the forest types except for beech deciduous forest. For them, the highest amount of emissions avoided is achieved with the 10 year rotation cycle. As the CO_2 emissions from energy conversion of the biomass are assumed to be zero, and the more natural gas is replaced, the better the overall carbon balance of the bioenergy system. It does not become clear from the paper why the benefits from avoided emissions are so much larger than the annual growth in the “no-use” scenario. Is the growth rate higher in the other scenarios? Is so, what is the rate? What happens to the forest carbon stock, does it remain constant? Is a considerable increase in growth rates achieved through increased harvests?

Main strengths

Part of the modelling approach and some of the assumptions made are explained clearly. Emphasis is placed also on the biodiversity impacts of increased forest biomass removal. Several different scenarios are assessed, including a “no use” scenario.

Summary continued **- Title and source of the study:** Fiorese, G. & Guariso, G. 2013. Modeling the role of forests in a regional carbon mitigation plan. Renewable Energy 52: 175-182.
Main weaknesses Not all the assumptions made in the modelling are specified. The annual growth of the forest in each of the scenarios is not specified except for the "protection" scenario. The conditions under which the conclusions of the study apply (e.g. the low growth of forests in the "protection" scenario and the apparently high growth) could be discussed more.
Transparency Moderate
Reported indicators t $CO_{2eq.}$/ha/y; t $CO_{2eq.}$/y

Title and source of the study: Jonker, J.G.G., Junginger, H.M., Faaij, A. 2013. Carbon payback period and carbon offset parity point of wood pellet production in the Southeastern USA. GCB Bioenergy (in press).
Aims and Objectives: The aim of the study is to address and discuss the long-term environmental consequences of possible policy choices related to forest management in Europe.
Summary of the study: This study examines the effect of methodological choices to determine the carbon payback time and the offset parity point for wood pellet production from softwood plantations in the South-eastern United States. The carbon accounting model GORCAM is used to model low-, medium- and high-intensity plantation management scenarios for a single stand level, an increasing stand level and a landscape level. Electricity production (MJ_e) is used as a functional unit and coal is considered as a reference fuel. No allocation procedure is applied. Emissions are expressed as absolute (actual) emissions including substitution credits. Rotation times of 20-25 years is used. This analysis points out that switching to highly productive plantations (only if sustainably managed) increases the uptake of carbon strongly, which offsets the additional emissions of silvicultural practices by far. Increased silvicultural emissions are compensated by faster (re) growth of plantations, and thereby increased uptake of carbon and increased fossil fuel displacement. However, due to the large amount of possible methodological choices and reference systems, there is a wide range of payback times and offset parity points. When the 'no-harvest' scenario is compared with the bioenergy scenarios, we conclude that initially, the carbon balance of the 'no-harvest' scenario is more favourable. However, after the carbon offset parity points (see above), the bioenergy scenarios are favourable.
Main strengths Sensitivities studied for productivity.
Main weaknesses In the stand level approach, no comparison is made to an appropriate baseline land use scenario, which certainly has influence on the conclusion about the importance of setting the system boundary, i.e. stand level vs. landscape level. The determination of the reference scenario for all the studied bioenergy scenarios is to some extent inconsistent. It is stated that the wood would be otherwise used for timber production. However, the influence of reduced timber wood supply from the region studied is not considered. The warming impact of dynamic carbon emission pulses through cumulative radiative forcing is not studied. Sensitivities are not considered for parameters other than productivity. The scope and goal of the study are to some extent unclear, e.g. the study does not determine which research questions are to be addressed. The reason why restoration of natural forests or long rotation forests are not considered as an option for plantations is not explained, thus possibly influencing the robustness of the conclusions about the GHG benefits of bioenergy use compared to forest protection.

Summary continued **- Title and source of the study:**
Jonker, J.G.G., Junginger, H.M., Faaij, A. 2013. Carbon payback period and carbon offset parity point of wood pellet production in the Southeastern USA. GCB Bioenergy (in press).
Transparency
Moderate
Reported indicators
Mg C / ha, g CO_2-eq./MJ_e

Title and source of the study:

Kallio, A.M.I., Salminen, O. & Sievänen, R. 2013. Sequester or substitute – Consequences of increased production of wood based energy on the carbon balance in Finland. Journal of Forest Economics, in press.

Aims and Objectives:

The paper compares scenarios in which the Finnish EU targets for bioenergy use are fully or partially met, to a reference case, where policies enhancing wood-based energy production are removed. The aim is to assess the trade-offs between sequestering carbon in forests and substituting wood for fossil fuels in Finland.

Summary of the study:

The purpose of the paper is to assess the net change in GHG emissions in the atmosphere in the period 2012-2035 under the assumption that Finland will achieve its RES policy goal of increasing the use of wood for energy. The policy aims at increasing the use of forest chips to 13.5 m^3 in heat and power production. Moreover, according to the targets, the use of wood for biodiesel production should be increased to 5-6 m^3. According to previous studies, this target is too high to be reached with mere wood chips and therefore pulpwood will also need to be harvested for energy. The paper considers three different scenarios: (a) 'Reference', in which policies favouring use of wood for energy are lifted in 2012; (b) 'Bio', in which all the bioenergy policies are included and a carbon price of 15 Eur/t is assumed. In addition 3 large biodiesel plants are set in operation in 2017; (c) 'Bio-no BD', which is the same as Bio, except that the biodiesel plants are excluded.

According to the results, in the scenarios Bio and Bio-no BD, the future forest carbon sequestration is reduced by a larger amount than fossil fuel emissions are reduced. This reduction comes through two factors: in the scenario Bio, reduction in the above ground biomass contributes ca. 75% to it, while the contribution of the reduction in soil carbon stocks is ca. 25%. Thus, the results suggest that reaching the policy target for wood based bioenergy, will increase the amount of carbon dioxide in the atmosphere. Increase in emissions is higher in the Bio scenario, in which production of biodiesel is included as planned under present policy. In the Bio-no BD scenario the increase in emissions is fairly small in both absolute and relative terms. The authors therefore conclude that it is possible that with less ambitious bioenergy targets and more restrictions on types of biomass that can be used for energy production, the impact on atmospheric carbon could become positive. However, this possibility has not been considered in the study.

The authors also point out that there are many other benefits obtained from the use of forests for energy, such as energy security, rural employment, and self-sufficiency. Thus, the best use of forests will depend on several, often conflicting, societal aims. However, when bioenergy policies are planned for climate change mitigation, it is important to consider their short- and medium-term impacts.

Main strength

The paper is clearly and transparently written. Considers the whole of Finland. Several different models are applied, making the assessment comprehensive. Bioenergy scenarios are compared to a counterfactual scenario.

Summary continued **- Title and source of the study:**
Kallio, A.M.I., Salminen, O. & Sievänen, R. 2013. Sequester or substitute – Consequences of increased production of wood based energy on the carbon balance in Finland. Journal of Forest Economics, in press.
Main weaknesses
Albedo is not taken into account, nor the risks of forest fires, wind damage or diseases.
Transparency
Good
Reported indicators
Mt CO_2-eq.

Title and source of the study: Lamers P, Junginger M, Dymond CC and Faaij A. GCB Bioenergy (2014). Damaged forests provide an opportunity to mitigate climate change.
Aims and Objectives: Assess the carbon implications of different management alternatives for forests in British Columbia (BC) affected by mountain pine beetle (MPB), and whether manufacturing wood pellets for bioenergy from slash (brash) and timber unsuitable as sawlogs (as a result of time since death) represents a better approach than simply making pellets from sawdust (BAU – business as usual), or no harvesting. Scenarios compared are BAU, no harvest, making pellets from slash, and making pellets from salvaged dead trees.
Summary of the study: In British Columbia (BC) considerable areas of forest have had significant mortality as a result of mountain pine beetle (MPB). Current practice is to harvest and send what is merchantable to sawmills, while slash is burned at roadside to reduce fire risk. While it is estimated that 70% of the dead trees are merchantable, as more inaccessible sites are harvested, this proportion is expected to decrease. This study aims to consider forest carbon stocks at both landscape and stand level, in the context of MPB infection and periodic wildfires, and compare carbon payback times. Harvested timber is used for a range of applications, including sawn wood for building products where possible, and also wood pellets. Pine only, pine dominated, spruce dominated and spruce & fir sites are considered. Times to carbon break-even (number of years until carbon in the harvested forest area and harvested wood and bioenergy products is lower than the pre-harvest level) and carbon parity (number of years until carbon in the harvested forest area and harvested wood and bioenergy products is lower than in the reference scenario) are the principal parameters considered. Forest carbon dynamics were simulated using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), which specifically allows inclusion of MPB infestation; usage of wood for different applications, and calculation of carbon parity, were modelled separately. Carbon substitution factors were selected for wood products (1.7 tC/tC) and wood pellets (0.923 tC/tC), but sensitivity analysis is used to consider different values. Wood products broken down into “long lived wood products” (50% of viable sawlogs), “short lived products” (pulp and paper – 35% of sawlogs) and wood pellets (15% of sawlogs, plus brash and some dead timber, depending on scenario). There is no further attempt to model a range of wood products and lifetimes. Carbon break-even times calculated range from 20 to 40 years, depending on forest type (pine/spruce/fir), for the BAU scenario, and 0 to 140 year for the no harvest scenario, and carbon parity from 0 years to 80 years when comparing to no harvesting, and 50 years to 110 year when comparing to BAU.
Main strengths Models a very specific situation (MPB infested forests in BC) in detail. Addresses insect damage and includes wildfire effect. Designed to answer specific questions about how best to manage a particular situation. Uses regionally specific tree growth curves and carbon pool dynamics to give a regionally accurate model. Allows consideration of uneven aged stands or landscapes.

