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

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

May 2014

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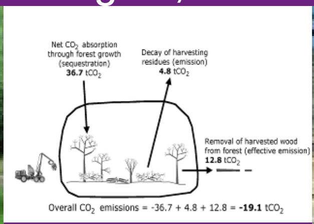







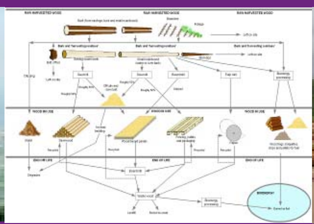


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Robert Matthews[1], Laura Sokka[2], Sampo Soimakallio[2], Nigel Mortimer[3], Jeremy Rix[3], Mart-Jan Schelhaas[4], Tom Jenkins[1], Geoff Hogan[1], Ewan Mackie[1], Allison Morris[1] and Tim Randle[1] (2014*) Review of literature on biogenic carbon and 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.

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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.

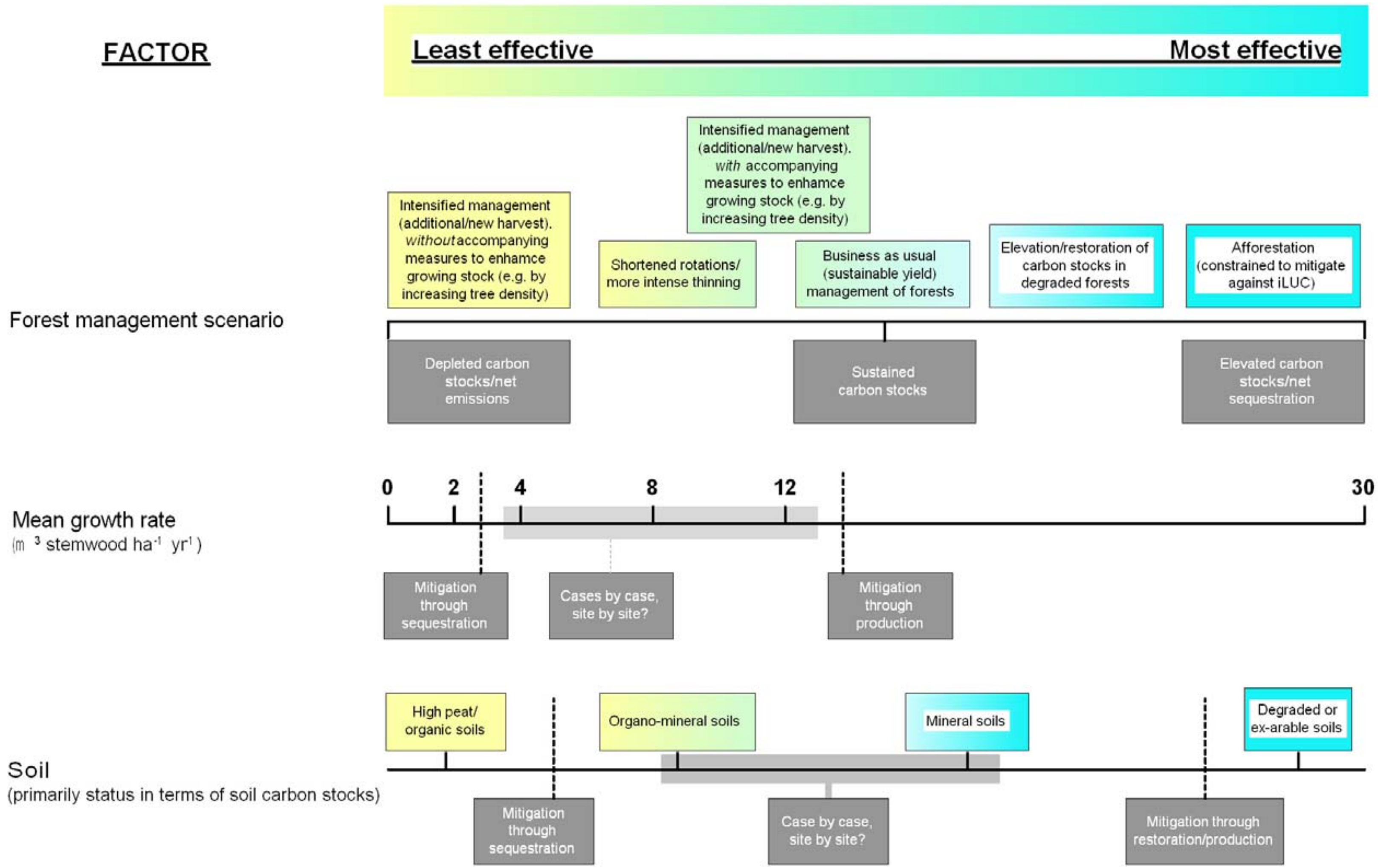

Figure ES1. Illustration of how the GHG emissions associated with the harvesting and use of forest bioenergy may depend on a number of factors.

