Forest Research

Feasibility study on sustainability criteria and the effect of wood pellet demand on forest carbon stock

Part A report: Literature review

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The Research Agency of the
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Introduction

This report has been produced in partial fulfilment of the project, "Feasibility study on sustainability criteria and the effect of wood pellet demand on forest carbon stock", project TRN 1702/11/2018, commissioned by BEIS in December 2018. This part of the project has set out to review the literature on the impacts on forest carbon stock and atmospheric greenhouse gases (GHGs) from the use of forest biomass for energy, in particular as a result of the demand for wood pellets for use in electricity generation in the UK. This has been in an attempt to use the existing literature to answer a number of specific questions:

1 What effect has the supply of wood pellets to UK power stations had on the forest carbon stock in the SE USA, Canada and Europe?

2 How would the situation have been different with alternative sustainability criteria in place?

3 How can we maximise the sustainable yield and what are the risks and challenges of doing this? How will that change in the future?

4 How applicable would any conclusions be to other areas of potential forest biomass supply?

The review is intended to inform the assessment of the feasibility and design of a possible full-scale study to address these questions more thoroughly, and to estimate the possible cost and timescale of such a study To meet these aims, for the purposes of the review, the first two questions above were further elaborated into four, more specific methodological questions:

1 Is there a way we can find out the impact UK demand for wood pellets is having on forest management in other countries?

2 Is there a way we can find out the impact UK demand for wood pellets is having on the wood supply chain in other countries?

3 Is there a way we can find out the impact UK demand for wood pellets is having on the development of forest carbon stocks and sequestration in other countries?

4 With regard to questions 1 to 3 above, is there a way we can work out, with reasonable justification, what would have happened to forest management, the supply chain, and carbon stocks and sequestration in other countries under different circumstances?

This resultant assessment of published papers with respect to these questions has assisted in identifying available options for methods suitable for carrying out the full-scale study under consideration.

Compilation and analysis of relevant published papers

A total of 352 papers formed an initial long list compiled for the review, which included not only those directly in scope for the aims of the review, but also a large number that provided supplementary information on some aspect of relevance to the subject of study. The long list of papers was categorised into those to be subjected to detailed review (69 papers), and eight other classes of publication, including review papers and meta-analyses, methodological studies, those offering wider consideration of carbon or GHG balance, wood product LCA, forest characteristics and management, and others.

Those papers subjected to detailed review were each analysed according to a list of seventeen characteristics, and further characterised by short statements describing the purpose and main conclusions of the study, as presented by the authors. This categorisation allowed the conclusions of each published study to be assessed in the context of the scope, methodology and assumptions involved. In addition, it allowed an assessment of the key insights and difficulties encountered in these studies when attempting to define scenarios and evaluate the impacts on forest carbon stocks and net GHG emissions.

Key findings of detailed review

The detailed review revealed that published studies are very diverse:

- Various different geographic regions are covered in studies
- A variety of forest tree species groups are studied
- A very wide range of scenarios are constructed to represent “with-bioenergy” and counterfactual scenarios, even within the same geographic region
- Various woody biomass feedstocks are utilised for energy purposes
- Individual studies use widely varying approaches for the development of “with-bioenergy” and counterfactual scenarios, with many simply making assumptions
- Most studies apply modelling methods to evaluate impacts on forest carbon stocks and sequestration associated with forest management and wood utilisation to supply woody biomass for use as an energy feedstock
- Studies are variable in their representation of land use, land-use change and spatial scales
- The completeness with which carbon stocks associated with forests (tree biomass, litter, soil, harvested wood products) are represented in studies is variable
- Studies have assessed carbon impacts over different timescales and have reported these using various different metrics
- The majority of studies do not address the specific question posed for this project, i.e. impacts on forest carbon stocks associated with forest management and wood utilisation to supply woody

biomass for use as an energy feedstock. Rather, most published studies present more integrated and comprehensive life cycle analysis results for woody biomass supply chains and their counterfactuals.

Perhaps unsurprisingly, given the variability in the objectives, scope and methods employed by studies, published results for the carbon impacts of utilising forest biomass as an energy feedstock suggest widely varying outcomes. However, the detailed analysis and categorisation of methodologies and assumptions undertaken in the detailed review of studies allowed a number of more concrete, and valid, conclusions to be drawn.

From the shortlist of 69 studies analysed it would appear that a wide range of approaches has been employed, and a wide range of conclusions has been drawn from study results, potentially leading to the impression either that there is no consensus on the GHG impact of the use of forest biomass for energy, or that the problem is insoluble and any result is equally valid.

However, the detailed analysis and categorization of methodologies and assumptions, discussed above, allows a number of more concrete, and valid, conclusions to be drawn.

Firstly, it has highlighted the importance of **transparency** in both techniques and the reporting of results. Without full transparency, it is simply not possible to analyse fully the relevance or validity of the results of a given study, or to clearly understand the methodology adopted. In particular it does not allow the scrutiny of the second most important factor, and that which may be considered to have the greatest single impact on the results obtained: the **assumptions** that have been made.

The great majority of studies were based on assumptions about forest management, particularly with regard to defining both the "with bioenergy" and the counterfactual scenarios. Even those based on economic modelling employ implicit assumptions concerning market and stakeholder behaviour. The results and conclusions of any study are so fundamentally linked to the assumptions made that the transparency with which assumptions are presented is critical to the ability to assess the relevance of an individual study. The studies assessed within the present literature review vary considerably in the degree to which assumptions are stated explicitly.

Even when assumptions are stated, the use of **terminology** that is inadequately defined can limit the ability to assess fully the details of a study, and this also makes comparison of different studies problematic.

The overwhelming majority of studies involved **modelling** of one kind or another. While this is a powerful tool to allow the multiple, interacting impacts of a set of circumstances or activity to be assessed, the results can only ever be as reliable as the assumptions behind the inputs, and the way in which the model itself reflects real world behaviour. A wide range of models have been employed, some commercially available, some open source and some proprietary or developed in-house, and confidence in the results obtained demand implicit faith in the model. The incorporation (or otherwise) of factors such as biogenic carbon, non-carbon GHGs, and market responses can influence results significantly. Also, the temptation to treat the model as an infallible "black box" can mask the possibility that it may have been employed beyond the purpose or range of parameters for which it was designed. Once again, transparency can increase confidence.

A particular case is that of **economic modelling** which seeks to predict the likely impact of market factors on the behaviour of disparate stakeholders from multiple sectors and with a wide range of personal motivations. However, the increased demand for biomass for energy may certainly be expected to have impacts on economically mediated behaviour.

Finally, the details of the **"with-bioenergy" scenarios** and **counterfactual scenarios** under investigation are of relevance. These range from the realistic to the implausible, and the extent to which an individual study may be of value in a particular situation will depend upon the choice of "with-bioenergy" and counterfactual scenarios, including the selection of region and forest type, management practices, feedstocks, spatial and temporal scale. However, good transparency allows these, and consequently relevance, to be assessed.

Within the constraints of the issues discussed in Section 4.1 and above, a somewhat superficial analysis of the conclusions of the 69 papers assessed showed a wide range of conclusions as to whether bioenergy represented a risk or benefit to forest carbon stocks and consequent net GHG emissions. Owing to the wide range of forest management practices, wood feedstocks, assumptions and methodologies represented in these studies, this is not surprising. The findings of this review have been compared to those of other review studies which assign different levels of impact to different feedstock sources.

Tentative characterisation of scenarios

Following on from the detailed review of studies, an attempt has been made to propose a provisional description of scenarios for forest management and feedstock use relevant to the supply of woody biomass for utilisation as an energy feedstock in the geographic regions of primary interest to this project, i.e. Europe, Canada and the USA. However, for reasons discussed in the detailed literature review, it is important to stress that it is very difficult to use the scenarios presented in published studies as a basis for specifying the most likely forest management activities and patterns of wood utilisation. Hence, the scenarios proposed in this report have been informed by published studies as far as possible, but also rely on the experience and judgement of the authors of this report.

The scenarios are defined as a list of forest management activities and wood feedstocks involved. For the "with-bioenergy" scenario, qualitative assessments are also made of the likely impacts on forest carbon stocks and the importance of each activity and feedstock under current conditions, in terms of the likely prevalence of the activity and significance of the feedstock to bioenergy industries. The speculative nature of the details of the scenarios must be stressed.

The analysis of scenarios suggests there are likely to be multiple forest management activities and wood feedstocks involved in supplying forest biomass as an energy source, and that responses within the forest sector to a demand for forest bioenergy are likely to be complicated. Furthermore, such responses to a change of scenario (e.g. counterfactual or revised criteria) are likely to be very complex and sensitive to wider surrounding circumstances (e.g. demands for wood from other markets). This may present difficulties to the reliable and clear development of scenarios representing the "with-bioenergy", the counterfactual or any alternative scenario. However, the approach adopted for constructing scenarios may serve as a method for developing and documenting scenario assumptions that is reasonably clear and could be reviewed by stakeholders. The reductive approach also provides a basis for defining inputs to any model-based assessment and for presenting results so that the contributions of different forest management activities and wood feedstocks can be distinguished.

Possible approaches for the development of scenarios

This report has briefly considered the possible approaches to developing scenarios to describe:

- Current forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes
- Counterfactual forest management activities and utilisation of wood feedstocks in the absence of forest bioenergy supply chains
- Changed forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes, in response to refined biomass sustainability criteria.

Five main approaches to scenario development have been identified:

1. Simply making assumptions about the forest management activities and wood feedstocks involved in scenarios
2. Applying economic models in conjunction with large-scale forest sector models to simulate the forest management activities and wood feedstocks involved in scenarios
3. Referring to forestry sector information on the consumption of woody biomass for use as an energy feedstock, and inferring forest management practices from this
4. Undertaking case studies involving actual wood-processing facilities and investigating the use of wood feedstocks and the management of the forest areas involved
5. Consulting with stakeholders within a relevant region to try to establish the forest management practices and wood feedstocks most likely to be involved in scenarios.

The detailed literature review identified a number of strengths and weaknesses with regard to each approach, as summarised in Table ES1.

Table ES1 Provisional assessment of possible approaches for scenario development

Approach	Strengths	Weaknesses
Assumptions	• Quick • Transparent • Understandable • Can combine with sensitivity analysis	• Possibly difficult to justify • "Just another study" • No guarantee of reflecting actual scenario • Potentially highly uncertain
Economic modelling	• Systematic • Handles sector and land use dynamics • Comprehensive • Can combine with sensitivity analysis	• Not transparent • Difficult to understand • Still reliant on implicit assumptions • High uncertainty • Possibly difficult to justify
Data from sector	• Transparent • Clear basis in data • Understandable • Verifiable	• Data required may not always be available • Data will not exist for a hypothetical scenario, still reliant on assumptions • There could be data quality issues • Can be over-simplistic
Case study	• Clearly defined • Clear basis in actual system(s) • Understandable • Verifiable	• Reliant on co-operation and availability of information • Commercial constraints • May not represent the more general situation within a region
Stakeholder consultation	• Transparent • Inclusive • Clear link to authoritative stakeholders • Can still draw on data and make assumptions • Possibility for consensus building • Objective(s) and scope can be varied	• Reliant on co-operation • May be compromised by limited pool of stakeholders • Potentially constrained by consultation protocols • May not achieve consensus

It would appear that none of the possible approaches stands out as being significantly better than the others in terms of the strengths and weaknesses identified. However, the weaknesses associated with some approaches seem to limit their applicability and possibly rule them out. In particular, it is recommended that the approach of relying on sectoral data should be discounted. The other approaches each have some desirable strengths (e.g. systematic, transparent, verifiable, understandable, inclusive of stakeholders). Further detailed assessment of these approaches is recommended.

Methods for evaluating forest carbon stock impacts

An assessment has also been made of the possible methods for evaluating the carbon impacts associated with scenarios for forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes.

Four methods for evaluating forest carbon stock impacts were identified:

1. Application of modelling approaches
2. Analysis of national forest inventory (NFI) data
3. Presentation of results from formally designed field experiments
4. Interpretation of CO_2 flux data collected from a forest monitoring network.

The detailed literature review identified a number of strengths and weaknesses with regard to each method (see Table ES2).

The methods based on modelling stand out as having the most advantages, whilst there may be scope to mitigate weaknesses. Hence, it is recommended that these methods are focussed on for further consideration. All the other data-based methods involve some important weaknesses, not least the unsuitability of methods for estimating longer-term impacts (i.e. outside the timescales for which field measurements have been taken). Nevertheless, NFI data, field experiments and flux results have a role in providing input data for models and/or verifying the outputs of models, and there may be a case for further consideration of these contributions by data-based methods.

Amongst the model-based methods, those based on the application of forest sector carbon accounting models would seem most relevant to the type of study being considered in this project. Relevant models have been developed by a number of organisations, which are applicable in the geographic regions of interest to this current project. In principle, any of these models could be applied to assess forest carbon stocks and sequestration, and the potential impacts of forest management and wood utilisation to supply woody biomass for use as an energy feedstock. There may be a case for applying more than one such model within a full-scale study, as a way of cross-checking their results.

Table ES2 Provisional assessment of possible methods for evaluating forest carbon stock impacts of scenarios

Approach	Strengths	Weaknesses
Modelling	• Relatively quick • Systematic • Can be adapted to work with available data • Straightforward to represent a range of forestry activities • Straightforward to represent hypothetical scenarios • Straightforward to project future impacts • Can combine with sensitivity analysis • Can be used as an educational tool, as well as for modelling scenarios • Relatively straightforward to transfer methods	• Dependent on robustness and accuracy of model implementation • Likely to be unreliable if applied outside the design specification (e.g. type of thinning not actually represented) • May need a lot of data processing and quality checks • May lack transparency, presenting obstacles to understanding how results have been produced
NFI data analysis	• Founded on actual data • Likely to be trusted by stakeholders, if results are clearly linked to data • Should provide a comprehensive assessment for the study region	• Dependent on a reliable NFI in the region • Short-term and retrospective results only, cannot project to future • Survey design may limit suitability of data for addressing certain questions • Assumptions need to be made to represent hypothetical situations in scenarios
Field experiments	• Founded on actual data • Likely to be trusted by stakeholders, if results are clearly linked to data • Systematic experimental treatments are represented	• Reliant on experiments existing, may need to set them up, then wait for results • Experimental treatments may not be relevant for addressing certain questions and may not represent relevant practices • Results limited to duration of experiment • Cannot project to future
Flux monitoring	• Founded on actual data • Likely to be trusted by stakeholders, if results are clearly linked to data	• Dependent on reliable flux monitoring network in the region • Flux results depend on implicit assumptions and modelling • Does not directly evaluate carbon stock impacts • Retrospective results only, cannot project to future

Approach	Strengths	Weaknesses
		• Assumptions need to be made to represent hypothetical situations in scenarios

Summary recommendations

Drawing on the above discussion, in summary it is recommended that:

- Further assessment is made of approaches to the development of scenarios based on simple assumptions, economic modelling, case studies and stakeholder consultation, including the possibility of employing some combination of these approaches
- Consideration should be given to testing the provisional scenarios developed in this report through consultation with relevant experts
- Further assessment is made of modelling methods for the evaluation of the potential impacts on forest carbon stocks and sequestration arising from forest management and wood utilisation to supply woody biomass for use as an energy feedstock, under different scenarios
- The assessments recommended above should form the basis for developing and evaluating options for a full-scale study as envisaged in this project.