Summary continued **- Title and source of the study:** Lamers P, Junginger M, Dymond CC and Faaij A. GCB Bioenergy (2014). Damaged forests provide an opportunity to mitigate climate change.
Main weaknesses Only considers a single, specific situation. Not very detailed analysis of potential range of wood products. Does not undertake full LCA. Uses single figures to represent carbon displacement by all wood products (1.7 tC/tC) and wood pellets (0.923 tC/tC), although it does undertake sensitivity analysis on these.
Transparency Uses a publically available forest model (CBM-CFS3) with documentation on the NRC website. Scenario assumptions given in supporting information tables.
Reported indicators Years to carbon parity; years to carbon break-even: tonnes of carbon.

Title and source of the study:

Matthews R, Mortimer N, Mackie E, Hatto C, Evans A, Mwabonje O, Randle T, Rolls W, Sayce M and Tubby I. 2014. Carbon impacts of using biomass in bioenergy and other sectors: forests.

Aims and Objectives:

An assessment of the potential carbon (GHG) impacts of using different types of bioenergy feedstocks (in the form of suitable woodfuels) to displace carbon (GHG) emissions from fossil fuels, against the role played by forest stocks as carbon storage facilities (including diverting wood from landfill/forest floor to bioenergy).

An assessment of the impact on carbon (GHG) emissions of diverting these woody biomass feedstocks from a range of other uses (such as construction) and from landfill at the end of the product life to bioenergy.

Summary of the study:

This report sets out to calculate lifecycle GHG emissions associated with the production of different combinations of harvested wood products, including woodfuel, per ha of forest, and compare them with emissions associated with both non-wood and imported wood counterfactuals. These are then ranked in terms of emissions benefits and compared with the option of simply leaving the forest to sequester carbon unmanaged. In order to take account of the different timescales of both emissions and sequestration (including "carbon debt"), the emissions are calculated over 20, 40 and 100 year timescales.

This report explicitly addresses the situation in the UK and the mixture of wood products potentially available from UK forests, together with some of the most realistic counterfactuals. It also explicitly addresses the concept of "carbon debt" and also sequestration foregone by current, or potential future, levels of management. Includes all carbon pools, including above and below ground biomass, litter, soil carbon and both long and short lived wood products.

Main strengths

It considers a great many different combinations of wood use scenarios, thus allowing them to be ranked in GHG benefits. Uses consequential LCA. Calculations based on emissions per ha of forest land, allowing best use of limited forest to be assessed. Includes forest carbon stock changes and both non-wood and imported wood counterfactuals for forest products. Explicitly includes both conventional "carbon debt" and sequestration lost by management.

Main weaknesses

Allocation approach not stated. Relatively limited range of counterfactuals.

Transparency

Good

Reported indicators

T CO_2-eq/ha/yr

Appendix 6. Summary of assessment against criteria of published case studies on GHG emissions of forest bioenergy

A detailed assessment was carried out of published case studies on GHG emissions of forest bioenergy, based on a set of more than 20 criteria. The full assessment is large and complex and is not included in this report. The summary in Table A6.1 is based nine of the most relevant criteria:

1. Geographical location
2. Scale (spatial)
3. Forest bioenergy feedstock
4. Bioenergy conversion system
5. Forest management scenario
6. Wood utilisation scenario
7. Counterfactual land use
8. Counterfactual energy source(s)
9. LCA approach.

For each criterion, a set of categories are defined and each published case study has been classified according to these categories. For example, Geographical location has three categories, Europe, North America and Theoretical. Of the 29 case studies covered by the meta-analysis, 15 consider locations in Europe, 13 consider locations in North America and one considers a notional, theoretical forest in an arbitrary location. Note that a total of 31 studies were included in the meta-analysis, but two papers (Cherubini *et al.*, 2011ab) were excluded from this assessment on the basis that their content was closer to a theoretical statement on methodology. Note that many studies considered several bioenergy systems or applied several methods of assessment, with the result that the totals of frequencies for most criteria are greater than 29.

Table A6.1 Summary assessment of published case studies on GHG emissions of forest bioenergy for nine criteria

Criterion	Category	Frequency
Geographical location	Europe	15
	North America	13
	Theoretical (notional forest in arbitrary location)	1
Scale	Individual stand	8
	Forest holding/landscape	10
	Region of country	12
	Country	4
	Region of world	2
Forest bioenergy feedstock	All (additional) harvested biomass	15
	All (additional) stemwood	4
	Raw sawlogs	2
	Sawlog co-products	3
	Small roundwood	2
	Harvest residues	14
	Recycled/waste wood	0
	Other	2
	Ambiguous	3
Bioenergy conversion system	Small scale heat	3
	District heat	6
	Power only (combustion)	10
	Power only (other, e.g. gasification, pyrolysis)	0
	Power only (co-firing)	1
	Combined heat and power	6
	Other	1
	Ambiguous	10
	Not stated	2
Forest management scenario	Business as usual	3
	Additional extraction on harvest	9
	Additional harvest	17
	Shortened rotation	4
	Conversion to plantation	2
	Enrichment of growing stock	1
	Afforestation	2
	Other	9
	Ambiguous	2
Wood utilisation scenario	Low value wood	17
	Diversion from use as material	4
	Other	14

Table A6.1 (continued) Summary assessment of published case studies on GHG emissions of forest bioenergy for nine criteria

Criterion	Category	Frequency
Counterfactual land use	Business as usual	20
	No harvesting	11
	No forest	2
	None	3
	Other	1
	Not stated	1
Counterfactual energy source(s)	Coal	12
	Oil	5
	Natural gas	7
	Unspecified/generic fossil energy source or mix	4
	None	6
	Other (e.g. detailed BAU scenario at large scale)	5
	Ambiguous	1
LCA approach	Consequential	22
	Attributional	4
	Other	3
	Unclear/not stated	6

Appendix 7. Assessment of transparency of case studies on GHG emissions of forest bioenergy

The assessment of transparency presented in Table A7.1 is based on seven tests:

1. A broad description is given of calculation methods, and of data, results and parameters used in calculations.
2. Citations are given for all data, results and parameters used in calculations.
3. All data results and parameters used in calculations are presented, with original sources and references cited where appropriate.
4. Citations are given for published statements of methods, models and approaches which set out the general principles adopted in calculations.
5. In addition to Test 4, it is stated that the published statements describe in detail the methods, models and calculation steps used.
6. Aspects of the detailed calculation methods and data, results and parameters used in calculations are described.
7. The calculation methods employed and the data, results and parameters referred to in calculations are fully described, so that it is possible to replicate the calculations and results.

Brief comments are also made on each paper.

The study of Ros *et al*. (2013) is not included in this analysis since it is a subject of discussion in Section 5.4.

Table A7.1 Meta-analysis of transparency in published case studies

Source	Test							Comments
	1	**2**	**3**	**4**	**5**	**6**	**7**	
Mitchell *et al.* (2009)	Y	Y	Y	Y	Y	Y	N	Detailed descriptions of models + input parameters used in the calculation are given in appendices.
Walker *et al.* (2010)	Y	Y	Y	Y	N	Y	N	A very long document with extensive appendices giving references and source data.
Werner *et al.* (2010)	Y	Y	N	Y	Y	N	N	Some assumptions given. Interaction between models explained.
Cherubini *et al.* (2011a)	Y	Y	Y	Y	Y	Y	Y	The paper proposes and describes a model in detail. References are given for equations and assumptions. No forest data is required. The paper is similar to Cherubini et al (2011b).
Cherubini *et al.* (2011b)	Y	Y	Y	Y	Y	Y	Y	The paper proposes and describes a model in detail. References are given for equations and assumptions. No forest data is required. The paper is similar to Cherubini et al (2011a).
Hudiburg *et al.* (2011)	Y	Y	N	Y	N	Y	N	The paper includes very little data, but following the link to www.nature.com gives supplementary information.
Kilpeläinen *et al.* (2011)	Y	Y	Y	Y	N	Y	N	Describes an LCA model, but does not give detailed description of all the calculations undertaken by the model.
Lecocq *et al.* (2011)	Y	N	N	Y	N	N	N	No information on the source of the data. Possibly it is data embedded within the model used, but the paper does not say this.
McKechnie *et al.* (2011)	Y	Y	Y	Y	N	Y	N	The supporting information to the paper is the main basis of the assessment.
Repo *et al.* (2011)	Y	Y	N	Y	N	Y	N	Good description of methods and approaches, but full knowledge of assumptions and replication of work would require understanding of and access to Yasso07 decomposition and soil carbon model.
Ter-Mikaelian *et al.* (2011)	Y	Y	N	Y	N	Y	N	
UN-ECE (2011)	Y	Y	N	Y	N	Y	N	Key forest resource indicators used in scenarios are given. Models used are not described in detail. The extensive nature of the work and the number of models used would make the calculations difficult to replicate.
Zanchi *et al.* (2011)	Y	Y	N	Y	N	Y	N	Very good explanation of calculation steps, including relevant equations.
Böttcher *et al.* (2012)	Y	Y	N	Y	N	N	N	Several models and several datasets are used and all are referenced. None of the actual datasets/input parameter values are given in the paper, possibly because they are so extensive.
Colnes *et al.* (2012)	Y	N	N	N	N	Y	N	A literature review and the development of a carbon accounting model. Data and references given in appendix.
Galik and Abt (2012)	Y	N	N	Y	N	Y	N	Comparison of results variation with assessment scales - one model used for all scales. Assumptions and input parameters for the model not given.