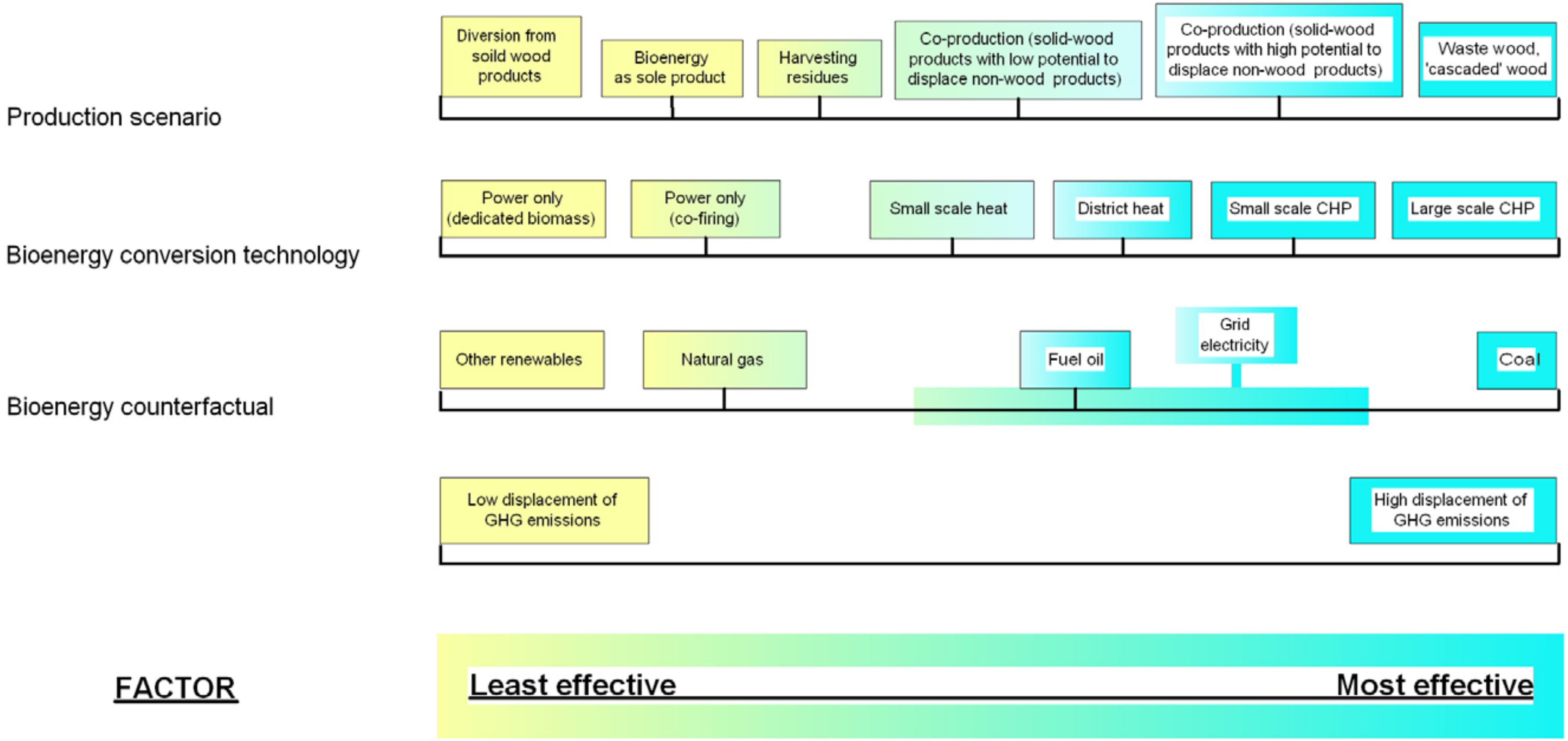

Figure ES1 (continued). Illustration of how the GHG emissions associated with the harvesting and use of forest bioenergy may depend on a number of factors.

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.