The option of not proceeding with a full-scale study should be considered as part of further assessments, given the many uncertainties and technical difficulties identified in this review. It is important not to underestimate the complexity of the analysis implied in trying to establish impacts on forest carbon stocks occurring as a result of UK biomass policy, within the context of large forest areas and multiple forest management activities and markets for woody biomass within relevant regions.

1. Introduction

This report has been produced in partial fulfilment of the project, “Feasibility study on sustainability criteria and the effect of wood pellet demand on forest carbon stock”, project TRN 1702/11/2018, commissioned by BEIS in December 2018 (referred to below as BEIS BCSI).

The purpose of this report is to present the findings of a review of the literature available on studies into forest carbon stock changes resulting from wood pellet demand.

The project aims to consider the feasibility of answering the following specified questions:

1. What effect has the supply of wood pellets to UK power stations had on the forest carbon stock in the SE USA, Canada and Europe?
2. How would the situation have been different with alternative sustainability criteria in place?
3. How can we maximise the sustainable yield and what are the risks and challenges of doing this? How will that change in the future?
4. How applicable would any conclusions be to other areas of potential forest biomass supply?
5. An estimate of the possible costs of a full-scale study. How long would it take?

This review of literature is of greatest relevance to Question 1 above, whilst aspects of Question 2 are addressed where possible. Key relevant findings of previous studies are summarised. The difficulties encountered in studies are also appraised, and consideration given to how these may be addressed.

1.1. Structure of this report

The structure of this report reflects the systematic approach taken to the review. Firstly, some refined supplementary questions to be addressed by the review are presented in Section 2. The detailed approach to the literature review is described in Section 3, whilst an overview of relevant literature is provided in Section 4. The findings of the review are presented in Section 5. In Section 6, a preliminary assessment is made of the scenario(s) of forest management and wood utilisation involved in supplying wood pellets to the UK from forests in SE USA, Canada and Europe. The options identified for developing methods for the more formal construction of these and other scenarios (including counterfactuals), and the evaluation of impacts on forest carbon stocks, are considered in Section 7. A preliminary assessment of these methods is given in Section 8. The conclusions and recommendations arising from the review are summarised in Section 9.

2. Elaboration of questions

As already explained, the primary purpose of this literature review is to assist with answering the first of the questions formally specified for this project: i.e. “What effect has the supply of wood pellets to UK power stations had on the forest carbon stock in the SE USA, Canada and Europe?” However, a major aim of this project is to establish the feasibility of a full-scale study into the effects of UK wood pellet supply chains on forest carbon stocks in North America and Europe. In this context, as part of the literature review, an assessment has been made of the extent to which previously published studies have addressed the following additional methodological questions:

1. Is there a way we can find out the impact UK demand for wood pellets is having on forest management in other countries?
2. Is there a way we can find out the impact UK demand for wood pellets is having on the wood supply chain in other countries?
3. Is there a way we can find out the impact UK demand for wood pellets is having on the development of forest carbon stocks and sequestration in other countries?
4. With regard to questions 1 to 3 above, is there a way we can work out, with reasonable justification, what would have happened to forest management, the supply chain, and carbon stocks and sequestration in other countries under different circumstances?

This assessment has assisted in identifying available options for methods suitable for carrying out the full-scale study under consideration.

3. Approach to literature review

The literature review for this project was specified to be systematic but also concise and focussed on addressing the specified questions. The approach to the literature review has aimed to follow these principles. However, when considering the requirement for conciseness, it is impossible to avoid the fact that the body of literature on the subjects of interest is very large, particularly if papers dealing partially with closely relevant points are included in the scope of the review. In addition, relevant scientific papers have been published across a range of journals, covering subjects such as forestry, energy policy, environmental management and life cycle assessment. This can make it time-consuming to identify all relevant literature. In addition, there is a significant body of grey literature that also needs to be considered.

In order to fully address the requirements of the review, whilst alleviating some of the problems with the extent and diverse sources of the literature, an approach was adopted that involved:

- Building on work done for previous literature reviews (for example as reported in Matthews *et al.*, 2014)
- Trawling through a range of potential literature sources to identify more recently published studies
- Compiling a “long list” of papers describing studies of direct relevance to the review, also including papers covering related subjects (e.g. papers describing studies of forest carbon stock changes in response to harvesting, but not necessarily explicitly in the context of wood pellet production from forests)
- Screening the papers in the long list for their relevance to this project, in particular to arrive at a “short list” of papers, directly dealing with studies that have included the consideration of carbon

stock impacts related to wood pellet production or the more general production of woody biomass for energy.

The papers in the short list were then subjected to a detailed review.

3.1. Sift of papers

The sift process for the long list of papers involved categorising papers as either:

- In scope for detailed review (papers of “type A”)
- Out of scope but of high relevance (generally consisting of previous reviews and/or meta-analyses of the literature – papers of “type B”)
- Out of scope and falling into some other category of wider relevance to the subjects addressed by this project (papers of “type C” to “type I”).

In order to qualify as a paper of type A, it needed to be evident that the content of the paper addressed at least one and preferably more than one of the additional methodological questions specified in Section 2 above. Priority was placed on identifying papers addressing the production and supply of woody biomass for energy from forests in the geographic regions of greatest interest to this project (North America and Europe).

The remaining papers were classified into the following categories:

- B – out of scope for detailed review but highly relevant and considered as part of the discussion of findings: an example of a review of studies of the impacts on forest carbon stocks in a relevant region arising from demand for wood (pellets) for use as an energy feedstock
- C – out of scope for detailed review: an example of a report presenting background scientific results or a wider study relevant to the carbon/GHG balance of forests or wider land use
- D – out of scope for detailed review: an example of a report presenting analysis and/or results related to the LCA of wood-based products
- E - out of scope for detailed review: an example of a study of the impacts (but not on forest carbon stocks, e.g. economic impacts) in a relevant region arising from demand for wood (pellets) as an energy feedstock
- F - out of scope for detailed review: an example of a position paper or methodological proposal relevant to assessing the carbon/GHG impacts of utilising forest biomass (or biomass from other origins) as an energy feedstock
- G - out of scope for detailed review: an example of a study or assessment of potentials of biomass available for use as an energy source, not covering carbon impacts
- H - out of scope for detailed review: an example of a report or paper providing relevant background information, e.g. about forest characteristics and/or silvicultural practices in relevant geographic regions

- I - out of scope for detailed review: an example of a statement of a methodology standard, user manual, guidelines or regulation with some relevance to the supply of biomass for use as an energy source.

A total of 352 documents were compiled for the long list, based on consideration of previous reviews and the trawl through relevant literature sources (see Annex 1). Table 3.1 gives the numbers of documents categorised into types A to I as described above. A few documents were eliminated from the long list for a range of reasons, e.g. confidentiality constraints or lack of sufficient relevance for the present study.

Table 3.1 Summary of long list of documents considered as part of review

Type	Short description	Number of papers
A	In scope for detailed review	69
B	Previous review/meta-analysis	6
C	Wider consideration of carbon/GHG balance	77
D	Wood product LCA	9
E	Non-carbon/GHG impacts	14
F	Position paper/methodological proposal	96
G	Biomass potentials	20
H	Forest characteristics/management	25
I	Methodology, manual, guidelines, regulations etc.	35
TOTAL		352

3.2. Detailed review of papers

The detailed review of the 69 selected papers (see Section 3.1) was carried out systematically by extracting a set of key information items and finding the answers to consistent set of enquiries, as listed in Annex 2. Key points covered were:

1. Geographic region(s) covered in study
2. Forest species type(s) considered
3. Forest management scenarios involved in supplying forest bioenergy
4. Counterfactual forest management scenarios
5. Methods used to identify or construct scenarios
6. Feedstock(s) involved in supplying woody biomass for use as an energy source
7. How land use/land-use change was represented in studies
8. Spatial scale(s) considered in the study
9. Assessment methodologies applied in studies (modelling or otherwise)
10. Representation of forest carbon stocks/biogenic carbon

11 Timescales considered in the study (e.g. for wood production and/or impacts on forest carbon stocks)

12 Metrics used for reporting main results

13 Main conclusions of the paper on carbon impacts of using woody biomass as an energy feedstock.

In addition, a brief subjective summary assessment or comment was made on each paper. This included commenting on any key difficulties associated with a particular study (e.g. methodological flaws, lack of transparency), as well as any notable lessons to be learnt or insights gained.

4. Key findings

4.1. Systematic analysis of studies

The systematic analysis of the 69 selected papers was recorded in an Excel workbook, "Review of forest carbon stock impacts studies v3.2.xlsx". Results obtained for aspects of the papers of particular interest to this current project (see list in Section 3.2) are described and discussed here.

4.1.1. Geographic regions

The geographic regions considered by studies are summarised in Table 4.1. It should be noted that the total number of geographic regions represented in studies exceeds the number of papers, because several papers considered more than one geographic region.

Table 4.1 Geographic regions considered by studies

Geographic region	Number of papers
Canada	18
Northern USA	3
Southern USA	12
USA general	6
Fennoscandia	16
Other Europe	10
Global/multiple	6
Other	7

As can be seen in Table 4.1, North America is the most studied region (39 papers in total, 18 covering Canada, 20 covering the USA of which 12 consider the Southern USA). Many studies are concerned with forests in parts of Europe (26 papers), with a particular focus on Fennoscandia (16 papers). Other countries in Europe are covered in one or two studies or have not been considered at all. Six studies have aimed to analyse the impacts of bioenergy policy on forest carbon stocks or GHG emissions at a very large scale, e.g. the whole of Europe or global forests. Seven studies have considered other regions (e.g. Australia), or have involved a more theoretical treatment that does not deal with forests in any specified region.

Whilst the representation of geographic regions in studies is good in some areas but patchy in others, it is apparent that the regions most covered in studies are of greatest current relevance to this project (i.e. representing the major sources of wood pellets currently imported to the UK).

4.1.2. Forest species groups

The forest species groups covered in studies are summarised in Table 4.2. It should be noted that the total number of forest species groups represented in studies exceeds the number of papers, because several papers specifically considered more than one forest species or species group.

It is apparent that studies of coniferous forests are most common (36 papers). This reflects the geographic regions most represented in studies, i.e. boreal forests in Canada, Fennoscandia and the Pacific Northwest of the USA, where coniferous forests are dominant. Studies in the Southern USA also frequently focus on coniferous (pine) forests, which represent the most actively managed resource there, including intensively managed industrial plantations.

Table 4.2 Forest species groups considered by studies

Forest species group	Number of papers
Coniferous	36
Broadleaved	9
Mixed	3
Multiple	25
Not stated	6

There is a reasonably substantial minority of studies of broadleaved and mixed tree species (12 papers), although some of these consider quite special cases (e.g. fast growing eucalyptus plantations in Spain). A significant number of papers consider “multiple” forest types, composed of varying tree species and growth rates. Generally, these are the studies that analyse large landscapes or whole regions, or global forests (see Sections 4.1.8 and 4.1.9).

Six studies do not explicitly state the types of forest under consideration. These studies have either taken a more theoretical approach to analysing forests, or have not actually included consideration of forest carbon stocks as part of the assessment of bioenergy (see Sections 4.1.5, 4.1.7, 4.18 and 4.1.10).

4.1.3. “With-bioenergy” forest management scenarios

Table 4.3 summarises the scenarios represented in studies describing forest management involved in supplying woody biomass for use as an energy feedstock. It should be noted that the total number of scenarios greatly exceeds the number of papers, because many papers considered more than one scenario.

Table 4.3 "With-bioenergy" forest management scenarios considered by studies

Forest management scenario	Number of papers
Extract residues	50
Increase harvesting	45
Change rotations	12
Convert to plantations	10
Enhance stocking/growth	11
Afforestation	8
Not stated/applicable	4

It is apparent from Table 4.3 that the scenario most commonly considered (50 papers) is the increased extraction of forest residues (otherwise left behind or burnt on site after harvesting). There are almost as many studies (45 papers) that consider a scenario in which the overall extent of forest harvesting activities (thinning and/or felling) is increased as a result of the supplying of woody biomass for use as an energy feedstock. Fewer papers but still a reasonable number (33) consider scenarios involving more detailed changes to silvicultural practices related to woody biomass supply for energy use. Relevant activities represented include:

- Adjustments to rotations applied to stands of trees (12 papers)
- Adjustments to the stocking or growth of trees in managed stands, through modified thinning practice, or by increasing the density of trees during the early phase of rotations, when planting or regenerating stands of trees (11 papers)
- Enhancing the productivity of stands of trees, notably through converting forest areas to intensively managed tree plantations (10 papers in this latter case).

Relatively few papers allow for land-use change as a result of the demand for woody biomass for use of an energy feedstock. Where this is considered, generally this involves afforestation activities stimulated by increased economic incentives to supply forest biomass (8 papers). In the case of 4 papers, no information was provided about the scenario(s) for forest management involved in supplying forest bioenergy, or otherwise consideration of forest management was not relevant (generally because the study did not include the dynamics of forest carbon stocks as part of the assessment).

Difficulties should be noted with regard to the terminology used in the definition and representation of certain forest management activities in scenarios, notably related to the terms, "forest residues" and "increased harvesting". These difficulties are discussed below.

Forest residues (and their extraction)

There is no widely agreed definition for forest residues, although some formal definitions exist (e.g. as part of forestry definitions published by FAO). Some stakeholders define forest residues relatively narrowly, limiting the types of woody biomass to those typically unsuitable for utilisation by the timber, panel and paper industries and usually not extracted as part of forest harvesting for these markets. Relevant components of forest biomass include small branches, tree stem tops, misshapen parts of tree stems discarded as part of conventional harvesting, over-size portions of the butts of tree stems (too big for processing by sawmills), tree stumps and roots. It is apparent that even this definition includes a diversity of types of woody biomass material. In this context, it should also be noted that different studies in the literature consider scenarios in which all of the forest residues as just defined are extracted, whilst others consider a selection of them (e.g. just small branches and stem tops).

The definitional issues described above may be further complicated by the inclusion in some studies of woody biomass, partly or wholly for use as an energy feedstock, extracted as part of “salvage logging” (i.e. the harvesting of stands of trees killed or mortally damaged by pests, disease, storms or fire). This is a very relevant situation in the current bioenergy debate, being practiced in Canada in response to large-scale damage to forest areas caused by beetles. Salvage logging can involve the extraction of whole trees and generally large-diameter roundwood, which may be utilised to produce sawn timber if it has not degraded too severely, but may potentially also be used as a feedstock for energy generation.

Whilst some stakeholders work with the relatively narrow definition of forest residues discussed above, others use the term in a wider and occasionally hypothetical sense. Specifically, an argument is constructed with regard to any biomass which is extracted for use as an energy feedstock, as follows:

1. The woody biomass components (which can sometimes include quite large diameter roundwood) are only being extracted as part of harvesting because there is a market for woody biomass for use as an energy feedstock.
2. There are no alternative markets for these woody biomass components (which might include observing a declining market for pulpwood for paper mills)
3. Given (1) and (2), it follows that the woody biomass components would otherwise be discarded in the forest, in the absence of a market for woody biomass for use as an energy feedstock.
4. Given (3), it follows that the woody biomass components can be regarded as “forest residues”.