Table A7.1 (continued) Meta-analysis of transparency in published case studies

Source	**Test**							**Comments**
	1	**2**	**3**	**4**	**5**	**6**	**7**	
Holtsmark (2012a)	Y	Y	N	Y	N	Y	N	Note that model descriptions and calculation steps are provided in the supplemental online data.
Krug *et al.* (2012)	Y	Y	N	N	N	Y	N	A critical appraisal of published research results. It does not include calculations so it is difficult to score the tests.
Mitchell *et al.* (2012)	Y	Y	N	Y	N	Y	N	The model used is described in the text and referenced. Some input parameters are given.
Nepal *et al.* (2012)	Y	Y	N	Y	N	N	N	Various models used to investigate scenarios. Some of the assumptions/inputs to the models are stated. A spreadsheet model is developed and used, but not described in detail.
Poudel *et al.* (2012)	Y	Y	N	Y	N	N	N	Various models used to investigate scenarios. Parameters used for these models not stated. General description of method, but little information regarding detailed calculations.
Repo *et al.* (2012)	Y	Y	N	Y	N	Y	N	Some description of detailed calculation methods given. Some input parameters given
Routa *et al.* (2012)	Y	Y	Y	Y	N	Y	N	Good description of methods and approaches, but full knowledge of assumptions and replication of work would require understanding of and access to SIMA ecosystem model and an LCA tool emissions calculations tool. Parameters for the emissions calculation are given in the paper.
Stewart and Nakamura (2012)	Y	Y	N	Y	N	Y	N	Utilises source data collected by the authors. Some of this data is presented.
Bernier and Paré (2013)	Y	Y	Y	Y	N	Y	N	
Eliasson *et al.* (2013)	Y	N	N	Y	N	N	N	Models used are described in outline and referenced, but very little information regarding parameters and scenario assumptions is given.
Fiorese and Guariso (2013)	Y	Y	N	Y	N	Y	N	Models used are described in some detail and referenced. Some detailed calculation steps also given.
Jonker *et al.* (2013)	Y	Y	Y	Y	Y	Y	N	Model described and referenced. States that reference provides detailed explanation of model. Text states that all relevant input parameters for the model are described in Appendix.
Kallio *et al.* (2013)	Y	Y	N	Y	N	N	N	Some assumptions given, though judged not to be a complete set of assumptions.
Lamers *et al.* (2014)	Y	Y	N	Y	N	Y	N	
Matthews *et al.* (2014)	Y	Y	N	Y	Y	Y	N	Not all input data and parameters presented, but models are described, indicating that the references given provide details about the models.

Appendix 8. Meta-analysis of methodological choices, scenario assumptions and model parameterisation in published case studies

The assessment in this appendix builds on the meta-analysis presented in Lamers and Junginger (2013), which compares the methodological choices, scenario assumptions and model parameterisation adopted in individual case studies (see Table 1 in Lamers and Junginger, 2013). Most of the criteria referred to in Table A8.1 derive directly from Lamers and Junginger, where they are described and discussed. In addition, Table A8.1 lists the time horizons adopted in individual case studies.

Table A8.1 Meta-analysis of methodological choices, scenario assumptions and model parameterisation in published case studies

Source	**Methodology**	**Forest data**	**Post-harvest carbon cycling**	**Full LCA**	**Baseline**	**Time horizon**	**Model**
Mitchell *et al.* (2009)	Fixed landscape	Representative theoretical plots	Y	N	BAU (current patterns of FM).	500	STANDCARB
Walker *et al.* (2010)	Stand-level	Representative theoretical plots	Y	Y	Essentially BAU forest management. Oil for heat or CHP. Coal for electricity. Natural gas for heat. Natural gas for electricity.	90	US Forest Service Forest Vegetation Simulator
Werner *et al.* (2010)	Dynamic landscape	Swiss National Forest Inventory	Y	Y	BAU (current patterns of FM, wood and fossil energy use).	100	MASSIMO, Yasso and Swiss timber industry model
Cherubini *et al.* (2011a)	Fixed landscape	Representative theoretical plots	N	N	-		Bern 2.5CC
Cherubini *et al.* (2011b)	Stand-level	Representative theoretical plots	N	N	No harvest (but no additional tree growth).		Bern 2.5CC
Hudiburg *et al.* (2011)	Dynamic landscape	Geospatially explicit (California, Oregon and Washington, USA)	Y	Y	Protection, no harvest.	20	NCAR CESM/ CLM4-CN
Kilpeläinen *et al.* (2011)	Stand-level	Representative, theoretical plots	N	N	None.	80	SIMA
Lecocq *et al.* (2011)	Dynamic landscape	French Regional Forest Inventories	N	N	BAU (current patterns of FM, wood and fossil energy use).	100	FFSM (French Forest Sector Model)

Table A8.1 (continued) Meta-analysis of methodological choices, scenario assumptions and model parameterisation in published case studies

Source	Methodology	Forest data	Post-harvest carbon cycling	Full LCA	Baseline	Time horizon	Model
McKechnie *et al.* (2011)	Dynamic landscape	Geospatially explicit (Ontario, Canada)	Y	Y	Decay of harvest residues + coal electricity. Decay of harvest residues fossil transport fuel. Protection (natural disturbances) + coal electricity. Protection (natural disturbances) + fossil transport fuel.	100	FORCARB-ON
Repo *et al.* (2011)	Fixed landscape	Representative, theoretical plots	Y	Y	BAU (timber harvest only), decay of residues + fossil fuel electricity.	100	Yasso07
Ter-Mikaelian *et al.* (2011)	Dynamic landscape	Geospatially explicit (Ontario, Canada)	Y	Y	Protection (natural disturbances) + coal electricity.	250	FORCARB-ON
UN-ECE (2011)	Dynamic landscape	European National Forest Inventories	N	N	BAU (current patterns of FM, wood and fossil energy use).	21	EFISCEN
Zanchi *et al.* (2011)	Fixed landscape	Representative, theoretical plots	Y	N	BAU (timber only harvest, agriculture) + coal/oil/natural gas electricity.	400	GORCAM
Böttcher *et al.* (2012)	Dynamic landscape	Forest inventory data for EU Member States (not including Cyprus, Greece, Malta)	N	N	Business as usual (current patterns of forest management, wood and fossil energy use, in the absence of RED and ESD). Business as usual energy consumption (market mediated displacement).	21	G4M, EFISCEN, GLOBIOM
Colnes *et al.* (2012)	Dynamic landscape	Geospatially explicit (Southeast USA)	Y	Y	BAU (timber only harvest) + fossil electricity (several).	100	Combination
Galik and Abt (2012)	Dynamic landscape	Geospatially explicit (Virginia, USA)	Y	N	BAU (current forest management, wood use). Coal fired electricity generation without co-firing.	25	FORCARB/SRTS

Table A8.1 (continued) Meta-analysis of methodological choices, scenario assumptions and model parameterisation in published case studies

Source	Methodology	Forest data	Post-harvest carbon cycling	Full LCA	Baseline	Time horizon	Model
Holtsmark (2012a)	Fixed landscape	Representative, theoretical plots	Y	N	BAU (timber harvest only) + coal electricity. BAU (timber harvest only) + fossil transport fuel.	400	Statistics Norway internal
Krug *et al.* (2012)	Fixed landscape	Empirical CO_2 flux data	N	N	None.	Current conditions	Meta-analysis of CO_2 flux measurements
Mitchell *et al.* (2012)	Fixed landscape	Representative, theoretical plots	Y	N	No use, natural disturbances, range of fossil energy sources.	10 000	LANDCARB
Nepal *et al.* (2012)	Dynamic landscape	Regional US forest inventory data	N	N	BAU (historical forest bioenergy harvest levels).	Year 2030	Spreadsheet model
Poudel *et al.* (2012)	Dynamic landscape	Regional Swedish forest inventories	Y	N	BAU (current patterns of FM, wood and fossil energy use).	100	BIOMASS, HUGIN, Q-model, wood products and bioenergy substitution model
Repo *et al.* (2012)	Fixed landscape	Representative, theoretical plots	Y	Y	BAU (timber harvest only), decay of residues + fossil based electricity.	100	Yasso07
Routa *et al.* (2012)	Stand and fixed landscape	Representative theoretical plots	N	N	-	120	SIMA
Stewart and Nakamura (2012)	Fixed landscape	Californian forest inventory	N	N	None.	None, implicitly current conditions	
Bernier and Paré (2013)	Fixed landscape	Empirical carbon flux data	Y	Y	Protection + oil heating.	120	Chrono-sequence of flux-net data

Table A8.1 (continued) Meta-analysis of methodological choices, scenario assumptions and model parameterisation in published case studies

Source	Methodology	Forest data	Post-harvest carbon cycling	Full LCA	Baseline	Time horizon	Model
Eliasson *et al.* (2013)	Stand and fixed landscape	Representative, theoretical plots	N	N	-	300	Q, Coup
Fiorese and Guariso (2013)	Stand and fixed landscape	Representative, theoretical plots	N	N	None.	100	CO_2FIX. Yasso07
Jonker *et al.* (2013)	Stand and fixed landscape	Representative, theoretical plots	Y	Y	Protection, no harvest and BAU.	75	GORCAM
Kallio *et al.* (2013)	Dynamic landscape	Finnish national forest inventory	N	N	A scenario resembling BAU (timber only harvest).	23	MELA, YASSO, SF-GTN
Ros *et al.* (2013)	Dynamic landscape	Regional National Forest Inventories within EU	N	N	BAU (current patterns of FM, wood and fossil energy use).	400	EFISCEN
Lamers *et al.* (2014)	Stand and fixed landscape	Representative, theoretical plots	Y	Y	Branchwood: burning at roadside. Protection (no use), disturbance BAU (timber only harvest).		CBM-CFS3
Matthews *et al.* (2014)	Stand and fixed landscape	Representative, theoretical plots	Y	Y	No use, fossil energy and non-wood products.	20, 40, 100	CSORT and spreadsheet model

Appendix 9. Meta-analysis of published results for GHG emissions associated with forest bioenergy

In Table A9.1 of this appendix, results relating to the GHG emissions associated with the production and consumption of forest bioenergy are collated and listed along with essential information about the type of forest management, production scenario, conversion technology, and details of any baseline scenario referred to in an individual case study. The format in Table A9.1 is based on the approach adopted in Tables 1 and 3 of the JRC technical report (Marelli *et al.*, 2013), with certain elaborations, e.g. to accommodate results for GHG emissions expressed in different units. An attempt has also been made to clarify details of forest management, production and baseline scenarios where this may assist with interpretation. The various case studies are classified with respect to a number of factors:

- Source (i.e. the publication in which the case study can be found)
- Geographical location
- Forest management/production scenario (i.e. the type of forest management, biomass extraction, processing and conversion involved in supplying the forest bioenergy)
- Counterfactual scenario (i.e. where relevant, the type of forest management and biomass extraction that would have occurred if the forest bioenergy were not to be supplied)
- Result type (essentially the metric used for presenting results, for example GHG emissions payback time, attributed emissions etc. and associated units where relevant)
- Result value
- Comments.

Wherever possible, results included in Appendix 9 are expressed as GHG emissions payback times (see Section 5.2.1). This has involved some interpretation and manipulation of results actually presented in some individual case studies.

It is important to understand that results for GHG emissions payback times reported in Table A9.1 have not always been calculated consistently. Rather, the details of calculations may be context-specific. For examples where harvesting is introduced in forests that were not previously in management for production, the payback time most likely relates to the period required to recoup the loss of forest carbon stocks as a result of the introduction of harvesting. For examples where forests are already in management for production (i.e. this is the business as usual scenario), but changes are made to existing management, the payback time is likely to represent the period required to achieve net GHG emissions reductions, compared to a business as usual reference case.

It should be noted that the results of Eliasson *et al*. (2013) have been excluded from this analysis partly for reasons suggested in the summary description in Appendix 5), and partly due to difficulties in interpreting the study results.