Note that this argument sometimes includes trees with low value for timber utilisation that may otherwise be left standing after harvesting and would continue to grow. The various definitional issues surrounding scenarios involving extraction of forest residues can create considerable confusion and misunderstanding, and leads to difficulties when reviewing or discussing studies concerned with the impacts of utilising forest residues on forest carbon stocks and/or biogenic carbon emissions.

Increased harvesting

A forest management scenario involving “increased harvesting” may cover one or more situations, such as:

- Increased extraction of forest residues (see discussion above)
- Increased thinning activities in forest stands, generally involving the harvesting of smaller diameter and misshapen trees, allowing for the remaining trees more space to grow and enhancing the

production of timber later in the rotation (but generally with related reductions in forest carbon stocks over the rotation)

- Increased clearfelling activities in forest stands, involving the utilisation of some lower value woody biomass components as energy feedstocks, as by-products of the supply of wood for higher value products such as sawn timber
- As in the case immediately above, but with all the harvested woody biomass utilised as energy feedstocks
- As in the case immediately above but involving situations in which trees in a clearfelled stand with low value for timber utilisation would otherwise be left standing after harvesting the higher value trees and would continue to grow (see preceding discussion of “forest residues”).

These cases are quite different from one another and may lead to different impacts on forest carbon stocks and/or biogenic carbon emissions associated with utilising forest biomass as an energy feedstock.

A further difficulty can arise in that some studies do not specify precisely which cases are involved in scenarios including increased harvesting activities. This is frequently a feature of large-scale modelling studies (regional, national or global) and in those studies applying economic/forest-sector models as part of the scenario development and assessment methods (see Sections 4.1.5 and 4.1.9). Typically (although not always) such modelling approaches are described in papers at quite a high level and the exact forest management activities involved in increased harvesting are not specified. When economic models are applied, it is possible that the study authors themselves may not know the exact details of the forest management activities assigned to forest areas by the economic and forest-sector models in simulations representing increased forest bioenergy supply.

As already observed (Table 4.3), the majority of studies include scenarios that involve the forest management activities of “extracting forest residues” or “increasing harvesting”. However, the issues with these terms discussed above make it difficult to determine exactly how these activities should be represented in any “definitive” scenarios describing forest management in a particular geographic region involved in supplying woody biomass for use as an energy feedstock. Furthermore, and more fundamentally from the point of view of this project, it is very doubtful whether the frequency with which forest management activities are represented in scenarios presented in published studies can be used as a guide to their likelihood of occurring. The reasons for this are discussed in Section 4.1.5.

4.1.4. Counterfactual forest management

Table 4.4 summarises the scenarios represented in studies constituting the counterfactual to that determined for the supply of woody biomass for use as an energy feedstock.

It should be noted that the total number of scenarios exceeds the number of papers, because some papers considered more than one possible counterfactual scenario.

Table 4.4 Counterfactual forest management scenarios considered by studies

Counterfactual management	Number of papers
"Business as usual"	17
Standard management	6
No bioenergy policy	6
Leave in forest	17
No increase in harvesting	14
Burned to waste	4
Harvested for other purposes	4
Multiple	4
None	3
Not specified	5

It is apparent from Table 4.4 that the studies have referred to a range of counterfactual scenarios, although these can be grouped into six broad types:

1. Scenarios representing "business as usual", i.e. how forests would be managed in the absence of an additional demand for woody biomass for use as an energy feedstock. Scenarios involving "standard" forest management generally fall into this category, as do those that consider the absence of a proposed or existing policy encouraging the use of bioenergy (this gives 29 papers in total).
2. Scenarios involving not harvesting trees or leaving potentially available woody biomass sources in the forest (31 papers). This includes the case of discarding forest residues to decompose in the forest, rather than extracting them.
3. Scenarios in which forest management is unchanged when compared with the "with-bioenergy" scenario (e.g. relevant forest stands are still managed in the same way for wood production, but for purposes other than the increased supply of woody biomass for use as an energy feedstock, 8 papers). Related scenarios involve residual woody biomass being burnt to waste, rather than left to decompose (in the forest or in piles of waste accumulated by timber mills)
4. Multiple versions of scenarios (e.g. more than one of the type described above, 4 papers)
5. No comparison with any sort of counterfactual scenario (3 papers)
6. No counterfactual scenario specified (5 papers).

The majority of studies have referred to counterfactual scenarios of the first two types listed above. However, it is doubtful whether this observation can be used as a basis for inferring the most likely counterfactual scenarios for forest management in the absence of a demand for woody biomass for use as an energy feedstock, for reasons explained in Section 4.1.5.

Counterfactual scenarios are not always clearly described in studies, whilst in a few studies there is no reference made to a counterfactual scenario (generally, these studies have undertaken what is effectively an attributional LCA).

As with the “with-bioenergy” scenarios (see Section 4.1.3), difficulties should be noted with the description and representation of counterfactual forest management scenarios. One issue concerns a potential lack of clarity regarding the basis for referring to a “business as usual” scenario, a “no increase in harvesting” or “leave in forest” scenario, or a “no change in forest management” scenario. Specifically, in certain circumstances, either of the latter two types of scenario may in fact represent “business as usual”, and may even be referred to as such in studies. In other contexts these scenarios may represent theoretical baselines against which to assess the “with-bioenergy” scenario. Studies may also apply a combination of counterfactual scenarios, for example, “no change in forest management” for assessing thinning and clearfelling activities related to bioenergy production, and “leave in forest” when considering forest residues. All such approaches may be perfectly valid, depending on the specific research purpose of an individual study. However, frequently, papers include only partial or non-systematic statements of the intended purpose of the research, or sometimes this is stated ambiguously.

The varying research questions/purposes addressed by studies, and the related application of varying counterfactual scenarios, presents difficulties when interpreting the results of papers, and particularly when comparing their results (see for example Sections 4 and 5, and Appendix 9 of Matthews *et al.,* 2014).

4.1.5. Identification and construction of scenarios

In the context of this project, it was particularly important to evaluate the approaches used in published studies to identify, develop and/or construct scenarios for forest management, both for “with-bioenergy” and “counterfactual” scenarios. Insights gained from such an evaluation may be important for determining the feasibility of the full-scale study being considered in this current project, and in arriving at recommendations for appropriate methodologies.

The review of studies revealed that a range of methods had been adopted for determining forest management scenarios:

1. Simply making assumptions about forest management activities involved in “with-bioenergy” and counterfactual scenarios, and then generally (but not always) stating these assumptions as part of the description of methods
2. Applying economic models in conjunction with large-scale forest sector models to simulate changes in activities under the “with-bioenergy” scenario, compared with a “without-bioenergy” (counterfactual) scenario
3. Referring to forestry sector information on the consumption of woody biomass for use as an energy feedstock, and inferring forest management practices from these
4. Considering a case study involving an actual set of sawmills and wood-fired energy plants and investigating the use of wood feedstocks by the mills and plants and the management of the forest areas involved in providing the feedstocks

5 Consulting with stakeholders within a relevant region (including forestry sector experts) to try to establish the forest management practices most likely to be involved in “with-bioenergy” and counterfactual scenarios.

Several studies used combinations of the above methods. A number of studies also included a sensitivity analysis, to explore relationships between the study results and the assumptions, model parameters and data scenarios from which they were derived.

The methods adopted by studies are summarised in Table 4.5.

Table 4.5 Methods used to identify and/or develop scenarios in studies

Methodology	Number of papers
Assumptions	46
Assumptions + sensitivity	5
Assumptions and economic modelling	1
Economic modelling	11
Economic modelling + sensitivity	1
Case study	1
Sectoral information/statistics	2
Stakeholder consultation and economic modelling	1
Not applicable	1

Assumptions

It is apparent from Table 4.5 that the great majority of studies (52 papers) simply made assumptions about forest management activities involved in scenarios. These findings strongly imply that it is difficult to use most of the scenarios referred to in published studies as a basis for determining definitive scenarios describing the management of forest areas to supply woody biomass for use as an energy feedstock, or equivalent counterfactual scenarios. In this context, it should be noted that papers frequently just state the assumptions made and do not provide supporting justification. Nevertheless, such an approach has the merits of transparency and simplicity.

Sensitivity analyses can inform understanding of the uncertainties around results based on assumptions but sometimes the uncertainty range is found to be very large, making it difficult to draw clear policy conclusions.

Economic modelling

Of the remainder of studies not relying on assumptions, nearly all (12 studies) applied economic models as the principal method for constructing scenarios. Studies based on economic modelling may provide a more systematic basis for determining scenarios, in the presence and absence of a demand for woody biomass for use as an energy feedstock. However, scenarios constructed in this way are only reliable if the economic models (and related forestry sector models) adequately represent market trends and responses in the energy and forestry sectors (and potentially other sectors, e.g. timber). In practice these models involve quite simplified representations, and assumptions are frequently involved (e.g. about cost curves), but less transparently than for those studies that make direct assumptions about forest management scenarios. Comments made about sensitivity analysis in the discussion of studies based on assumptions also apply to studies applying economic modelling.

Sectoral information/statistics

Only two published studies were based principally on the interpretation of sectoral information (Booth, 2018; Giuntoli and Searle, 2019).

Study of Booth (2018)

The study presented by Booth (2018) is interesting in that it endeavours to make best use of reported information on biomass feedstocks utilised within the energy sector as a basis for setting up scenarios for modelling. The study focussed principally on the US energy sector and took information reported by the US Energy Information Administration (EIA) and the US Environmental Protection Agency (EPA) on feedstocks derived from biomass used in energy generation. In addition, data on the utilisation of woody biomass for wood pellet manufacture (mainly for export) was obtained from a "forest-industry tracking company".

For each feedstock, a simple model was used to estimate biogenic carbon impacts (effectively impacts on carbon stocks in forests or elsewhere) arising from the use of the feedstock for energy generation. Whilst the modelling approach adopted in the study is simplistic, it has the merits of being very transparent and relatively understandable.

The modelling of complex forest carbon stock dynamics is avoided, essentially by regarding each biomass feedstock as some sort of "residue" if not utilised for energy. Hence, when constructing counterfactual scenarios (depending on the specific feedstock):

- Either the feedstock was assumed to be burnt without energy recovery
- Or the feedstock was assumed to be left to decompose (generally in the forest).

For many of the feedstocks considered, these assumptions seem reasonable, but for others the validity of the approach is open to question. This is specifically the case for the significant reported feedstock of "wood solids", which includes "forestry wood", "mill residues", "urban tree trimmings" and "construction and demolition wood". (Incidentally, this illustrates problems that can occur in the reporting of wood biomass feedstocks, in which a number of heterogeneous biomass components are reported as a combined category.) In the particular case of "forestry wood" this could consist of woody biomass components such as branchwood but also parts of stemwood, the latter of which may only fit the definition of "residues" in a very wide sense (see relevant discussion in Section 4.1.3). Strictly, such situations require more detailed consideration of forest management activities involved in feedstock harvesting, and likely counterfactual activities. Similar observations apply with regard to the modelling of wood pellet production in the study, for which hard data on feedstocks involved is less strong and required assumptions to be made. The study well illustrates how information about feedstock utilisation in the energy sector might be analysed and interpreted to infer carbon impacts, but also highlights the limitations of such an approach.

Study of Giuntoli and Searle (2019)

Very late on during work on this project, a study by Giuntoli and Searle (2019) has been published. This study is important to consider here since it goes very much further than the study of Booth (reviewed immediately above) in trying to analyse information on the forest sector, so as to draw inferences about how forest management and patterns of wood utilisation may be changing in response to a rising demand for forest bioenergy, notably wood pellets. It is very likely that the study can be regarded as an exemplar of how currently available forest sector data can be applied and interpreted as far as practicable for such purposes. Hence, this study is important for understanding how sectoral data may be used systematically to inform the construction of scenarios for forest management and wood utilisation in response to demand for bioenergy.

Before proceeding to consider the methods employed in the study, it is crucial to clarify the study objectives. In this regard, Giuntoli and Searle initially develop a thesis:

- Firstly, the existence of diametric disagreements in published literature about the impacts on GHG emissions arising from the use of forest biomass for energy purpose (beneficial or deleterious) is highlighted.
- Secondly, it is asserted that the opposing conclusions drawn in the various published studies reflect specific assumptions made about the types of forest management and wood feedstocks involved in supplying bioenergy. In effect, it is concluded that there are “good” and “bad” practices in terms of forest management and wood feedstock utilisation to supply bioenergy.
- Thirdly, based on the preceding points, an objective is set for the study, which is to establish whether there is any evidence that recently increased demand for bioenergy is leading to any of the “good” forest management practices or “good” uses of wood feedstocks.

There are of course a number of precedents in the literature for the observations made in the first two points above, some of which are cited by Giuntoli and Searle, including the report of Matthews *et al*. (2018).

The setting of the question in the third point above, to the effect, ‘is there evidence for “good” practices occurring’, limits the usefulness of the study from the point of view of this project – the more relevant question would have been, “what does sectoral information tell us about the practices that have been taking place and are expanding?” This well illustrates how the answers reached by a study depend on the purpose of the study (assuming one is stated), and why a review of literature can be of limited value when looking for an answer to a specific (new or different) research question. Despite this limitation, the methods employed in the study of Giuntoli and Searle are worthy of careful consideration because they may be relevant for wider application to other questions.

The study considers three geographic regions with obvious relevance to wood pellet and/or general wood energy production, namely Canada (mainly British Columbia), Sweden and the Southeastern USA. For each region, the study report presents three key assessments:

1. An overview of the current status and development of forestry and the utilisation of wood for different purposes in the region

2 A review of relevant research literature on possible forest management practices and wood feedstocks utilised for energy purposes, and their associated carbon impacts (beneficial or deleterious)

3 An analysis of data available from forest inventories and from the forestry sector, with the aim of establishing whether any of the beneficial practices identified in (2) are actually occurring or expanding and, if so, whether this can be attributed to an increased demand for bioenergy.

The presentation of these assessments is impressively succinct and at the same time informative and reasonably transparent.

Generally, the study identifies a number of possible activities as potentially leading to positive impacts on forest carbon stocks, or to limited negative impacts or otherwise to net GHG emissions reductions within policy relevant timescales:

- Utilisation of forest residues (particularly in situations where the residues would otherwise have been burnt in the forest)
- Utilisation of wood salvaged from sites subject to disease infestation, as part of the restitution of forest stands (only of recent relevance in Canada)
- Improved site preparation (including e.g. ground scarification, herbicide application)
- Improved site/tree tending (including fertilizing, planting improved tree stock and pre-commercial thinning)
- Enhancement of forest growth rates (sometimes involving site preparation and/or tree tending but also including making changes to tree species to higher yielding types, including genetically improved trees, when restocking forest areas).
- Increased thinning in tree stands
- Afforestation (and/or reduced deforestation).

For each of the three study regions, sectoral statistics are reviewed for evidence of the occurrence of the above activities, and in particular any trends in the extent of each type of activity (notably any increase). The study authors note that relevant data sources are not always adequate for this purpose and that sometimes information on other sorts of activity needed to be referred to as a proxy. The specific types of data referred to are summarised here in Table 4.6. Generally these data are available as annual statistics reported in National Forest Inventories or in sectoral reports published in the relevant countries.