Table A9.1 Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Mitchell *et al.* (2009)	Northwest USA	Coast range forest type ('old growth' stand types): forest biomass removed for fire prevention, involving understory removal, overstorey thinning, and prescribed fire every 25 years. Harvested wood used for bioenergy only.	Non-implementation of fire prevention measures. Assumed emissions displacement factor representative of solid biomass displacing US average fossil energy mix.	Payback time	169	Referred to in JRC review and Lamers and Junginger.
			Forest management same as previous entry. Assumed fossil energy emissions displacement factor representative of liquid transport fuel replacing fossil transport fuel.		201	
		Coast range forest type ('secondary' stand types): forest biomass removed for fire prevention, involving understory removal, overstorey thinning, and prescribed fire every 25 years. Harvested wood used for bioenergy only.	Forest management same as previous entry. Assumed emissions displacement factor representative of solid biomass displacing US average fossil energy mix.		34	
			Forest management same as previous entry. Assumed fossil energy emissions displacement factor representative of liquid transport fuel replacing fossil transport fuel.		339	
		West cascades forest type ('old growth' stand types): forest biomass removed for fire prevention, involving understory removal, overstorey thinning, and prescribed fire every 25 years. Harvested wood used for bioenergy only.	Forest management same as previous entry. Assumed emissions displacement factor representative of solid biomass displacing US average fossil energy mix.		228	
			Forest management same as previous entry. Assumed fossil energy emissions displacement factor representative of liquid transport fuel replacing fossil transport fuel.		459	
		West cascades forest type ('secondary' stand types): forest biomass removed for fire prevention, involving understory removal, overstorey thinning, and prescribed fire every 25 years. Harvested wood used for bioenergy only.	Forest management same as previous entry. Assumed emissions displacement factor representative of solid biomass displacing US average fossil energy mix.		107	
			Forest management same as previous entry. Assumed fossil energy emissions displacement factor representative of liquid transport fuel replacing fossil transport fuel.		338	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Walker *et al.* (2010)	Northeast USA	Additional felling of stemwood and also extraction of harvest residues to supply bioenergy only (3 scenarios with increasing levels of felling).	Essentially 'business as usual' forest management. Oil for heat or CHP.	Payback time	3 to 15	Referred to in JRC review.
			Forest management same as previous entry. Coal for electricity generation.		12 to 32	
			Forest management same as previous entry. Natural gas for heat.		17 to 37	
			Forest management same as previous entry. Natural gas for electricity generation.		59 to > 90	
Werner *et al.* (2010)	Switzerland	Optimisation of harvesting from forests (e.g. selection of rotations) for production of wood for construction plus bioenergy (co-production).	Business as usual (current patterns of forest management, wood and fossil energy use).	Payback time	0	Interpreted from annual trajectories of GHG emissions reported in paper.
Hudiberg *et al.* (2011)	Northwest USA	Fire prevention measures	No fire prevention measures. Fossil energy counterfactual unclear, possibilities are regional energy consumption or coal.	Consequential (increase in) GHG emissions (MtC yr^{-1})	2.3	Referred to in Lamers and Junginger.
		Fire prevention measures with associated harvesting of biomass for bioenergy.			9.5	
		Harvesting of biomass for bioenergy only, regardless of fire risk.			20.3	
Kilpeläinen *et al.* (2011)	Finland	Increased harvesting of stemwood for solid wood products and bioenergy, use of wood for bioenergy restricted to feedstocks unsuitable for materials.	None.	Attributed GHG emissions ($kgCO_2$ MWh^{-1})	~180	
Lecocq *et al.* (2011)	France	Increased extraction of harvest residues for bioenergy. Several scenarios for bioenergy use, co-firing for electricity considered here.	Conservation of forest carbon stocks (i.e. 'no use'). Coal fired electricity generation without co-firing.	Payback time	~20	Interpreted from annual trajectories of GHG emissions reported in paper.
		Increased harvesting of trees for bioenergy only. Several scenarios for bioenergy use, co-firing for electricity considered here.			~40	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
McKechnie *et al.* (2011)	Canada (Ontario)	Additional felling of stemwood to supply bioenergy only. Co-firing for electricity.	Business as usual (current patterns of forest management, wood and fossil energy use, implying conservation of forest areas where additional felling takes place). Coal fired electricity generation without co-firing.	Payback time	38	Referred to in JRC review and Lamers and Junginger.
		Additional felling of stemwood to supply bioenergy only. Transport fuel.	Forest management same as previous entry. Fossil transport fuel.		> 100	
		Increased extraction of harvest residues for bioenergy. Co-firing for electricity.	Forest management same as previous entry. Coal fired electricity generation without co-firing.		16	
		Increased extraction of harvest residues for bioenergy. Transport fuel.	Forest management same as previous entry. Fossil transport fuel.		74	
Repo *et al.* (2011)	Finland	Increased extraction of harvest residues (branchwood) for bioenergy (electricity generation).	Business as usual (no extraction of harvest residues). Coal fired electricity generation.	Payback time	0	Referred to in Lamers and Junginger.
			Forest management same as previous entry. Oil fired electricity generation.		3	
			Forest management same as previous entry. Natural gas fired electricity generation.		4	
		Increased extraction of harvest residues (stumps) for bioenergy (electricity generation).	Forest management same as previous entry. Coal fired electricity generation.		0	
			Forest management same as previous entry. Oil fired electricity generation.		15	
			Forest management same as previous entry. Natural gas fired electricity generation.		22	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Ter-Mikaelian *et al.* (2011)	Canada (Ontario)	Additional felling of stemwood to supply bioenergy only. Co-firing for electricity.	Business as usual (current patterns of forest management, wood and fossil energy use, implying conservation of forest areas where additional felling takes place). Coal fired electricity generation without co-firing.	Payback time	42 to 105 (mean 61)	Referred to in Lamers and Junginger.
UN-ECE (2011)	Europe	Four policy scenarios: (1) maximising biomass carbon without affecting the level of harvest; (2) priority to biodiversity; (3) promoting wood energy; (4) fostering innovation and competitiveness.	Assumed fossil energy emissions displacement factor for fossil energy counterfactual.	Qualitative-quantitative socio-economic score	-	European Forest Sector Outlook Study (EFSOS II). Referred to in Lamers and Junginger.
Zanchi *et al.* (2011)	Austria	Additional felling in conifer forests, harvest levels constrained to be less than forest increment. Stemwood used for bioenergy only.	Business as usual (current patterns of forest management, wood and fossil energy use). Coal fired electricity generation.	Payback time	175	Referred to in JRC review and Lamers and Junginger.
			Forest management same as previous entry. Oil fired electricity generation.		230	
			Forest management same as previous entry. Natural gas fired electricity generation.		300	
		Additional felling in conifer forests, harvest levels not constrained to be less than forest increment. Stemwood used for bioenergy only.	Forest management same as previous entry. Coal fired electricity generation.		230	
			Forest management same as previous entry. Natural gas fired electricity generation.		295	
			Forest management same as previous entry. Natural gas fired electricity generation.		400	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Zanchi *et al.* (2011)	Austria	Increased extraction of harvest residues (essentially branch wood) for bioenergy (electricity generation).	Business as usual (no extraction of harvest residues). Coal fired electricity generation.	Payback time	0	Referred to in JRC review and Lamers and Junginger.
			Forest management same as previous entry. Oil fired electricity generation.		7	
			Forest management same as previous entry. Natural gas fired electricity generation.		16	
		Clearfelling of existing forest and replacement with low-productivity short rotation forest plantation (harvested on a 20 years rotation). All harvested wood for bioenergy (electricity generation).	Business as usual (no production, constant carbon stock). Coal fired electricity generation.		114	
			Forest management same as previous entry. Oil fired electricity generation.		145	
			Forest management same as previous entry. Natural gas fired electricity generation.		197	
		Clearfelling of existing forest and replacement with high-productivity short rotation forest plantation (harvested on a 10 years rotation). All harvested wood for bioenergy (electricity generation).	Business as usual (no production, constant carbon stock). Coal fired electricity generation.		17	
			Forest management same as previous entry. Oil fired electricity generation.		25	
			Forest management same as previous entry. Natural gas fired electricity generation.		20	
		Clearfelling of existing forest and replacement with high-productivity short rotation forest plantation for bioenergy production (harvested on a 10 years rotation). Harvested wood from initial clearfelling used for solid wood products and bioenergy (co-production). Bioenergy used for electricity generation.	Business as usual (no production, constant carbon stock). Coal fired electricity generation.		0	
			Forest management same as previous entry. Natural gas fired electricity generation.		8	
		Afforestation of low grade agricultural land with low initial carbon stock.	Business as usual (continues as agricultural land). Coal, oil or natural gas fired electricity generation.		0	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Böttcher *et al.* (2012)	EU24	Increased harvest (for bioenergy): same as baseline scenario but with changes to meet national targets for renewable energy set in the RED and the GHG Effort Sharing Decision (2009/406/EC) by 2020.	Business as usual (current patterns of forest management, wood and fossil energy use, in the absence of RED and ESD). Business as usual energy consumption (market mediated displacement).	Consequential (decrease in) carbon sink compared to BAU (Mt CO_2 yr^{-1})	10 to 30	Referred to in Lamers and Junginger.
Colnes *et al.* (2012)	Southeast USA	Additional thinning and felling of stemwood in plantations for bioenergy only. Biomass-fired electricity generation.	Business as usual (current patterns of forest management, wood and fossil energy use). Several fossil energy counterfactuals, coal fired electricity generation considered here.	Payback time	35	Referred to in Lamers and Junginger.
			Forest management same as previous entry. Several fossil energy counterfactuals, natural gas fired electricity generation considered here.		50	
Galik and Abt (2012)	Southeast USA (Virginia)	Additional thinning and felling of stemwood in plantations for bioenergy only. Biomass-fired electricity generation.	Business as usual (current patterns of forest management, wood and fossil energy use, implying conservation of forest areas where additional felling takes place). Coal fired electricity generation without co-firing.	Consequential (increase in) GHG emissions compared to BAU (tC ha^{-1} yr^{-1})	-	Very variable with spatial scale/ system boundary.
Holtsmark (2012a)	Norway	Additional felling of stemwood for bioenergy only. Biomass fired electricity generation.	Business as usual (current patterns of forest management, wood and fossil energy use). Assumed fossil energy emissions displacement factor (broadly representing coal fired electricity).	Payback time	190	Referred to in JRC review and Lamers and Junginger.
		Additional felling of stemwood for bioenergy only. Biomass derived transport fuels.	Forest management as previous entry. Assumed fossil energy emissions displacement factor (broadly representing fossil transport fuels).		340	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Krug *et al.* (2012)	Europe	Forests not in management for production.	None.	Net CO_2 flux (tCO_2 ha^{-1} yr^{-1})	-	
Mitchell *et al.* (2012)	Northwest USA	Afforestation, various forest management scenarios (thinning intensities and rotations for felling).	Ex-agricultural land. A range assumed for a fossil energy emissions displacement factor (value here based on quoted US average fossil fuel).	Payback time	0	Based on discussion of scenario in paper.
		Partial felling ('thinning') of trees for bioenergy only, instead of for solid wood products (diversion of wood feedstock), rotations for partial fellings of 25, 50 or 100 years.	Business as usual (current patterns of forest management, wood and fossil energy use). Represented by felling of trees for solid wood products and bioenergy every 50 years. A range assumed for a fossil energy emissions displacement factor (value here based on quoted US average fossil fuel).		4	Referred to in JRC review.
		Clearfelling of trees for bioenergy only, instead of for solid wood products (diversion of wood feedstock), rotations of 25, 50 or 100 years.			4 to 1000	Sensitive to rotation of forest management scenario.
		Salvage logging of recently disturbed forest for bioenergy only. On restoration of forest, partial felling ('thinning') of trees for bioenergy only, instead of for solid wood products (diversion of wood feedstock), rotations for partial fellings of 25, 50 or 100 years.			100 to 125	Sensitive to rotation of forest management scenario. Referred to in JRC review.
		Salvage logging of recently disturbed forest for bioenergy only. On restoration of forest, clearfelling of trees for bioenergy only, instead of for solid wood products (diversion of wood feedstock), rotations for partial fellings of 25, 50 or 100 years.			400 to 2500	
		Partial felling ('thinning') of old growth forest on rotations of 25, 50 and 100 years.			315 to 600	
		Clearfelling of old growth forest on rotations of 25, 50 and 100 years.			900 to 2500	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Nepal *et al.* (2012)	USA forest sector	Four different scenarios involving forest management required for wood consumption based on the SRES scenarios of the IPCC 2000 (A1B, A2, B2 and a variant of the A1B called historical fuelwood or HFW scenario). The A1B scenario is considered here.	Arguably the HFW scenario (effectively, current patterns of forest management, wood and fossil energy use). Business as usual consumption of solid wood products and energy including bioenergy (market mediated displacement).	Consequential (decrease) in carbon sink in forests and harvested wood products (MtCO$_2$ yr^{-1})	200	
Poudel et al. (2012)	North-central Sweden	Two scenarios with increased harvesting of wood for solid wood products and bioenergy. One scenario with increased environmental ambitions (8% forest set aside for protected reserves, 14% set aside for special environmental care). Increased production scenarios considered here.	Business as usual (current patterns of forest management, wood and fossil energy use). Business as usual consumption of solid wood products and energy including bioenergy (market mediated displacement). Climate change assumed in all scenarios in accordance with the SRES B2 scenario (warmer climate enhances tree growth).	Payback time	0	Both production scenarios Interpreted from decadal values reported in paper. Negligible over first 10 to 20 years.

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Repo *et al.* (2012)	Finland	Increased extraction of harvest residues (branchwood) for bioenergy (electricity generation).	Business as usual (no extraction of harvest residues). Coal fired electricity generation.	Payback time	0	Sensitive to region in Finland (south to north). Referred to in JRC review and Lamers and Junginger.
			Forest management same as previous entry. Oil fired electricity generation.		3 to 4	
			Forest management same as previous entry. Natural gas fired electricity generation.		6 to 8	
		Increased extraction of harvest residues (stumps) for bioenergy (electricity generation).	Business as usual (no extraction of harvest residues). Coal fired electricity generation.		0	
			Forest management same as previous entry. Oil fired electricity generation.		10 to 12	
			Forest management same as previous entry. Natural gas fired electricity generation.		17 to 23	
		Increased extraction of harvest residues (stumps) for bioenergy (electricity generation).	Business as usual (no extraction of harvest residues). Coal fired electricity generation.		0	
			Forest management same as previous entry. Oil fired electricity generation.		18 to 22	
			Forest management same as previous entry. Natural gas fired electricity generation.		32 to 45	
Routa *et al.* (2012)	Finland	Thirty scenarios in total. Three different management regimes (standard thinning for bioenergy only; late pre-commercial thinning for bioenergy in dense stand; late thinning for bioenergy in very dense pre-commercial stand) with five different rotation periods (40, 60, 80 100, and 120 years). In addition, two different fertilisation regimes in combination with each scenario. All the simulations were done for both high and medium fertility sites.	None.	Attributed GHG emissions (kgCO_2 MWh^{-1})	60 to 300	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Routa *et al.* (2012)	Finland	Thirty scenarios in total. Three different management regimes (standard thinning for bioenergy only; late pre-commercial thinning for bioenergy in dense stand; late thinning for bioenergy in very dense pre-commercial stand) with five different rotation periods (40, 60, 80 100, and 120 years). In addition, two different fertilisation regimes in combination with each scenario. All the simulations were done for both high and medium fertility sites.	None.	Attributed GHG emissions ($kgCO_2$ MWh^{-1})	60 to 300	
Stewart and Nakamura (2012)		Business as usual (partial-cut and clearfell harvest) for co-production of solid wood products and bioenergy.	No baseline for forest management. Notional displacement factor broadly equivalent to coal.	Consequential (reduction in) GHG emissions (tCO_2 m^{-3})	~1	
Bernier and Paré (2013)	Canada	Additional clearfelling (range of stand ages from 60 to 120 years), stemwood harvested for bioenergy only. Biomass-fired domestic heating.	Business as usual (current patterns of forest management, wood and fossil energy use, implying conservation of forest areas where additional felling takes place). Oil fired domestic heating.	Payback time	90 to 150	Sensitive to stand age (and implied rotation). Referred to in Lamers and Junginger.

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Fiorese and Guariso (2013)	Northern Italy	Harvest above ground biomass, effectively for bioenergy only, whilst maintaining forest carbon stocks at pre-existing levels. Commercial or industrial heat.	Effectively ‘no use’. Commercial or industrial heat from natural gas.	Consequential (reduction in) GHG emissions (tCO_2 ha^{-1} yr^{-1})	2.8	
		Maximise production of biomass from forests, effectively for bioenergy only. Commercial or industrial heat.			4.11	
		Management of forests for bioenergy only, with rotation of 5 years. Commercial or industrial heat..			3.01	
		Management of forests for bioenergy only, with rotation of 10 years. Commercial or industrial heat.			3.74	
		Management of forests for bioenergy only, with rotation of 20 years. Commercial or industrial heat.			1.94	
		Maximise production of biomass, effectively for bioenergy only, with rotation of 10 years. Commercial or industrial heat.			1.52	
		Clearfelling of high productivity coniferous plantation for bioenergy. Moderate input to management of restocking (includes some inputs of fertliser). Bioenergy fired electricity generation.			21 to 37	
		Clearfelling of high productivity coniferous plantation for bioenergy. High input to management of restocking (includes inputs of fertliser). Bioenergy fired electricity generation.			8 to 17	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Jonker *et al.* (2013)	Southeast USA	Clearfelling of high productivity coniferous plantation for bioenergy. Low input to management of restocking. Bioenergy fired electricity generation.	'No use'. Coal fired electricity generation.	Payback time	39 to 57	Sensitive to relative efficiency of bioenergy and fossil energy scenario. Referred to in JRC review and Lamers and Junginger.
		Clearfelling of high productivity coniferous plantation for bioenergy. Moderate input to management of restocking (includes some inputs of fertiliser). Bioenergy fired electricity generation.			21 to 37	
		Clearfelling of high productivity coniferous plantation for bioenergy. High input to management of restocking (includes inputs of fertiliser). Bioenergy fired electricity generation.			8 to 17	
		Clearfelling of high productivity coniferous plantation for bioenergy. Low input to management of restocking. Bioenergy fired electricity generation.	Abandonment after first clearfelling, unassisted forest regeneration. Coal fired electricity generation.		6 to 46	
		Clearfelling of high productivity coniferous plantation for bioenergy. Moderate input to management of restocking (includes some inputs of fertiliser). Bioenergy fired electricity generation.			2 to 7	
		Clearfelling of high productivity coniferous plantation for bioenergy. High input to management of restocking (includes inputs of fertiliser). Bioenergy fired electricity generation.			2 to 4	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Jonker *et al.* (2013)	Southeast USA	Clearfelling of high productivity coniferous plantation for bioenergy. Low input to management of restocking. Bioenergy fired electricity generation.	No use’. Electricity generation (average fossil energy mix)	Payback time	69 to 106	Sensitive to relative efficiency of bioenergy and fossil energy scenario. Referred to in JRC review and Lamers and Junginger.
		Clearfelling of high productivity coniferous plantation for bioenergy. Moderate input to management of restocking (includes some inputs of fertiliser). Bioenergy fired electricity generation.			46 to 68	
		Clearfelling of high productivity coniferous plantation for bioenergy. High input to management of restocking (includes inputs of fertiliser). Bioenergy fired electricity generation.			21 to 39	
		Clearfelling of high productivity coniferous plantation for bioenergy. Low input to management of restocking. Bioenergy fired electricity generation.	Abandonment after first clearfelling, unassisted forest regeneration. Coal fired electricity generation.		60 to 91	Referred to in JRC review and Lamers and Junginger.
		Clearfelling of high productivity coniferous plantation for bioenergy. Moderate input to management of restocking (includes some inputs of fertiliser). Bioenergy fired electricity generation.			25 to 59	
		Clearfelling of high productivity coniferous plantation for bioenergy. High input to management of restocking (includes inputs of fertiliser). Bioenergy fired electricity generation.			6 to 15	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Kallio *et al.* (2013)	Finland	Increased harvesting of wood and diversion of small roundwood to meet increased demands for bioenergy, not including transport fuels.	Business as usual (current patterns of forest management, wood and fossil energy use). National energy consumption (market mediated displacement).	Consequential (increase in) GHG emissions (MtCO$_2$ for time horizon)	-1	Sensitive to time horizon.
		Increased harvesting of wood and diversion of small roundwood to meet increased demands for bioenergy including production of transport fuels.	Business as usual (current patterns of forest management, wood and fossil energy use). National energy consumption including biodiesel in place of fossil transport fuels (market mediated displacement).		4	
Ros *et al.* (2013)	Europe	Moderate increase in final felling of stemwood for bioenergy only. Eight indicative forest types.	Business as usual (current patterns of forest management, wood and fossil energy use). Assumed GHG emissions displacement factor.	Payback period	~100	
		Large increase in final felling of stemwood for bioenergy. Eight indicative forest types.			~380	
		Moderate increase in thinning of stemwood for bioenergy. Eight indicative forest types.			~40	
		High increase in thinning of stemwood for bioenergy. Eight indicative forest types.			~140	
		Moderate increase in extraction of harvest residues for bioenergy. Eight indicative forest types.			~0	
		High increase in extraction of harvest residues for bioenergy. Eight indicative forest types.			~10	
		Moderate increase in extraction of harvest residues for bioenergy. Eight indicative forest types.	Business as usual (current patterns of forest management, wood and fossil energy use). Assumed GHG emissions displacement factor representative of natural gas.		~10	
		High increase in extraction of harvest residues for bioenergy. Eight indicative forest types.			~50	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	**Geographical location**	**Forest management/production scenario**	**Counterfactual scenario**	**Result type**	**Result value**	**Comments**
Lamers *et al.* (2014)	Western Canada	'No use'	Forest carbon stocks at time of disturbance. Coal fired electricity generation.	Payback time	0 to 142	Referred to in Lamers and Junginger.
		Salvage logging of stemwood for solid wood products and bioenergy, burning of harvest residues on site (business as usual). Biomass-fired electricity generation (possibly co-firing).			8 to 54	
		Salvage logging of stemwood for solid wood products and bioenergy, extraction of harvest residues for bioenergy. Biomass-fired electricity generation (possibly co-firing).			0 to 30	
		Salvage logging of trees including branchwood (first harvest) for bioenergy only. Biomass-fired electricity generation (possibly co-firing).			56 to 75	
		Salvage logging of stemwood for solid wood products and bioenergy; harvest residues for bioenergy. Biomass-fired electricity generation (possibly co-firing).	Business as usual (salvage logging of stemwood for solid wood products, no extraction of harvest residues, burning on site instead). Coal fired electricity generation.		0	
		Salvage logging of trees including branchwood (first harvest) for bioenergy only. Biomass-fired electricity generation (possibly co-firing).			53 to 109	