For the Southeastern USA region only, the study also assesses the possibility of shifts in the mix of wood-based products (structural timber, wood-based panels, paper and wood pellets), as a result of competition from increasing demand for bioenergy. Statistics published in a USDA Forest Service report and data from FAOSTAT are referred to for this purpose.

For Sweden only, an assessment is also made of the overall level of wood biomass production for energy purposes (allowing for a range of feedstock types), reflecting the availability of relevant data for this region.

It should be noted that Giuntoli and Searle comment on the difficulties that can be encountered when interpreting statistics on forest residues, due to definitional issues, as already discussed earlier and subsequently in this report (see Sections 4.1.3 and 4.1.6).

Having used the best available data to establish where evidence exists for the extent and trends in relevant types of activity (if any), an investigation is made of the possibility of the existence of linkages between these activities (where present) and growing demand for wood for use for energy purposes (notably as wood pellets). For this purpose, a range of data sources are considered, where available:

- Annual wood pellet production statistics
- Annual statistics on the production of other types of wood energy
- Annual price data for wood energy feedstocks
- Annual price data for pulpwood (used as a surrogate for wood energy price in the analyses of Canada and the USA)
- The development of the distribution of tree ages in forest areas
- Annual atmospheric deposition of nitrogen (NH_4)
- Annual change in (mean air?) temperature.

The last three data sets listed above are used as part of the interpretation of data indicating a progressively increasing rate of forest growth in Sweden.

Table 4.6 Types of data referred to in the study of Giuntoli and Searle (2019) for evidence of the occurrence of specific forest management and wood utilisation activities

<table>
<tr><th>Activity</th><th>Canada (British Columbia)</th><th>Sweden</th><th>Southeast USA</th></tr>
<tr><td>Extraction of forest residues</td><td><u>Proxy (inverse):</u> Reported GHG emissions from burning residues on forest sites expressed as a ratio with respect to the total harvested forest area</td><td>National statistics on forest fuel production (by type)</td><td><u>Proxy:</u> Statistics on products derived from “non-growing stock”</td></tr>
<tr><td>Salvage logging</td><td rowspan="3">Relevant data in National Forest Database (British Columbia)</td><td colspan="2">Considered not be relevant in these regions</td></tr>
<tr><td>Site preparation</td><td rowspan="2">National statistics on relevant activities</td><td rowspan="2">No data available</td></tr>
<tr><td>Site/tree tending</td></tr>
</table>

Activity	Canada (British Columbia)	Sweden	Southeast USA
Thinning	Not discussed explicitly (but pre-commercial thinning considered as part of site/tree tending)	National statistics on relevant activities	No data available
Enhancement of growth (changes to higher yielding tree species)	Not discussed explicitly (but planting of improved tree stock considered as part of site/tree tending)	Proxy: National statistics on changes in tree species composition of forest areas Also (proxy): National statistics on growth rate of forest areas	Proxy: Mean and distribution of stand productivity (pines and broadleaves), reported in National Forest Inventory Also (proxy): Statistics on changes in tree species composition of forest areas (softwoods versus hardwoods)
Afforestation/ reduced deforestation	National/regional statistics	Proxy: Statistics on total forest area	

The approach taken in the study of Giuntoli and Searle to exploring links between forest sector activities and bioenergy demand is to look for correlations between the "activity" data and the production and price data described above. Simple linear regression was carried out in Microsoft Excel and tests performed for statistical significance. The authors caution that correlation does not necessarily imply causation and that correlation can sometimes occur for spurious reasons. It may also be noted that a lack of correlation may not rule out the possibility that bioenergy demand is leading to changes in practices in the forestry sector.

A tabular summary of results is provided for each study region, describing the relevant activities, the historical trend for each activity, the evidence (if any) for a link to an increased demand for bioenergy and the likely carbon impact. Similar summary assessment tables are included here as Tables 4.7, 4.8 and 4.9, presenting the assessments for Canada, Sweden and the Southeastern USA respectively. However, it must be stressed that the content of these tables has been modified significantly, compared to those in the original report, for the purposes of conciseness and clarity.

The study of Giuntoli and Searle does not make an independent evaluation of the carbon impacts of different forest sector activities; rather it relies on evidence from previous studies covered in the literature reviews for each region.

Table 4.7 Assessment of "beneficial" forest sector activities in Canada related to forest bioenergy production (modified from Giuntoli and Searle)

Activity	Historical trend	Driven by bioenergy demand?	Carbon impact
Extraction of forest residues	Seems to be increasing (based on inverse proxy data)	"Plausible" (correlated with pellet production)	Clearly beneficial if otherwise burnt in forest
Salvage logging	Historically important but no longer significant	"Likely" historically, but unlikely to continue	Unclear – requires intensive forest restocking efforts for beneficial outcome
Site preparation	Decreasing	No evidence (trend is opposite to that expected)	Unclear – possibly no significant effects
Site/tree tending	Use of improved trees and fertilizing has increased; pre-commercial thinning and pruning have declined	No evidence (increasing trends appear to be in line with unrelated government programmes)	Unclear – increasing activities may provide benefits but decline in others may have deleterious effects
Afforestation	Afforestation in line with government programme; no change in rate of deforestation	No evidence (increasing afforestation appears to be in line with unrelated government programme)	Afforestation is likely to have beneficial impacts

Table 4.8 Assessment of "beneficial" forest sector activities in Sweden related to forest bioenergy production (modified from Giuntoli and Searle)

Activity	Historical trend	Driven by bioenergy demand?	Carbon impact
Extraction of forest residues (including a proportion of tree stumps)	Increasing then decreasing[1]	"Unlikely" (correlated with bioenergy prices but overall supply has increased, see next)	Unclear – branchwood extraction may be beneficial within relatively short timescales, but this is unlikely in the case of stump extraction
Extraction of other forest biomass feedstocks for energy purposes	Increasing, notably extraction of "firewood"[2]	"Likely" (correlated with bioenergy prices)	Unclear – depends on the composition of "firewood" which is not well defined
Site preparation and site/tree tending	Continually increasing overall forest growth rate over 45 years (proxy)	"Unlikely" – no significant changes in relevant activities except for some increase in fertilization. Likely to be caused by other environmental factors	Potentially beneficial – increasing growth rates could mitigate negative impacts of increased biomass production
Thinning	Thinning (in various forms) has increased	"Likely" (correlated with bioenergy prices)	Potentially beneficial – if negative impacts on growing stock later in forest rotations are avoided
Enhancement of growth (changes to higher yielding tree species)	Slightly increasing area of lodgepole pine[3]	"Plausible" – could reflect increased demand for bioenergy but the magnitude of the activity is small	Potentially beneficial – increasing growth rates could mitigate negative impacts of increased biomass production[3]
Afforestation	No long-term change in total forest area (proxy)	No evidence (no evident activity)	Afforestation is likely to have beneficial impacts

Notes to Table 4.8:

1 It is suggested here that the changes in the level of utilisation of forest residues over the period 2008-2017 is in fact fairly stable at between about 1.5 and somewhat over 2 million oven-dry tonnes per year (see Figure 7 in Guintoli and Searle).

2 Increasing supply of "roundwood chips" and "whole tree chips", suggested by the authors, does not seem to be strongly supported by annual data over the period 2008-2017 (see Figure 7 in Guintoli and Searle).

3 See subsequent discussion of potential issues associated with lodgepole pine.

Table 4.9 Assessment of "beneficial" forest sector activities in Southeastern USA related to forest bioenergy production (modified from Giuntoli and Searle)

Activity	Historical trend	Driven by bioenergy demand?	Carbon impact
Extraction of forest residues	No apparent trend, whilst wood pellet production has increased	No evidence (no apparent increase in activity)	If practiced, branchwood extraction could be beneficial within relatively short timescales
Site preparation and site/tree tending	Increasing average productivity of pine plantations over 20 years (proxy)[1]	"Likely" (correlated with pellet production and pulpwood prices)	Potentially beneficial – increasing growth rates could mitigate negative impacts of increased biomass production[1]
Enhancement of growth (changes to higher yielding tree species)	Increasing area of (faster growing) softwoods, compared with hardwood areas	"Plausible" (correlated with pulpwood prices but trend was occurring before increase in bioenergy demand)	Potentially beneficial – increasing growth rates could mitigate negative impacts of increased biomass production
Afforestation	Increasing total (production) forest area over about 40 years	"Likely none" – trend appears to be related to other factors	Afforestation is likely to have beneficial impacts
Reduced supply of long-lived wood products	Increasing production of wood-based panels	Unlikely – production of pellets and wood-based panels has "increased together"; possibly pellet production has constrained panel production	Reduced supply of long-lived products (including wood-based panels) is likely to have deleterious impacts
Reduced supply of paper products	Declining production of pulp	"None" – trend appears to be related to other factors	"None. Use of stranded plantations for bioenergy reduces forest carbon stock, which must be accounted for."[2]

Notes to Table 4.9:

1 Giuntoli and Searle suggest that the magnitude of the potential increase in growth rate is smaller than suggested in relevant research literature – see subsequent discussion.

2 This appears to be a rather confused assessment – see subsequent discussion.

For the majority of relevant activities, the study concludes either that the activities are not occurring to a significant extent in each of the three regions (or are not relevant), or that demand for bioenergy is not driving such activities when they do occur. These cases are characterised as having a complete lack of evidence, weak or moderate evidence, or simply as not applicable within a given region. However, for a minority of cases, the study concludes that there is strong evidence for certain activities taking place (or becoming more commonplace) and that this is likely to be related to increased bioenergy demand. The relevant cases are:

- Extraction and utilisation of “salvage logs” from disease-infested forest areas in Canada
- The practice of thinning stands in Sweden and the Southeastern USA
- “More intensive management” in the Southeastern USA, consisting of improved site preparation and fertilization of (pine) stands.

Two activities for which the study concludes that “moderate” evidence exists of a link to bioenergy demand may also be noted, namely:

- Improved site preparation in Sweden
- Changing tree species to higher yielding types (including genetically improved trees) when restocking stands in the Southeastern USA.

Finally, four high-level policy-relevant conclusions are drawn:

- [There is] weak evidence that bioenergy demand increases collection of tree tops and branches in Canada and Sweden, although data availability is poor. Bioenergy demand does not appear to have increased the collection of logging residues – tree tops and small branches – in the United States.
- [There is] moderate evidence that bioenergy demand drives more-intensive forest stand management, which may have a weak positive effect on growth.
- [There is] weak evidence that bioenergy demand drives a shift toward higher-yielding tree species during replanting.
- [There is] no evidence that bioenergy demand results in increased forest area compared with a baseline scenario.

Overall, the study concludes that most assumptions on forest management changes in these studies cannot be justified by the available evidence. The historical evidence better supports studies that assume little or no change in forest management.

The study authors suggest that “policies that only promote bioenergy from forest biomass without conditional requirements on forest management practices most likely do not deliver GHG benefits over a reasonable timeframe.” And that “for bioenergy policies to provide any meaningful carbon benefit, it is necessary to couple the demand for forest biomass with specific measures to improve forest management to increase carbon stocks and biomass output simultaneously. It may be noted that these inferences are in fact fairly consistent with those offered by Matthews *et al*. (2018).

The study of Giuntoli and Searle is impressive in its systematic and generally objective search for evidence in available forest inventory and forestry sector data, in order to establish whether or not certain activities in the forestry sector classified as beneficial in terms of carbon impacts may be occurring in response to a demand for bioenergy, and possibly expanding. The methods employed, in terms of reference to data sources, their analysis and interpretation are an excellent example of probably the best that can be achieved by such an approach, particularly for the purposes of defining scenarios in terms of forestry activities related to bioenergy production.

The basis on which each conclusion has been reached is clearly explained and generally the transparency of the study is high, in terms of presentation of data sources and their analysis. One small improvement would have been to include the details of the regression analyses performed, perhaps in an appendix.

Unfortunately, the research question addressed by the study is not exactly of relevance to those of interest to this current project. As already noted, this well illustrates the critical point made by experienced life cycle assessment (LCA) practitioners (usually about LCA studies), that the results and conclusions of a study need to be understood in terms of the research question or purpose originally set for the study (assuming one was). However, the report for this study does provide a reasonable statement at the outset of the motivation, purpose and question(s) to be addressed. More importantly, the lack of immediate and direct relevance of the study does not preclude the possibility that the methods employed could be applied to other questions, including those of interest here, i.e. in terms of constructing reasonable scenarios involving forestry sector practices associated with bioenergy production. In this respect, the study of Giuntoli and Searle offers valuable lessons for any future study in which scenario development is informed by forestry sector information.

Similarly to the study of Booth (see earlier), the analyses attempted in this study are sometimes hampered by gaps in data reported in the regions of interest, even when information from national forest inventories is combined with wider forestry sector data such as production and price statistics. The reference made to proxy data sets in the study is creative and an approach worthy of consideration in any future study involving similar methods. However, in some cases the proxies are quite weak substitutes for the data of real interest (e.g. pulpwood prices referred to in place of bioenergy prices). It must also be noted that the regions covered in the study are relatively data-rich. Hence, the methods are likely to be even more difficult to transfer to other regions where suitable data sets are scarce, sparse or not collected/reported at all.

It is interesting to note that this study seems to accept that certain forestry practices, and the utilisation of certain wood feedstocks, when associated with bioenergy production, could lead to beneficial carbon impacts. To an extent this reflects the reliance of the study on reviews of the findings of previously published assessments, including that of Matthews *et al*. (2018). In fact, some of the conclusions in those studies are speculative or tentative and require further testing. However, these qualifying comments do not invalidate the general methodology developed by Giuntoli and Searle. The findings of this study support the conclusion that certain practices may require active support and/or incentivisation, in some or all cases. (As a minor point, it should also be clarified that some of the previous studies included in the literature reviews also did not necessarily claim that the practices identified as potentially “beneficial” were actually happening in practice, rather that such practices should be supported.)

Before concluding this review of the study of Giuntoli and Searle, some detailed qualifying points should be noted.

Firstly, in the assessment of Sweden, a very modest increase in the planting of a North American tree species, lodgepole pine, probably in place of Scots pine, is discussed as an example of how management of the tree species composition of forest areas could lead to enhanced forest growth and production. This specific example illustrates the risks that can be associated with such practices, because lodgepole pine can be very susceptible to a fungus, *Dothistroma septosporum*. This has devastated areas of lodgepole pine planted in the UK (K. Tubby, Forest Research, personal communication) and in North America (Woods *et al*., 2005). The potential for such issues has also been identified Sweden (Ennos, 2001). Whilst these observations do not negate the validity of the concept of enhancing forest productivity through tree species selection, it highlights the importance of not relying too strongly on a single measure and the need to be aware of and manage risks associated with specific measures.

Secondly, and in contrast to the point above, when considering the enhancement of growth rates in pine forests in Southeastern USA, particularly through improved stand tending, including the planting of genetically improved trees, it is noted that the magnitude of the increase in growth rate reported in national forest inventories appears to be modest compared to claims made in some studies referred to in the literature review. However, it seems likely that this is “comparing apples with oranges”. Specifically, the average increase in productivity reported for management of pine stands assessed as part of a forest inventory is being compared with results reported for the improvement of specific, individual stands of trees on specific sites. Published research data for pine stands in the Southern USA suggests that productivity can be at least doubled and possibly tripled by the adoption of a combination of intensive silvicultural practices (Fox *et al*., 2004; Jokela *et al*., 2004; Zhao *et al*., 2011) However, clearly the level of increase in an individual stand will not be reflected in estimates of the average increase in the productivity of all stands reported in a forest inventory. The situation appears to be exacerbated by the rather restricted range of productivity classes reported in US forest inventories. In addition, the USA Forest Inventory Assessment, whilst an example of an extremely robust forest inventory, aims to collect statistics on forest areas at very large scales. Hence, it may be possible that areas of intensively managed, fast-growth pine plantations register only marginally from a statistical viewpoint in inventory reports. On the other hand, this observation would appear to support the conclusion that the total area of intensively managed pine plantations currently remains small, relative to the total forest area in the Southern USA.

Thirdly, when considering interactions between the utilisation of wood from pine (“pulpwood”) plantations for bioenergy in the Southeastern USA, it is acknowledged by Giuntoli and Searle that this may be compensating for reduced demand for pulpwood for paper manufacture. The reduced demand for pulp in the region may be leading to a surplus of so-called “stranded” pine plantations, that would not have a market were it not for the new demand for bioenergy. However, it is then asserted that these circumstances cannot be taken to mean that there are no deleterious carbon impacts associated with harvesting these stands and utilising the wood for bioenergy (in whole or part). The reason given is that, “if [these] plantations were not harvested for bioenergy, the forest carbon stock would remain standing, providing carbon storage benefits … The reduction in forest carbon stock when harvesting these trees for bioenergy should be accounted for in estimating the GHG balance of bioenergy”. Note here that implicitly a counterfactual scenario for these pine stands of "no use/no harvesting" is being presumed. However, this seems to be a very unlikely counterfactual in the case on an industrial pine plantation managed actively for wood production. (It may be a reasonable counterfactual to assume in other cases.) In this case, a more likely counterfactual scenario would seem to be that the affected forest owners, lacking markets for the products of their plantations, would remove them (perhaps in a final loss-making or low-profit harvesting) and convert the land to some other use, e.g. growing an agricultural crop.

Fourthly, whilst the study of Giuntoli and Searle is generally well conceived and conducted, one important forest sector activity related to bioenergy production receives relatively scant attention – this is the utilisation of industrial residues (generally sawmill co-products or by-products) for manufacturing wood energy products (generally wood pellets or chips). The utilisation of this type of wood feedstock for energy purposes is generally regarded as being potentially beneficial in terms of carbon impacts, particularly in the event that the material would otherwise be burnt as waste. At the same time, risks of competition for this resource for the manufacture of wood-based panels must also be noted. The assessment of the utilisation of industrial residues in the study report is different to that presented for other activities:

- In the assessment for Canada, a reduction in the level of total harvesting is observed. Based on this, the study report comments, "if total wood harvests continue to decline in Canada, the production of sawmill residues will also decrease". It is then suggested that any "significant" expansion in the wood pellet industry will require wood feedstocks from other sources, including "… trunks, such as pulpwood". On the other hand, later in the discussion of Canada, it is noted that "… increased demand for wood pellets could translate into higher demand for sawmill by-products, which could in turn lead to greater profitability for sawmills and potentially an increase in the harvesting of sawlogs [for the manufacture of sawn timber]".
- In the assessment for Sweden, no comment is made on the utilisation of industrial residues as a feedstock for bioenergy. However, the statistics available for Sweden on the use of wood feedstocks for energy purposes appear to have some limitations that frustrate such an assessment. Giuntoli and Searle note a number of issues with these statistics, notably in terms of the definitions of certain classes of wood types. In the case of the utilisation of industrial residues as an energy feedstock, this may reflect a classification issue, specifically that industrial residues are not classified as a "primary forest fuel" (see Figure 7 in Giuntoli and Searle).
- In the assessment for the Southeastern USA, it is noted that "…pellet production in the US South had shifted from [utilising] 100% sawmill residues … to … less than 40% [in 2013]", although, "the share of residues [considered likely to be sawmill residues rather than forest residues] rebounded to 47% in 2017…". Later, it is noted that "… bioenergy may be replacing the use of pulpwood and sawmill by-products for paper products …". However, the ensuing discussion concentrates on the implications of this for the management of "pulpwood plantations" (see third point discussed above).

These rather partial and conjectural commentaries on the contributions made by industrial/sawmill residues as a feedstock for bioenergy products seem to be in contrast to the systematic treatment of other activities. However, it should be acknowledged that there may be limited scope for such systematic analyses, if data on the uses of industrial residues are lacking or insufficiently detailed.

Finally, an aspect of the approach taken by Giuntoli and Searle highlights a general and possibly important conceptual question from a policy standpoint, which may be stated as: “must bioenergy policy be expected to be self-contained and single-handedly deliver all required outcomes?” Many bioenergy commentators appear to implicitly assume an affirmative answer to this question. This is also implicit in some of the assessments presented in Giuntoli and Searle. For example, it is explained in the study report that policies exist in Canada supporting afforestation and certain improved silvicultural practices. These activities could mitigate risks of deleterious impacts on forest carbon stocks occurring as a result of increased bioenergy production from Canadian forests. However, the potentially mitigating role of these activities is discounted because this cannot be attributed directly to bioenergy (i.e. in terms of bioenergy demand, its production or policies promoting bioenergy use). However, importantly, in their conclusions, Giuntoli and Searle highlight that, “… it is necessary to couple the demand for forest biomass with specific measures to improve forest management to increase carbon stocks and biomass output simultaneously”. Examples of relevant measures are then given. The question arises as to whether the full range of measures needed to achieve effective climate change mitigation through the conservation, restoration, improvement, management and use of forests is best delivered through a single policy or a set of linked policies, of which bioenergy policy is just one component. Nevertheless, the point that such a set of policies (including bioenergy policy) need to act in concert and certainly not in antagonism is well taken, and this means that bioenergy policy must harmonise with other policies, particularly relevant to land use and land management. These observations are strictly of peripheral concern to the subject of this current project but may be worthy of further consideration.

Studies based on sectoral information appear to be potentially effective in systematically characterising aspects of recent (i.e. retrospective) trends in forestry sector practices related (or otherwise) to bioenergy production. It is much less clear how the methods might be applied to the construction of scenarios describing the evolution of such activities into the future. This is also the case for the development of alternative scenarios, such as representing the absence of increased demand for bioenergy, or the introduction of additional measures to support the effective utilisation of bioenergy resources.

The success of such methods is also dependent on the availability and quality of relevant forest inventory and forestry sector data, and on assumptions made when interpreting these data sources to develop scenarios.

Generally, the study authors are open in acknowledging a number of other potential limitations to their study and its methods. These, and the qualifiying points discussed above, do not detract from the many strengths of the study and the apparent care with which it has been undertaken.

It is pertinent to compare the assessments of Giuntoli and Searle (particularly as summarised here in Tables 4.7 to 4.9) with the tentative characterisation of scenarios prepared for the purposes of this project and discussed in Section 5 of this report (see Tables 5.1 to 5.3). It should be emphasised that these scenarios were developed entirely independently and without foreknowledge of the report of

Giuntoli and Searle. There are some differences in the scenarios developed for this project, compared to the activities covered in Giuntoli and Searle, notably in that the scenarios developed here attempt to characterise all relevant practices, not just potentially "good" practices, there is also a remarkable consistency between the two assessments.

Case study

Only one published study involved a "case study" approach. The case study methods applied by Stewart and Nakamura (2012) illustrate how it is possible in the USA to:

- Identify a distinct group of wood processing facilities (sawmills and wood-fired energy plants)
- Trace back wood feedstocks supplying these facilities with woody biomass to relevant forest areas
- Establish the forest management activities involved in harvesting the biomass.

Interviews were conducted with relevant industry practitioners, including forest owners and forestry contractors, to obtain information about the utilisation of woody biomass for different products and actual harvesting practices (generally involving clearfelling or partial clearfelling). These are strong aspects of the study that could form part of a template for a robust approach for scenario construction as part of the full-scale study considered in this current project. Unfortunately, the study also has two critical weaknesses:

- Firstly, the simplifying assumption was made that harvested woody biomass utilised for energy is "carbon-neutral" (i.e. it can be assumed that burning the biomass involves no net CO_2 emissions).
- Secondly, in line with the above assumption, the study did not consider forest carbon stock changes related to woody biomass supply for the manufacture of products for use as an energy source. Related to this, the study did not make any reference to a counterfactual scenario for forest management and none was developed.

These assumptions were consistent with the aims of the study, which was related to the reporting of GHG emissions for harvested wood products consistently with conventions adopted in IPCC Good Practice Guidance.

The above weaknesses render the study of no value for providing results for forest carbon stock changes arising from the supply of woody biomass for use as an energy feedstock. However, it is possible to see how the methods of the study might be adapted to address some and possibly all of the questions of interest to this project. One qualifying issue is the requirement for reliable sources of information, which depends on the existence of a well-managed and regulated industrial infrastructure, well documented supply chains, strong forest inventory data and co-operation from plant owners and forest owners. These requirements might limit the transferability of the methods to some geographic regions.

Stakeholder consultation

One study (Howes, *et al.* (2016)) set out to assess the likelihood that scenarios classified as "high GHG intensity" in the study of Stephenson and MacKay (2014) would occur in practice. To this list they added a further eleven scenarios that had not previously been covered. This was addressed through consultation with stakeholders from the North American wood pellet supply chain using a questionnaire approach to identify their views of likely practice and the parameters which could influence behaviour. The questionnaire approach was accompanied by a literature review to characterise parameters such as costs, constraints and forestry practice. This approach was combined with modelling the impact of pellet demand on forest management in Southeastern USA, the region deemed most likely to be affected by demand from Europe. The model employed, SRTS (the Sub-Regional Timber Supply model), uses economic and market factors to estimate the response of the forest sector to demand.

Questions asked in the questionnaire addressed not only the likelihood of individual scenarios and counterfactuals, but also the parameters that could influence behaviour, and that formed the inputs to the modelling that accompanied the consultation. Respondents were also asked to rate their confidence in their own responses, as well as their level, and areas, of expertise, in an attempt to help assess uncertainty.

The approach of stakeholder consultation has the benefit that it does attempt to solicit the views of those best placed to comment authoritatively on what actually happens in practice, the factors that are most likely to influence practice, and the likely range of values of those parameters. It is therefore an approach that could well be relevant as part of a full-scale study such as envisaged in this current project.

It does however potentially suffer from those weaknesses that apply to most questionnaire based studies. With a limited pool of potential respondents of sufficient expertise, reduced further to those with the time and inclination to complete a detailed questionnaire, it is likely to be difficult to undertake meaningful statistical analysis on responses. In order to provide structure and keep the questionnaire to a form that is reasonably straightforward both to complete and subsequently analyse, questions must be asked relating to a specific set of scenarios, thus investigating the likelihood of these rather than allowing the consultation itself to develop the scenarios. Although this was the remit of the study of Howes, *et al.*, it potentially excludes the gathering of information on practices or behaviour not considered in the design of the questionnaire.

It is also notable that the consultation exercise in the study of Howes *et al.* (2016) was limited to the gaining of information and data from forestry sector experts, rather than aimed at wider consensus-building amongst all concerned parties (e.g. including policy analysts, land owners and NGOs). Such a narrow approach to consultation would appear to have no particular merits, compared with other methods considered earlier, if the aim is to support a study and its results in gaining wide acceptance, or win the confidence of potential critics. This was not an objective of the stakeholder consultation conducted by Howes *et al.*, but it raises the question of whether such a more all-embracing consultation exercise would be feasible, and how it might be designed and conducted, and indeed how the objectives for the exercise could be clearly defined in the first instance.

No representation of forest management

One paper presented what is essentially a pure attributional LCA of wood pellet supply and as part of this did not include any representation at all of forest areas and their management (Magelli *et al.* (2009)). Such approaches are completely unsuitable for assessing impacts on forest carbon stocks arising from a demand for woody biomass for use as an energy feedstock (or for any other purpose).

4.1.6. Woody biomass feedstocks

The woody biomass energy feedstocks considered by studies are summarised in Table 4.10. It should be noted that the total number of feedstocks greatly exceeds the number of papers, because many papers considered more than one feedstock.

It is apparent from Table 4.10 that the feedstock most commonly studied is “forest residues” (50 papers). Other feedstocks commonly considered are “small roundwood” (or “pulpwood”) or “small early thinnings” (25 papers), “roundwood” and “stemwood” defined more generally, including “complete trees” (31 papers) and “sawmill/processing residues” (18 papers). A few studies considered black liquor and municipal solid waste as an energy feedstock. Four studies did not consider specific wood feedstocks or did not state any specific feedstock as being the subject of particular study.

Table 4.10 Woody biomass energy feedstocks considered by studies

Feedstock	Number of papers
Forest residues	50
Small roundwood	16
Small early thinnings	9
Roundwood/stemwood	20
Complete trees	11
Sawmill/processing residues	18
Black liquor	2
Municipal solid waste	1
Not considered/stated	4

The range of feedstocks covered in studies is fairly comprehensive, whilst it is apparent that some feedstocks receive particularly prominent treatment. However, for reasons explained in Section 4.1.5, it is unlikely that the relative importance given to different feedstocks in studies can be taken as an indication of those feedstocks more or less likely to be utilised in practice for energy purposes. There are also issues with the terminology used to refer to some key wood feedstocks, similar to those encountered when discussing certain forest management activities (see Section 4.1.3). Definitional issues surrounding the feedstock category of “forest residue” have already been discussed in Section 4.1.3. Similar issues arise with the terms, “roundwood”, “small roundwood”, “pulpwood”, “small early thinnings”, “complete stemwood” and “complete trees”.

The term “roundwood” can be used to refer to any “wood in the round”, i.e. parts of tree stems and (larger) branches that have not been subsequently processed, e.g. made into square posts. It is, therefore, a very general term that does not distinguish between different components of tree branches and stems that may be suitable, or unsuitable, for different end uses. For example, roundwood could include fuel logs, small roundwood (suitable for conversion into paper, particleboards and small fence posts and pallet wood), sawlogs (suitable for conversion into sawn timber products), and/or complete tree stems. Referring to “roundwood” in discussions about bioenergy feedstocks can thus lead to confusion. Complications also arise when applying some of the terms mentioned here to tree stems or complete trees of different dimensions. Notably, the woody biomass of a “small early thinning”, taken in total, is also “complete stemwood” or a “complete tree”. The implications (for net biogenic carbon emissions) of using small early thinnings as an energy feedstock may be different from using “complete stemwood” or a “complete tree” of larger dimensions. This raises the question, when exactly is a complete tree stem or complete tree “small enough” to be regarded as derived from a “small tree”? There is no generally agreed answer to this question, although a definition for a “small early thinning” has been suggested by Matthews *et al.* (2018).