Table A9.1 (continued) Meta-analysis of published results for GHG emissions associated with forest bioenergy

Source	Geographical location	Forest management/production scenario	Counterfactual scenario	Result type	Result value	Comments
Matthews *et al.* (2014)	UK	Introduction of thinning in previously neglected broadleaf forests with relatively low productive potential. Use of all stemwood and 50% branchwood for bioenergy only. A range of bioenergy conversion technologies including small scale heat and electricity generation.	'No use' (effectively business as usual for neglected broadleaf forests). Coal fired equivalents to bioenergy conversion systems.	Payback time	0	Interpreted from detailed results for over 600 scenarios produced in study.
			Forest management same as previous entry. Oil and natural gas fired equivalents to bioenergy conversion systems.		> 100	
		Introduction of thinning in previously neglected broadleaf forests with relatively low productive potential. Use of stemwood for solid wood products and bioenergy (co-production) and 50% branchwood for bioenergy only. A range of conversion technologies including small scale heat and electricity generation.	Forest management same as previous entry. Various fossil energy equivalents to bioenergy conversion systems (coal, oil, natural gas). High potential displacement GHG emissions by solid wood products.		0	
			Forest management same as previous entry. Various fossil energy equivalents to bioenergy conversion systems (coal, oil, natural gas). Low potential displacement GHG emissions by solid wood products.		> 100	
		Continued harvesting of conifer and broadleaf forests already managed for production, but diversion of wood feedstock (small roundwood, sawlogs, sawlog offcuts, or complete stems) currently used for solid wood products to production of bioenergy. A range of conversion technologies including small scale heat and electricity generation.	Business as usual (current patterns of forest management, wood and fossil energy use). Various fossil energy equivalents to bioenergy conversion systems (coal, oil, natural gas). High potential displacement GHG emissions by solid wood products.		> 100	Effectively, there is an indefinite increase in GHG emissions. Highly specific to context. Interpreted from detailed results for over 600 scenarios produced in study.

Appendix 10. Analysis of estimates for GHG emissions payback time associated with production of forest bioenergy as reported in Appendix 9

Forest management/ production scenario	**Fossil energy counterfactual**				**Source**
	Coal	**Oil**	**Natural gas**	**Mix**	
Bioenergy only production associated with fire prevention measures in biologically mature stands with high carbon stocks.				Min = 169 Median = 458 Max = 4500	Mitchell *et al.* (2009)
Bioenergy only production through salvage logging of recently disturbed forest (generally with high carbon stocks), followed by restoration of forest areas with high harvesting intensity for bioenergy only.				Min = 400 Median = 1450 Max = 2500	Mitchell *et al.* (2012)
Diversion of harvested wood from solid wood products to bioenergy, leaving harvesting intensity unchanged or increased.	Increased emissions	Increased emissions	Increased emissions	4 to 1000	Mitchell *et al.* (2012); Matthews *et al.* (2014)
Bioenergy only production from additional thinning of stemwood in forest areas with high initial carbon stocks.	0	> 100	> 100	Min = 40 Median = 228 Max = 600	Mitchell *et al.* (2012); Matthews *et al.* (2014); Ros *et al.* (2013)
Co-production of solid wood products and bioenergy through introduction of thinning in previously unmanaged forest areas with high initial carbon stocks, low potential for displacement of GHG emissions associated with solid wood products.	> 100	> 100	> 100		Matthews *et al.* (2014)
Harvesting forest with high carbon stocks for bioenergy only, followed by restoration of forest areas with low productivity plantation forest for bioenergy only.	114	145	197		Zanchi *et al.* (2011)
Bioenergy only production through salvage logging of recently disturbed forest (generally with high carbon stocks), followed by restoration of forest areas with moderate harvesting intensity for bioenergy only.	Min = 56 Median = 66 Max = 75			Min = 100 Median = 113 Max = 125	Mitchell *et al.* (2012); Lamers *et al.* (2014)

Appendix 10 (continued) Analysis of estimates for GHG emissions payback time associated with production of forest bioenergy as reported in Appendix 9

Forest management/ production scenario	Fossil energy counterfactual				Source
	Coal	Oil	Natural gas	Mix	
Bioenergy only production from additional clearfelling of stemwood in forest areas already under management for production.	Min = 8 Med = 39 Max = 230	Min = 13 Med = 64 Max = 295	Min = 50 Med = 100 Max = 400	Min = 21 Med = 69 Max = 380	Walker *et al.* (2010); Lecocq *et al.* (2011); McKechnie *et al.* (2011); Ter. Mikaelian *et al.* (2011); Colnes *et al.* (2012); Holtsmark (2012a); Zanchi *et al.* (2011); Jonker *et al.* (2013); Ros *et al.* (2013)
Bioenergy only production associated with fire prevention measures in relatively mature stands with moderate carbon stocks.				Min = 34 Med = 71 Max = 107	Mitchell *et al.* (2009)
Co-production of solid wood products and bioenergy through salvage logging of recently disturbed forest (generally with high carbon stocks), followed by restoration of forest areas with moderate harvesting intensity for co-production.	Min = 8 Med = 31 Max = 54				Lamers *et al.* (2014)
Harvesting of forest with high carbon stocks for bioenergy only, followed by restoration of forest areas with high productivity plantation forest for bioenergy only.	17	20	25		Zanchi *et al.* (2011)
Co-production of solid wood products and bioenergy through salvage logging of recently disturbed forest (generally with high carbon stocks), including extraction of harvest residues, followed by restoration of forest areas with moderate harvesting intensity for co-production.	Min = 0 Med = 15 Max = 30				Lamers *et al.* (2014)
Additional extraction of harvest residues including stumps for bioenergy only.	Min = 0 Med = 0 Max = 0	Min = 15 Med = 18 Max = 22	Min = 22 Med = 32 Max = 45		Repo *et al.* (2011, 2012)

Appendix 10 (continued) Analysis of estimates for GHG emissions payback time associated with production of forest bioenergy as reported in Appendix 9

Forest management/ production scenario	Fossil energy counterfactual				Source
	Coal	**Oil**	**Natural gas**	**Mix**	
Additional harvesting of pre commercial thinnings for bioenergy only.	Min = 0 Med = 0 Max = 0	Min = 10 Med = 11 Max = 12	Min = 17 Med = 20 Max = 23		Repo *et al.* (2012)
Additional harvesting of branch wood for bioenergy only.	Min = 0 Med = 0 Max = 20	Min = 3 Med = 4 Max = 35?	Min = 4 Med = 9 Max = 50		Lecocq *et al.* (2011); McKechnie *et al.* (2011); Repo *et al.* (2011, 2012); Zanchi *et al.* (2011); Ros *et al.* (2013)
Harvesting forest with high carbon stocks for 50% bioenergy and 50% additional solid wood products, followed by restoration of forest areas with high productivity plantation bioenergy only.	0	0	8		Zanchi *et al.* (2011)
Diversion of harvested wood from solid wood products to bioenergy, combined with reduced harvesting intensity.				4	Mitchell *et al.* (2012)
Co-production of solid wood products and bioenergy through introduction of thinning in previously unmanaged forest areas with high initial carbon stocks, high potential for displacement of GHG emissions associated with solid wood products.	0	0	0		Werner et al (2011); Poudel *et al.* (2012); Matthews et al (2013)
Creation of new forests for bioenergy only on marginal agricultural land with low initial carbon stock.	0	0	0	0	Zanchi *et al.* (2011)

Appendix 11. Provisional qualitative assessment of sources of forest bioenergy that may contribute to increased bioenergy consumption

This appendix describes a provisional qualitative assessment of the types of bioenergy system, forest bioenergy feedstock and forest management that are more or less likely to occur in response to incentives for increased consumption of forest bioenergy.

Before considering the potential effects of increased consumption of forest bioenergy in the EU, it is important to characterise how forest bioenergy has been, and still is being, used in the absence of bioenergy policies (including existing policies). Existing levels of forest bioenergy consumption and patterns of production of bioenergy feedstocks have been reviewed in Section 2. However, there is limited systematic information on the extent of forest management for bioenergy production, consumption of forest bioenergy feedstocks and deployment of conversion systems within the various EU Member States. A subjective, provisional assessment based on limited data sources and anecdotal accounts suggests:

1. There is some existing harvesting of thinnings, small roundwood and some branchwood, particularly in broadleaf forests for local use as fuel logs, wood chips, wood pellets and briquettes (small scale heat). In some cases stumps may also be harvested. This type of activity may be significant in some Member States.
2. There is some existing use of sawmill and boardmill co-products internally within these processing facilities (industrial process heat and power).
3. There is some consumption of the above feedstocks and additionally recovered waste wood for district heating or combined heat and power (CHP). This activity is important for some Member States.

This set of activities represents a baseline for comparison with assessments of potential impacts of bioenergy policies, including existing policies.