In North America, the term “pulpwood” is widely used to refer to what is essentially “small roundwood”. In effect, these wood stem biomass components are defined by exception, i.e. stemwood that is not of large enough diameter to be a “sawlog” (i.e. large enough diameter to produce sawn timber). Sawlog definitions can vary but are reasonably consistent across different geographic regions. A specific issue arises in the Southern USA, where stemwood is sometimes harvested and extracted in lengths referred to as “chip ‘n saw”. This material can consist of a quite long section of tree stem, a significant part of which is of small diameter, consistent with small roundwood/pulpwood. However, typically, a length of “chip ‘n saw” also includes some stemwood of larger diameter, that may be suitable for conversion to smaller sawn timber products, e.g. small fence posts and battens. In some situations, notably in the case of wood harvested from pine forests in the Southern USA, the stemwood of thinnings which have the dimensions of “chip ‘n saw” may be harvested “in the length”, and used for the manufacture of wood pellets. Alternatively, a larger tree felled later in the rotation of a pine stand may be converted into a sawlog (or sawlogs) for supply to sawmills, whilst a remaining length of “chip ‘n saw” may be used for wood pellets. Some environmental NGOs describe the harvesting of trees in this way and the use of “chip ‘n saw” lengths as a feedstock for wood pellet manufacture as “burning whole trees for fuel”, or as “tree trunks” (see for example Booth (2018), notably Figure 7 in this paper and its caption). For their part, forest and wood-processing sector practitioners refer to the same material as “thinning” or “pulpwood” and sometimes as “forest residues” (as defined in a wide sense, see relevant discussion in Section 4.1.3). Whilst there is some validity to the positions of both groups of stakeholder in using these terms, the use (and sometimes misuse) of ambiguous terminology when talking about woody biomass feedstocks is confusing and it is easy to see how this may lead to disagreements and disputes. Hence, currently, the utilisation of tree biomass components such as “chip ‘n saw” as an energy feedstock is contentious and the subject of confusion amongst stakeholders.

Whilst there may always be difficulties in reaching agreement or consensus on this subject, there would seem to be a case for clarifying the basis of the debate over the use of parts of stemwood or complete trees for energy purposes, certainly in terms of the way in which particular types of wood feedstock are described.

4.1.7. Representation of land use/land-use change

Table 4.11 summarises the approaches taken in studies to representing forest areas and interactions with other land uses.

Table 4.11 Representation of land use/land-use change in studies

Representation of land use	Number of papers
Dynamic	12
Static	47
Static – hypothetical	6
Not stated/represented/applicable	5

It is apparent from Table 4.11 that the great majority of studies (53 papers) involved an assumption (frequently implicit) of a static forest area. In seven of these cases, the representation of forest area was based on a hypothetical composition of tree species, growth rates and distribution of tree/stand ages.

A few studies (5 papers) did not represent forest areas explicitly. Generally these were studies that did not allow fully for forest carbon stock changes and/or biogenic carbon emissions as part of the assessment.

Of the remaining studies, 12 allowed for the possibility of land-use change occurring as a result of a demand for woody biomass for use as an energy feedstock, as well as in the case of an absence of such a demand. Generally (but not exclusively), these were the studies that involve the application of large-scale economic models of the forest sector and wider land use.

In principle, it would seem reasonable to assume that the presence or absence in a given geographic region of demand for woody biomass for use as an energy feedstock could lead to an expansion or contraction of the forest area within the region (or some other regions). If so, studies that represent static forest area could be making a critical simplification. Equally, such a simplification could be valid in some situations (e.g. in regions where forestry is strongly regulated and land available for afforestation is limited).

In the Southern USA, forest sector experts stress that land use is highly dynamic. The argument is put forward that private land owners will plant new forest areas, or convert existing forests to other land uses, quite responsively to prevailing economic circumstances. These behaviours are represented in the forest sector economic models applied in a number of studies in the Southern USA, such as the SRTS model mentioned in Section 4.1.5. With one exception, studies that simulated dynamic changes in forest area at the landscape scale relied on this type of economic modelling. These studies consistently suggest that the demand for woody biomass for use as an energy feedstock in the Southern USA provides substantive incentives for land owners to undertake afforestation activities and for existing forest owners to sustain existing tree stock. For example, in the conclusions of their global-scale study, Daigneault *et al.* (2012) state that, “when market factors are included in the analysis, expanded demand for biomass energy increases timber prices and harvests, but reduces net global carbon emissions because higher wood prices lead to new investments in forest stocks”.

As already noted, the representation of land-use dynamics involving forests in studies of the carbon impacts of forest bioenergy sources seems reasonable. However, the significance of these effects are likely to be very variable from region to region, thus representing such effects may not always be justified. Moreover, the land-use development predicted by economic modelling in the Southern USA does not appear to have gained acceptance by all stakeholders. In this context, the uncertainties and limited transparency associated with the simulations made by economic models (see Section 4.1.3) may be relevant. A precautionary approach might be to assume a fixed forest area as the default situation. In geographic regions where the possibility of land-use change is considered important, this could be explored in scenarios as part of a sensitivity analysis, with the details determined through consultation with stakeholders, possibly informed by results produced by economic models.

4.1.8. Spatial scale

Table 4.12 summarises the spatial scales with which forest areas have been represented in studies. It should be noted that the total number of examples of spatial scale considered exceeds the number of papers, because several papers explored the implications of working with different spatial scales.

Table 4.12 Spatial scales considered in studies

Spatial scale	Number of papers
Plot	1
Stand	25
Landscape/regional	44
Global	3
Not specified/relevant	8

Examples of assessments at plot/stand scale and at landscape/regional scale are both commonly represented in published studies (26 papers and 44 papers respectively). A few studies (3 papers) presented assessments that work with forest areas at the global scale. In a further 8 papers, forests were not represented explicitly, if at all, hence spatial scale was not relevant to the assessments made. These studies did not fully consider impacts on forest carbon stocks or biogenic carbon emissions arising from the supply of woody biomass for use as an energy feedstock.

There is some lack of clarity in the literature about the consistency of results for impacts on forest carbon stocks arising from forest management, depending on whether impacts are considered at the plot/stand scale or landscape/regional scale. For example, Cherubini *et al.* (2013) conclude that their landscape-level results, "perfectly align with those obtained at a single stand for which characterization factors have been developed". On the other hand, Cintas *et al.* (2017) present results showing that, "for a conceptual forest landscape, constructed by combining a series of time-shifted forest stands, the two approaches sometimes yield different results".

In the experience of the authors of this current report, the consistency of stand-scale and landscape-scale results appears to depend on the details of a given study, in particular, the type of forest management intervention considered, and over what timescale. In many cases it is necessary to consider the impacts of forest management implemented progressively in a population of forest stands comprising a forest "block", landscape or region. As a corollary, assessments based on individual forest plots or stands can be misinterpreted to arrive at misleading conclusions, for example with regard to "payback times" involved in compensating for losses of forest carbon stocks associated with increased forest harvesting. This is because it is difficult to represent a progressive or year-on-year increase in wood supply when working with calculations at the stand scale. These observations are based on modelling undertaken by the report authors, variously based on stand and landscape scales (see for example Matthews *et al.,* 2014, 2015). It follows that there can be difficulties in interpreting the results from published studies of the impacts on forest carbon stocks arising from the supply of woody biomass for use as an energy feedstock, given that the results of different studies are based on assessments made at a diversity of spatial scales.

4.1.9. Assessment methodologies applied in studies

Table 4.13 summarises the types of assessment methodology employed in studies to assess the impacts on forest carbon stocks or biogenic carbon emissions as a result of the supply of woody biomass for use as an energy feedstock.

Table 4.13 Carbon assessment methodologies in studies

Assessment methodology	Number of papers
Modelling	59
Analysis of National Forest Inventory data	1
Analysis of field experiments	1
Analysis of CO_2 flux measurements	1
Not relevant	7

As can be seen in Table 4.13, a preponderance of the studies use modelling approaches (59 papers). Of the remainder, seven studies do not explicitly assess forest carbon stock impacts or biogenic carbon emissions, hence the studies do not involve relevant methodologies. There are just three examples of studies that employ assessment methodologies that are not based on modelling, one each employing:

- Analysis of national forest inventory data
- Presentation of results from formally designed field experiments
- Interpretation of CO_2 flux data collected from a forest monitoring network.

Studies based on modelling

As already noted, the application of models is prevalent in the studies reviewed for this project. A great variety of different types of model have been used, depending on the study:

- Forest sector carbon accounting models, including notable examples developed by forestry research organisations in Europe, Canada and the USA

- Forest growth models and growth simulators, which produce results for forest carbon stocks and stock changes as part of their outputs, or which produce other outputs from which these results can be derived (e.g. stemwood growth)
- Large-scale models of the forestry sector (and sometimes wider land use) and wood industry sector, generally applied at regional or global scale (see relevant discussion in Section 4.1.5)
- Models of specific elements of forest carbon dynamics, e.g. models of detritus and wood decomposition and models of soil carbon dynamics
- Simple equations, taken as representing the essential characteristics of tree growth or some other relevant variable (e.g. wood decomposition)
- Models for estimating GHG emissions associated with wood supply and processing chains (and their counterfactuals), applied when calculating LCA results for wood products, including woody biomass used as an energy feedstock.

It is apparent from the above list that modelling approaches vary considerably from one study to another, in terms of the complexity and sophistication of the models applied, and also the comprehensiveness with which forestry systems are represented (e.g. inclusion/non-inclusion of different forest carbon pools such as trees, litter, soil and harvested wood products). Frequently, this variety is just a reflection of the different research questions and scopes addressed in different studies, but sometimes models have simply been applied pragmatically in studies (being readily available and accessible), and their limitations (where relevant) accepted and noted in presenting results. The range of modelling approaches applied in studies, and the inconsistencies in their outputs, can make it difficult to compare or synthesise the results of different studies, for example when undertaking a meta-analysis of study results.

Methods based on the application of models have a number of important advantages:

- Firstly, in many situations, the use of models enables relevant assessments to be made without the high costs and effort likely to be associated with methods involving the collection of bespoke field data. Generally, data are needed as inputs to models but it may be possible to work with the data already available, in association with assumptions where needed (e.g. about detailed forest composition or growth rates). In the extreme case, models can work with entirely theoretical data inputs, e.g. about notional forest areas and stand ages, with uncertainties explored through sensitivity analysis.
- Secondly, often models are able to represent a range of forest management activities and patterns of wood utilisation, permitting the sophisticated representation of different scenarios, representing situations involving the supply of woody biomass for use as an energy feedstock, or the counterfactual case. Moreover, models can be applied to represent scenarios for forest management and wood utilisation that are completely hypothetical and have never been tried in practice. Hence, it should be possible to use models to explore different “what if” options for managing forests and using woody biomass, either to supply energy feedstocks or otherwise, to

identify those options associated with low or high impacts on forest carbon stocks and sequestration.

- Thirdly, if suitably designed, complete LCA modelling frameworks can be developed to address not just questions about the impacts on forest carbon stocks, but also whole-system GHG emissions, e.g. for forests, wood supply chains, wood end-use, recycling and disposal, as well as for the counterfactual systems.
- Fourthly, and very importantly, generally models are able to produce simulations describing forest carbon stocks and sequestration, under different scenarios, not just representing contemporary conditions but also projected into the future for periods of decades and even centuries if needed. Hence, models can support the assessment of both the current and future impacts of decisions taken now regarding forest management, in relation to bioenergy policy or any other relevant policy.
- Fifthly, in some cases, models can assist with helping different stakeholders to understand the impacts of different scenarios for forest management and wood use on forest carbon stocks and sequestration. For example, it is possible to use some models to illustrate very simple (e.g. stand-scale) projections of forest carbon stocks under different management scenarios, which should be relatively easy to follow, and then build up these example simulations into more complex cases, for example for forest landscapes and multiple forest management interventions, which are introduced progressively over the landscape.
- Finally, if models are designed flexibly with regard to the provision of input data and the setting of parameters, it should be possible to transfer the application of models and their associated assessment frameworks, developed for one geographic region, to new situations encountered in other regions. Depending on the region, this would involve a balance between working with available data sources and developing appropriate assumptions to fill data gaps.

However, relying on models as a basis for assessing the impacts on forest carbon stocks and sequestration arising from the supply of woody biomass for use as an energy feedstock also has several potential weaknesses:

- Firstly, results produced by studies based on models rely on the robustness of their design and calibration, their flexibility (which will affect a model's capacity to represent a comprehensive range of forest management scenarios) and the general reliability with which they have been implemented. Hence, the results produced by these studies are only as good as the underlying models and there are risks of significant errors arising in results when mistakes are made in model implementation.
- Secondly, related to the previous point, even if a model has been designed and implemented with a certain aspect of functionality (e.g. the ability to represent thinning treatments in forest stands), this may be implemented with varying levels of simplicity or sophistication in different models. For example, thinning treatments can involve the harvesting of a greater or smaller proportion of the trees in a forest stand. Also, thinning can be carried out to favour the removal of small and suppressed trees, or to favour the removal of larger, more valuable trees, or completely neutrally

with regard to tree size and value. These details can be important when trying to represent forest management practices in different geographic regions and different forest types, with the aims of producing woody biomass as an energy feedstock or for other applications. It is not always apparent that models applied in forest bioenergy studies have the level of sophistication needed to represent these types of important variations in forest management activities.

- Thirdly, as with the application of any modelling system in any context, the principle of "garbage in, garbage out", applies. Hence, model results are very reliant on the correct specification of input data (forest composition etc.) and parameters (e.g. underlying forest growth relationships referred to in calculations). Significant errors can occur in model calculations if data inputs and parameter settings are poorly or incorrectly specified. This includes situations in which a model is applied outside the limits of the applications for which the model has been designed.
- Finally, some models applied in studies of carbon impacts of forest bioenergy supply are very complex and it can be very difficult for stakeholders to understand how they work and how they have produced specific sets of results. This particularly tends to be the case when models are applied at large scales (landscapes, entire regions and the globe), involving numerous forest areas, types of forest stands and a variety of different forest management interventions taking place over time. A further difficulty can arise in this context, in that calculations made as part of model simulations frequently involve some very important implicit assumptions (see for example the second point in this list). These assumptions may have a big influence on the results, or may limit their applicability, but such issues may not always be clearly explained to stakeholders. It is important for stakeholders to be able to "trust" model simulation results, but this is not always achieved when model calculations lack transparency or are difficult to follow.

There may be ways in which certain weaknesses of models such as described above can be addressed or mitigated, for example:

- Quality assurance procedures (such as test plans and version control) can be implemented to reduce risks of errors being introduced as part of model design and implementation
- Documentation such as technical descriptions and user manuals for models can support transparency
- Information can be provided illustrating simple and more complicated examples of model simulations, to assist model users and stakeholders in understanding how models work.

Study based on forest inventory data

The study reported by Hudiburg *et al.* (2011) was an attempt to analyse and interpret national forest inventory data for a significant region (the Pacific West Coast of the USA), with the aim of determining the impacts of certain possible forest management activities in the region on forest carbon stocks and sequestration. The principal data source consisted of inventory plots from the US Forest Inventory and Analysis National Program (FIA). This was combined with information from other sources including:

- Remote sensing data (forest fires)

- Some supplementary data from forest plots
- Data on rates of wood decomposition
- Data on levels of wood production (by US State).

These data sources were analysed to estimate, at the ecosystem and regional levels:

- Current carbon stocks in forests (principally trees and detritus)
- Rate of net carbon sequestration (for a 20 year period)
- Losses from forests associated with either forest fires or forest harvesting.

The analysis was entirely reliant on available data when obtaining these estimates for the baseline case (i.e. a business as usual scenario). However, the study also assessed scenarios involving changed forest management activities, with the aims of fire prevention, or increased wood product and bioenergy supply, or both objectives). For these scenarios, it was necessary to estimate impacts on forest carbon stocks (and future carbon sequestration) by adjusting the forest inventory data, generally to represent increased levels of thinning in forest stands. It was also necessary to estimate a possible change in subsequent forest carbon sequestration, as a result of forest regrowth following harvesting. Both of these estimation procedures involved making assumptions in order to characterise the forest management practices in the scenarios and as part of making calculations of carbon stocks and carbon sequestration.

A methodology based on actual field measurements, rather than reliant on modelling, is of great interest to this project because, potentially, direct measurements of forest carbon stocks are more likely to be trusted by stakeholders than the results of model simulations (see earlier discussion of modelling studies). However, such an approach has several weaknesses:

- Firstly, approaches based on direct monitoring of forest carbon stocks through surveys, such as forest inventories, provide a snapshot of the situation over a relatively short period. This point was acknowledged by Hudiberg *et al.* (2011), who commented, “Our reliance on a data-driven approach versus model simulations strengthens our analysis in the short term, but limits our ability to make long-term predictions. Extending our study beyond a 20-year timeframe would overstretch data use because current forest growth is unlikely to represent future growth due to changes in climate, climate related disturbance, and land use”. In this context, only the application of models would appear to permit projecting forest carbon stocks (and stock changes), whilst allowing for the effects of forest management, over a period of several decades or longer.
- Secondly, field monitoring data still require analysis and interpretation to determine the likely effects of different forest management treatments (as was the case in the study of Hudiburg *et al.* (2011)). It is very likely that, in general, assumptions would need to be made about forest management activities associated with producing wood products including bioenergy feedstocks (or alternatively not producing them), raising the same issues as with any study that relies on assumptions as part of its assessment (see Section 4.1.5).

- Thirdly, such methods are only possible in geographic regions where there has been (and will continue to be) a strong track record of collecting data from forest inventories or similar systematic forest surveys. In practice, the quality of forest inventory data is very variable between countries and regions, limiting the transferability of such methods.

Study based on field experiments

The study of Tamminen *et al.* (2012) illustrates how the impacts on forest carbon stocks occurring as a consequence of the supply of woody biomass for use as an energy feedstock might be assessed by analysing the results of formal (designed) experiments carried out in forest stands.

The study made use of data from a series of experimental trials established in spruce and pine stands across Finland. The main purpose of these experiments was to investigate some of the potential impacts of harvesting complete trees (above ground), or harvesting forest residues (branchwood and needles), alongside conventional harvesting of stemwood, in comparison with a treatment involving just extracting the stemwood. The main focus of these experiments was on impacts on soil nutrients, but soil carbon was also assessed.

Studies of this type have the strengths that they are founded on actual data, collected according to a formal experimental design. However, such an approach also has inherent weaknesses:

- Firstly, the approach relies on existing field experiments, which may not have been designed for the objectives considered here (i.e. assessing the impacts on carbon stocks and future carbon sequestration arising from forest management associated with biomass production for use as energy). Hence, the forest management treatments or assessments may not be ideally suited to addressing the questions of interest.
- Secondly, if not relying on existing experiments, new experimental studies would need to be established, and it would be necessary to wait for a period of up to some decades for the results. Furthermore, it would be necessary to decide on the forest management activities to include as part of experimental treatments, which may involve making assumptions about the types of forest management involved in harvesting wood for use as an energy feedstock.
- Thirdly, impacts could only be assessed for the period over which the field experiments remain viable and data are collected from them. This can be compromised, for example if experimental trials become damaged by disturbance events or there is a loss of commitment to maintaining the trials.
- Finally, similar points to those made at the conclusion of the preceding discussion of the study based on national forest inventory data also apply to experimental studies.

Study based on CO_2 flux measurements

In the study reported by Bernier and Paré (2013), the possibility was explored of using data from a network of forest CO_2 flux monitoring sites for estimating the impacts of forest harvesting activities on the carbon balances of forest stands. The study made use of field-based data on CO_2 exchanges in boreal forest sites in Canada, obtained from the Fluxnet Canada Research Network and subsequently by the Canadian Carbon Program. More specifically, the study referred to the data representing two chronosequences providing estimates of CO_2 exchanges in stands of different ages, starting with very young stands regenerating after a preceding clearfelling event.

The paper is very unclear about how estimates of wood production were derived but these appear to be based on estimates of standing biomass in tree stands at an assumed clearfelling age of 120 years. It was assumed that all harvested biomass was used as an energy feedstock.

This is another example of a study that has the advantage of being based on data rather than modelling. Instead, in the words of the authors, the study involves, "the use of whole ecosystem field-measured CO_2 exchanges obtained from eddy covariance flux towers to assess the GHG mitigation potential of forest biomass projects as a way to implicitly integrate all field-level CO_2 fluxes and the inter-annual variability in these fluxes".

However, the approach involves similar difficulties and weaknesses to those already discussed for the studies based on forest inventory data and formal field experiments. Notably, the flux-based study still required some key assumptions to be made, about forest management activities involved in scenarios, and for the details of some calculations. As an example of an assumption relevant to calculations, for the counterfactual scenario, the notable assumption was made that the net CO_2 flux from the atmosphere to forests observed in stands around 120 years old would continue indefinitely into the future.

The study nevertheless presents an interesting alternative approach, applying research-oriented CO_2 flux measurements to address a practical policy question. In the context of this current project, perhaps the most relevant outcome of the study is the authors' observation that their results were very consistent with those of modelling-based studies in which similar types of forests and scenarios (including forest management activities) were considered. Hence, the study results provide some evidence to support the view that model-based methods are reliable, certainly indicating that such methods do not give wildly inaccurate results.

4.1.10. Representation of forest carbon stocks/biogenic carbon

Of the 69 papers subjected to detailed review in this project, 61 included assessments, in some form, of the impacts on forest carbon stocks and/or sequestration, or biogenic carbon emissions, arising from the production of woody biomass from forests for use as an energy feedstock. Given the objectives of this current project, it may seem surprising that eight of the reviewed papers did not include such assessments. In fact, the sift criteria (see Section 3.1) for the review did allow for this possibility, provided that papers included assessments of changes in forest management activities related to scenarios involving bioenergy production (or otherwise), since the approaches to scenario development could be relevant for this project.

Of the 61 papers addressing impacts on forest carbon in some way, the development of forest carbon stocks or sequestration is not reported according to a consistent format. In some studies, such results are not presented directly at all but are embedded implicitly within more complex LCA results for complete biomass supply chains. As a consequence, it is difficult to extract a consistent set of results from different studies, e.g. to provide a range of results for forest carbon stock/sequestration impacts under various scenarios for biomass energy production. Furthermore, different studies may consider specific components of forest carbon stocks, for example focussing on soil carbon dynamics or those associated with forest residues and litter, rather than assessing forest carbon stocks comprehensively (i.e. for the components of tree biomass, deadwood, litter, soil and with or without carbon stocks in harvested wood products). These aspects of the study results present a serious obstacle to any attempt at meta-analysis of findings published in different studies.

Assuming that results are directly available for impacts on forest carbon stocks and/or sequestration, a difficulty can then arise in situations where woody biomass is being harvested from forest areas alongside wood utilised for other purposes, such as the manufacture of sawn timber and wood-based panels. Specifically, it may be possible to estimate the collective impact of all these activities on forest carbon, but frequently it will not be clear what proportion or parts of these impacts is the result of harvesting wood specifically for use as an energy feedstock. This is particularly the case because wood-based energy products are usually low in value, e.g. compared to sawn timber products. Industry stakeholders often emphasise that, for this reason, wood energy markets rarely drive decisions to harvest or not harvest wood (particularly stemwood) from forest areas. Hence, it can be difficult to characterise how harvesting activities in forest areas would be different if there were no demand for wood energy products, so as to establish a basis for ascribing specific forest carbon stock impacts to these products. Methodologically, this is a classic LCA problem and solutions have been proposed based on the established LCA methodologies of consequential LCA and attributional LCA. However, it is the opinion of the authors of this report that none of the currently defined methodologies gives particularly unambiguous or understandable results for woody biomass products when they are harvested from forests in which numerous forest management activities are taking place for various objectives (including the supply of other types of wood product).

Metrics used for reporting main carbon impacts results

Nearly every one of the studies considered in this review has used a different metric for presenting carbon impact results, with examples in the literature including:

- Cumulative carbon stock changes over a defined period, in units of tonnes carbon or CO_2 (or some other related units)
- Annualised net carbon balance over a defined period in units of tonnes carbon or CO_2 per year (or some other related units)
- Net GHG emissions (cumulative or annualised), allowing for counterfactual emissions of alternative products (e.g. fossil fuels), in tonnes carbon-equivalent or CO_2-equivalent (or some other related units)
- GHG emissions factors for biomass energy feedstocks or derived energy sources, in units of kilograms carbon-equivalent or CO_2-equivalent per gigajoule (or some other related units)
- Indices intended to indicate the “carbon neutrality” or otherwise of harvested woody biomass (these may be dimensionless results); these indices can involve quite complicated calculations, e.g. based on ratios between two estimated Global Warming Potentials.

- "Carbon payback" or "carbon parity" times, generally in units of years, expressing the time taken before a biomass energy source delivers net GHG emissions reductions compared with a counterfactual energy source, or some other similarly defined property of a biomass energy source.

This considerable diversity in the metrics used to present results highlights the lack of consistency in the analysis systems and methods applied in different studies, and the consequent challenges in making any sense of the results of studies when reviewing them.

4.1.11. Timescales

Table 4.14 summarises the timescales or time horizons that have been considered in studies over which to assess the impacts on forest carbon stocks or biogenic carbon emissions as a result of the supply of woody biomass for use as an energy feedstock. It should be noted that the total number of timescales considered in studies exceeds the number of papers, because several papers considered the implications of adopting more than one timescale when making assessments.

Table 4.14 Timescales/time horizons considered in studies

Timescale/time horizon	Number of papers
5 to 10 years	2
20 to 25 years	15
30 to 50 years	19
80 to 100 years	27
Greater than 100 years	16
Indefinite	7
Not specified/relevant	6

It is apparent from Table 4.14 that a wide range of timescales has been considered in studies. The fact that the carbon impacts of using forest biomass as an energy feedstock can vary significantly over time is discussed in many papers. Most studies consider longer timescales to capture these variations in impacts over time. Other studies purposefully consider shorter timescales because shorter periods are considered to be of the greatest relevance to policy (e.g. from present up to 2030 or 2050). Some studies explore the sensitivity of results to the timescale considered by looking at impacts over both short and long timescales. Timescale is not relevant in a few studies (6 papers); in those for which timescale is not relevant to the assessment, generally this is because impacts on forest carbon stocks/biogenic carbon emissions are not considered.

As encountered when considering other aspects of published studies, as discussed above, the range of timescales referred to for analysing forest bioenergy sources and presenting results can make it very difficult to compare or synthesise results from different studies as part of a review or meta-analysis.

4.1.12. Main conclusions about carbon impacts

Table 4.15 summarises the conclusions reached in different studies regarding the risks or benefits (in terms of the net GHG balance) associated with the harvesting of forest biomass for utilisation as an energy feedstock. It should be noted that the total number of stated conclusions on this subject greatly exceeds the number of papers, because many papers considered more than one geographic region, forestry system, scenario for biomass energy production and/or possible woody biomass energy feedstock.

Table 4.15 Summary of main conclusions reached in studies regarding benefits and/or risks of forest bioenergy sources in terms of carbon impacts

Main conclusion	Number of papers
High risk	30
Moderate risk	38
No net benefit	42
Moderate benefit	48
High benefit	39

In Table 4.15, the conclusions reached in different studies have been classified into the categories of:

- High risk of increases in GHG emissions
- Moderate risk of increases in GHG emissions
- No net benefit in terms of GHG emissions reductions
- Moderate benefit in terms of GHG emissions reductions
- High benefit in terms of GHG emissions reductions.

These categories were not referred to in the original papers. The conclusions of papers have been classified in this way for the purposes of this review. The classification system is qualitative and to an extent subjective, but this approach was necessary given the great variety of ways in which results and conclusions were presented in different studies (see for example Section 4.1.11). As part of the classification of conclusions, consideration was also given to the relative magnitudes of risks and/or benefits before and after 2050.

It is apparent from Table 4.15 that the conclusions reached in the various papers are quite evenly spread across the five categories denoting risks and benefits. However, this outcome cannot necessarily be taken to suggest that the actual carbon impacts of forest bioenergy sources are very variable and uncertain. As discussed earlier in this section, different studies have investigated a wide range of forest bioenergy sources and, in the process, have applied a diversity of assessment methods, frequently making assumptions about which bioenergy sources are relevant and how forests are, or would be managed to produce the bioenergy. Some papers have assessed a range of possible forest bioenergy sources, and have suggested varying risks or benefits in terms of carbon impacts, depending on each source considered.

An attempt was made to analyse the classified conclusions of the reviewed studies with respect to a number of factors (see e.g. Sections 4.1.1 to 4.1.11), to see if it was possible to relate the estimated risks or benefits of bioenergy sources to one or more key factors. However, no obvious patterns could be discerned, reflecting the large number of factors (as discussed earlier in this report) that can influence carbon impacts.

Previous reviews of papers assessing the carbon impacts of forest bioenergy sources have proposed systematic interpretations of results for the carbon impacts of forest bioenergy sources, with respect to a number of key factors. Examples of such interpretations are shown in Table 4.16 (from Marelli *et al.*, 2013) and in Table 4.17 (from Birdsey *et al.*, 2018).

Note that the assessment of Birdsey *et al.* (2018) in Table 4.16 only covers wood feedstocks and does not consider interactions with forest management activities.

The assessments in Tables 4.16 and 4.17 aim to identify situations in which forest bioenergy sources are likely to be beneficial or detrimental in terms of contributing towards net GHG reductions. The review by Matthews *et al.*, (2014) included a qualitative assessment of a number of factors that influence biogenic carbon impacts associated with forest bioenergy sources (see Figure 4.1), including:

- Forest management scenario
- Mean growth rate of forest stands
- Soil type
- Wood production scenario (i.e. wood utilised for energy purposes)
- Bioenergy conversion technology
- Counterfactual energy source.