Table A11.1 describes two provisional assessments of the types of activities already taking place in the EU, or likely to take place, as a consequence of policies aimed at increasing consumption of bioenergy[20], assuming that forest bioenergy makes a major contribution. As with the preceding assessment for the baseline, these assessments involve identifying a set of activities involving forest management, forest bioenergy feedstocks and conversion systems which are relevant for the scenario. The first assessment ('Towards 2020 targets' scenario) considers a scenario of existing policies, which set targets for bioenergy consumption in 2020. Thus, the scenario involves the assumption that bioenergy consumption increases in the EU up to 2020 but then remains constant at 2020 levels. The second assessment ('Increase beyond 2020 targets' scenario) considers a scenario of further policies going beyond the existing targets for

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[20] It must be stressed that policies relating to liquid biofuels are not considered as part of the scope of this report.

bioenergy set for 2020. The scenario is thus concerned with the possibility of further increases in bioenergy consumption beyond targets for 2020, perhaps taking place up to 2050. A further assessment (‘Less likely’ scenario) is made in Table A11.1 of types of activity considered less likely to occur in these scenarios.

The sets of activities in Table A11.1 can be compared with those already considered in Table 5.11 in Section 5, for which assessments have already been made of associated risk of adverse outcomes for GHG emissions reductions (see Section 5.2.1 and Table 5.2). The ranges of risks associated with activities relevant for each scenario are also summarised in Table A11.1.

For the case of importation of wood as part of the two scenarios for increased consumption of forest bioenergy, further provisional assessments are made in Tables A11.2, A11.3 and A11.4 of possible activities in the Russian Federation and Eastern Europe, Canada and the USA, respectively.

The assessment in Tables A11.1 to A11.4 presents some challenges, since it would seem that there is no particular correlation between the level of increased consumption of forest bioenergy and the level of risk attached to consequent GHG emissions. However, the range of activities associated with each scenario in Tables A11.1 to A11.4 are strictly identified as *potentially*, not *definitely* involved in the increased consumption of forest bioenergy. Further research is required to clarify the detailed responses which may occur in the forest and energy sectors, depending on future levels of bioenergy consumption in the EU.

Table A11.1 Risk to GHG emissions from increased consumption of forest bioenergy in the EU: provisional qualitative assessment of bioenergy systems, forest biomass feedstocks and forest management activities potentially involved in the EU

Scenario	Relevant activities	Risk[1]
'Towards 2020 targets' scenario	• Importation of wood pellets (large scale power only or co-firing).	See note 2
	• Additional extraction of harvest residues, mainly branchwood and poor quality stemwood for chips and pellets (small scale heat, district heating, power only, CHP or co-firing).	Moderate[3]
	• Diversion of some small roundwood from previous use as feedstock for particleboard, fibreboard, paper, to produce chips and pellets (small scale heat, district heating, power only, CHP or co-firing).	Very high
	• Additional use of sawmill co-products for chips and pellets, to the extent that this can be supported by increased sawmill output (small scale heat, district heating, power only, CHP or co-firing).	Low
	• Diversion of some sawmill co-products from previous use as feedstock for particleboard, fibreboard, paper, to produce chips and pellets (small scale heat, district heating, power only, CHP or co-firing).	Very high
	• Additional use of recovered waste wood (district heating, power only, CHP).	Low to high[4]
	• Some limited additional thinning and felling for chips and pellets, to the extent that this is economic when co-production with material/fibre products is considered (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard).	Low to high[5]
'Increase beyond 2020 targets' scenario	• Significantly increased importation of wood pellets (small scale heat, district heating, power only, CHP or co-firing).	See note 2
	• Modest further increases in other 'Towards 2020' activities.	See above

Notes to Table A11.1:

1. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1.
2. The importation of forest bioenergy is assessed separately in Tables 5.13 to 5.15, for the Russian Federation and Eastern Europe, Canada and the USA as potential suppliers.
3. Moderate risk has been assigned on the assumption that harvesting of stumps would not increase significantly. A high risk would be assigned in the case of stump harvesting.
4. It should be noted that, strictly, this activity was not assessed as part of the meta-analysis of the literature review. The assessment of risk is therefore based on expert judgement. The outcome is very sensitive to the counterfactual for the fate of waste wood, e.g. incineration without energy recovery of landfill.
5. The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals.

Table A11.1 (continued) Risk to GHG emissions from increased consumption of forest bioenergy in the EU: provisional qualitative assessment of bioenergy systems, forest biomass feedstocks and forest management activities potentially involved in the EU

Scenario	Relevant activities	Risk[6]
'Less likely' scenario	• Enrichment of existing forest areas with low growing stock/productive potential to enhance carbon stocks and increase production of wood chips or pellets, most likely as part of co-production (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard). • Planting of agricultural land with trees managed as short rotation biomass forests for dedicated production of wood chips or pellets (small scale heat, district heating, power only, CHP or co-firing). • Planting of agricultural land with trees managed as high forest for co-production with material/fibre products is considered (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard). • Additional thinning and felling for chips and pellets only (small scale heat, district heating, power only, CHP or co-firing).	Low Low[7] Low[7] Very high

Notes to Table A11.1:

6. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1.
7. It must be stressed that these activities have been classified as low risk on the assumption that risks of iLUC would be mitigated, e.g. by restricting the activities to marginal/low productivity agricultural land.

Table A11.2 Risk to GHG emissions from increased consumption of forest bioenergy in the EU: provisional qualitative assessment of bioenergy systems, forest biomass feedstocks and forest management activities potentially involved in the Russian Federation and Eastern Europe

Scenario	Relevant activities	Risk[1]
'Towards 2020 targets' scenario	- Some additional thinning and felling for small roundwood to produce chips and pellets within the EU, to the extent that this is economic when co-production with material/fibre products is considered (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard). The material/fibre products may be consumed internally or exported.	Low to high[2]
'Increase beyond 2020 targets' scenario	- Additional thinning and felling for stemwood, for internal processing to make pellets for export, to the extent that this is economic. This may or may not involve co-production with material/fibre products (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard).	Low to very high[2]

Notes to Table A11.2:

1. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1.
2. The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals.

Table A11.3 Risk to GHG emissions from increased consumption of forest bioenergy in the EU: provisional qualitative assessment of bioenergy systems, forest biomass feedstocks and forest management activities potentially involved in Canada

Scenario	Relevant activities	Risk[1]
'Towards 2020 targets' scenario	• Additional extraction of harvest residues, mainly branchwood and poor quality stemwood for internal processing to make chips and pellets for export (small scale heat, district heating, power only, CHP or co-firing).	Moderate[2]
	• Additional use of sawmill co-products for internal processing to make pellets for export, to the extent that this can be supported by increased sawmill output (small scale heat, district heating, power only, CHP or co-firing).	Low
	• Additional thinning and felling for internal processing to make pellets for export, to the extent that this is economic when co-production with material/fibre products is considered (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard). The material/fibre products may be consumed internally or exported.	Low to high[3]
	• Additional salvage logging for internal processing to make pellets for export. This may or may not involve co-production with material/fibre products (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard). The material/fibre products may be consumed internally or exported.	High
'Increase beyond 2020 targets' scenario	• Further increases in 'Towards 2020' activities.	See above

Notes to Table A11.3:

1. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1.
2. Moderate risk has been assigned on the assumption that harvesting of stumps would not increase significantly. A high risk would be assigned in the case of stump harvesting.
3. The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals.

Table A11.4 Increased Risk to GHG emissions from increased consumption of forest bioenergy in the EU: provisional qualitative assessment of bioenergy systems, forest biomass feedstocks and forest management activities potentially involved in the USA

Scenario	Relevant activities	Risk[1]
'Towards 2020 targets' scenario	• Additional extraction of harvest residues, mainly branchwood and poor quality stemwood for internal processing to make chips and pellets for export (small scale heat, district heating, power only, CHP or co-firing).	Moderate[2]
	• Additional use of sawmill co-products for internal processing to make pellets for export, to the extent that this can be supported by increased sawmill output (small scale heat, district heating, power only, CHP or co-firing).	Low
	• Additional thinning and felling for internal processing to make pellets for export, to the extent that this is economic when co-production with material/fibre products is considered (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard). The material/fibre products may be consumed internally or exported.	Low to high[3]
'Increase beyond 2020 targets' scenario	• Further increases in 'Towards 2020' activities.	See above
	• Additional thinning and felling for stemwood, for internal processing to make pellets for export, to the extent that this is economic. This may or may not involve co-production with material/fibre products (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard). The material/fibre products may be consumed internally or exported.	Low to very high[3]
	• Additional salvage logging for internal processing to make pellets for export. This may or may not involve co-production with material/fibre products (small scale heat, district heating, power only, CHP or co-firing; sawn timber, particleboard, fibreboard). The material/fibre products may be consumed internally or exported.	High

Notes to Table A11.4:

1. It is very important to understand how risk of adverse effects on GHG emissions has been defined. This has been discussed in detail in Section 5.2.1.
2. Moderate risk has been assigned on the assumption that harvesting of stumps would not increase significantly. A high risk would be assigned in the case of stump harvesting.
3. The risk is extremely sensitive to the types of material/fibre co-products associated with the bioenergy production and their counterfactuals.