Matthews *et al.* (2014) noted that “[biogenic carbon impacts] are very sensitive to these factors but outcomes are predictable, at least in principle”. Matthews *et al.* (2014) also presented an assessment of different forest bioenergy sources in terms of risks of high emissions or potential to contribute to emissions reductions, similar to those reported by Marelli *et al.* (2013) and Birdsey *et al.* (2013). The review of Lamers and Junginger (2013) also arrived at broadly similar conclusions. Buchholz *et al*. (2015) attempted a statistically-based meta-analysis of carbon payback times reported in (or derived from) published studies. The results of their analysis show some common features with the conclusions of other reviews, but also some notable differences. However, in the opinion of the authors of this report, it is difficult to draw definite conclusions from the analysis of Buchholz *et al*. (2015) because some of the results and outcomes suggested are influenced by significant confounding factors. The existence of issues with confounding factors in the data obtained from study factors is a key reason why such an approach was not attempted as part of this review. A further review by Trømborg *et al*. (2011) did not contain a systematic analysis of published results of forest carbon stock impacts, as was included in the studies discussed above, so is of less relevance here; the findings and conclusions of Trømborg *et al*. (2011) are discussed in Matthews *et al*. (2014)

Table 4.16 Interpretation of results for the carbon impacts of forest bioenergy sources (from Marelli *et al.*, 2013)

Biomass source	CO_2 emission reduction efficiency					
	Short term (10 years)		Medium term (50 years)		Long term (centuries)	
	Coal	Natural gas	Coal	Natural gas	Coal	Natural gas
Temperate stemwood energy dedicated harvest	---	---	+/-	-	++	+
Boreal stemwood energy dedicated harvest	---	---	-	--	+	+
Harvest residues*	+/-	+/-	+	+	++	++
Thinning wood*	+/-	+/-	+	+	++	++
Landscape care wood*	+/-	+/-	+	+	++	++
Salvage logging wood*	+/-	+/-	+	+	++	++
New plantation on marginal agricultural land (if not causing iLUC)	+++	+++	+++	+++	+++	+++
Forest substitution with fast growth plantation	-	-	++	+	+++	+++
Indirect wood (industrial residues, waste wood, etc.)	+++	+++	+++	+++	+++	+++

+/-: the GHG emissions of bioenergy and fossil are comparable; which one is lower depends on specific pathways
-; --; ---: the bioenergy system emits more CO_2eq than the reference fossil system
+; ++; +++-: the bioenergy system emits less CO2eq than the reference fossil system
*For residues, thinning & salvage logging it depends on alternative use (roadside combustion) & decay rate

Table 4.17 Greenhouse gas and climate effects of using different wood biomass feedstocks from the Southeast US for electricity generation (from Birdsey *et al.* 2018)

Feedstock	Available supply	Impacts on net greenhouse gas emissions	Temporal effects on emissions	Additional and indirect effects
Sawmill residues	Limited—most already used for fuel by mills. Could increase if harvesting for other wood products increases.	Will reduce net emissions compared with alternative fuel if emissions from combustion and supply chain emissions are low.	Emissions reductions occur in a few years; no long-term effects since harvesting occurs for other wood products.	Few other effects since using biomass that would otherwise be wasted. Mill residues used for other wood products could be reduced.
Logging residues	Limited—generally involves areas harvested for other products. Subject to sustainability guidelines on leaving residues on-site for other purposes.	Will reduce net emissions compared with alternative fuel if emissions from combustion and supply-chain emissions are low, and effects on soil C and post-harvest tree growth are low.	Net emissions reductions may occur in 20 years or less, depending on decay rates that would have occurred if residues were left in forest (Figure 4), or if residues would have been burned on-site.	May affect site productivity if insufficient biomass left on site. May affect wildlife habitat. May help forest landowners retain forest as forest because of increased income. 20 years may be a long time if climate policies require reductions sooner.
Roundwood	Large because growth exceeds removals in many regions especially for hardwoods. Subject to sustainability guidelines and willingness of landowners to harvest.	Will increase net emissions in most cases because emissions from combustion plus supply-chain emissions plus loss of future forest growth and soil C is larger than displaced emissions from alternative fuel.	Over several decades to a century or more, or over multiple rotations, net emissions may be reduced instead of increased because of the cumulative effects from displaced emissions plus re-growth (Figure 3).	Depends on source of roundwood. Other effects may be small if roundwood is low-grade wood associated with harvest for higher-value products. If forest is harvested specifically for bioenergy, then other effects may be large including albedo changes, impacts on forest retention, effects on wildlife, etc.

The analysis of Matthews *et al.* (2015) built upon the earlier literature review of Matthews *et al*. (2014) and the overall findings were further interpreted in Matthews *et al.* (2018) to arrive at a proposal for a set of sustainability criteria relevant to managing risks and opportunities associated with biogenic carbon impacts potentially arising from the utilisation of forest bioenergy sources.

Occasionally, studies have explored the theoretical and actual relationships between the carbon impacts of bioenergy sources and underlying factors, in an attempt to identify critical thresholds to distinguish between beneficial and detrimental bioenergy sources, the earliest example probably being the theoretical study of Marland and Schlamadinger (1997). The paper by Röder *et al.* (2019) is a recent example of a study exploring similar issues but based on actual examples of forestry systems and potential biomass energy supply chains.

The various reviews, meta-analyses and systematic modelling analyses support the conclusions that:

- Impacts on forest carbon stocks as a result of the production of woody biomass as an energy feedstock can be very variable
- This variability is systematic rather than due to random effects
- The factors influencing forest carbon stocks can be identified and managed.

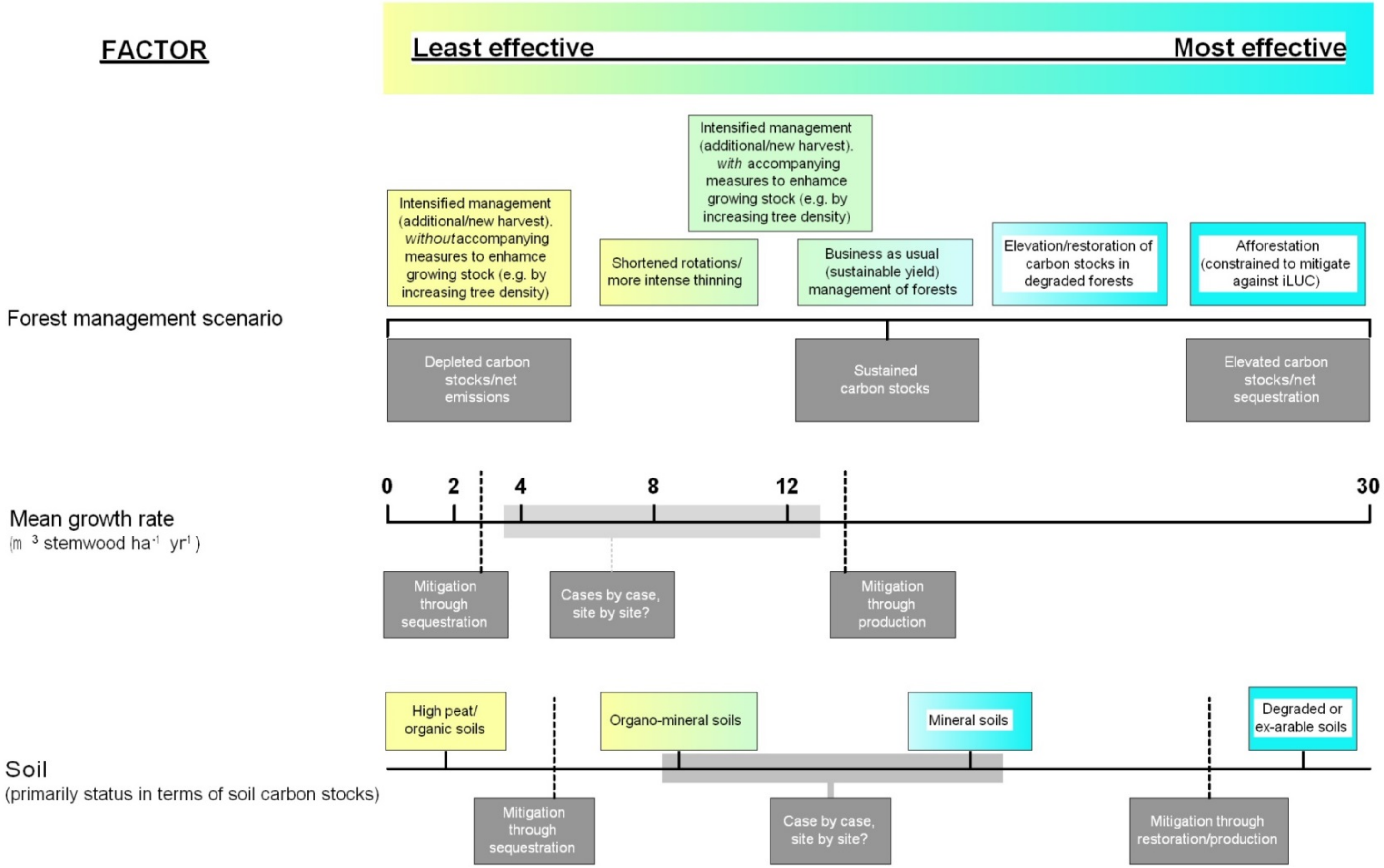

Figure 4.1 Illustration of how the GHG emissions associated with the harvesting and use of forest bioenergy may depend on a number of factors.

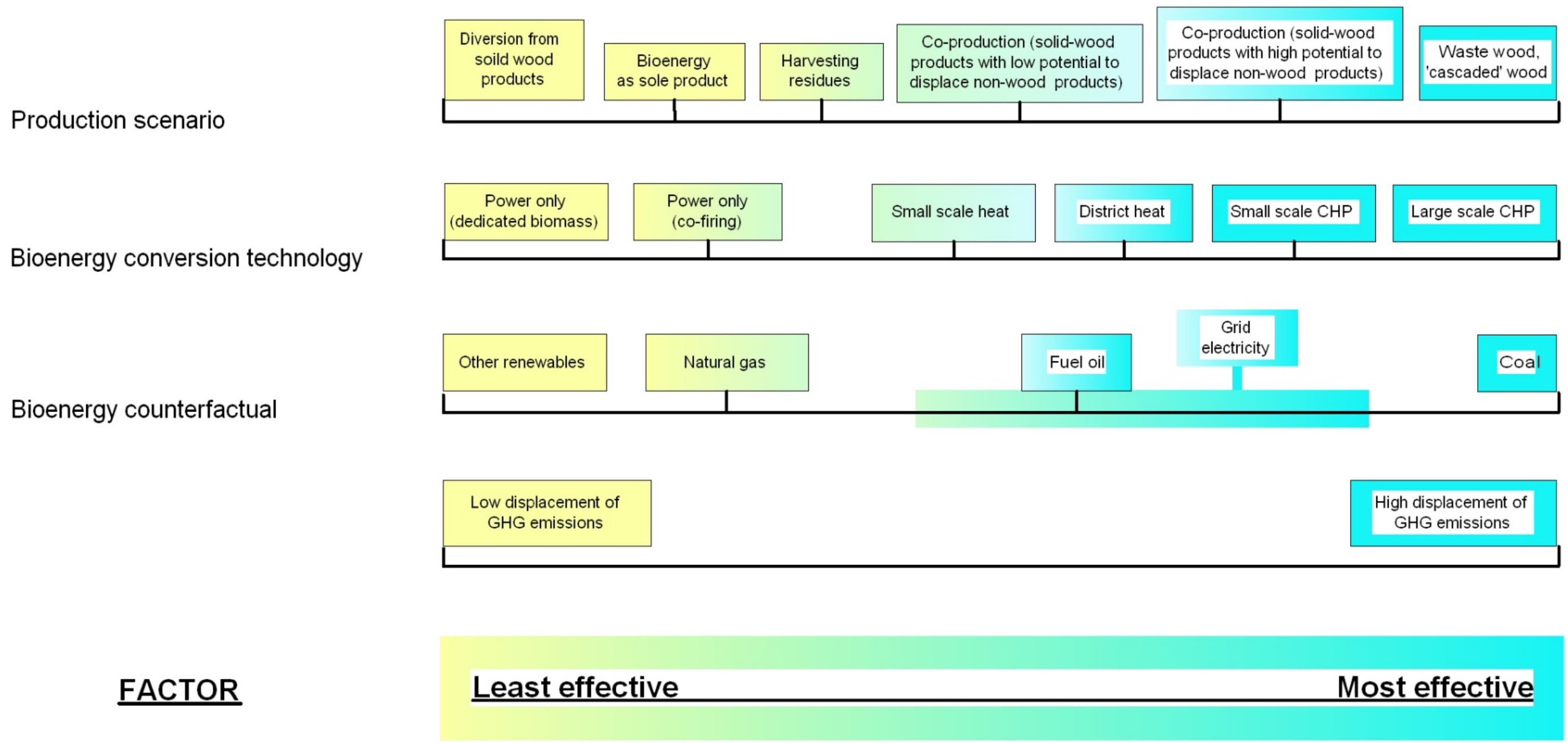

Figure 4.1 (continued). Illustration of how the GHG emissions associated with the harvesting and use of forest bioenergy may depend on a number of factors

4.2. Summary of key insights and difficulties

From the shortlist of 69 studies analysed it would appear that a wide range of approaches has been employed, and a wide range of conclusions has been drawn from study results, potentially leading to the impression either that there is no consensus on the GHG impact of the use of forest biomass for energy, or that the problem is insoluble and any result is equally valid.

However, the detailed analysis and categorization of methodologies and assumptions, discussed above, allows a number of more concrete, and valid, conclusions to be drawn.

Firstly, it has highlighted the importance of **transparency** in both techniques and the reporting of results. Without full transparency, it is simply not possible to analyse fully the relevance or validity of the results of a given study, or to clearly understand the methodology adopted. In particular it does not allow the scrutiny of the second most important factor, and that which may be considered to have the greatest single impact on the results obtained: the **assumptions** that have been made.

As discussed in Section 4.1.5, the great majority of studies were based on assumptions about forest management, particularly with regard to defining both the "with bioenergy" and the counterfactual scenarios. Even those based on economic modelling employ implicit assumptions concerning market and stakeholder behaviour. The results and conclusions of any study are so fundamentally linked to the assumptions made that the transparency with which assumptions are presented is critical to the ability to assess the relevance of an individual study. The studies assessed within the present literature review vary considerably in the degree to which assumptions are stated explicitly.

Even when assumptions are stated, the use of **terminology** that is inadequately defined can limit the ability to fully assess the details of a study, and this also makes comparison of different studies problematic.

As highlighted in Section 4.1.9, the overwhelming majority of studies involved **modelling** of one kind or another. While this is a powerful tool to allow the multiple, interacting impacts of a set of circumstances or activity to be assessed, the results can only ever be as reliable as the assumptions behind the inputs, and the way in which the model itself reflects real world behaviour. A wide range of models have been employed, some commercially available, some open source and some proprietary or developed in-house, and confidence in the results obtained demand implicit faith in the model. The incorporation (or otherwise) of factors such as biogenic carbon, non-carbon GHGs, and market responses can influence results significantly. Also, the temptation to treat the model as an infallible "black box" can mask the possibility that it may have been employed beyond the purpose or range of parameters for which it was designed. Once again, transparency can increase confidence.

A particular case is that of **economic modelling** which seeks to predict the likely impact of market factors on the behaviour of disparate stakeholders from multiple sectors and with a wide range of personal motivations. However, the increased demand for biomass for energy may certainly be expected to have impacts on economically mediated behaviour.

Finally, the details of the **"with-bioenergy" scenarios** and **counterfactual scenarios** under investigation are of relevance. These range from the realistic to the implausible, and the extent to which an individual study may be of value in a particular situation will depend upon the choice of "with-bioenergy" and counterfactual scenarios, including the selection of region and forest type, management practices, feedstocks, spatial and temporal scale. However, good transparency allows these, and consequently relevance, to be assessed.

Within the constraints of the issues discussed in Section 4.1 and above, a somewhat superficial analysis of the conclusions of the 69 papers assessed showed a wide range of conclusions as to whether bioenergy represented a risk or benefit to forest carbon stocks and consequent net GHG emissions. Owing to the wide range of forest management practices, wood feedstocks, assumptions and methodologies represented in these studies, this is not surprising. The findings of this review have been compared to those of other review studies (Lamers and Junginger, (2013); Marelli *et al.* (2013); Matthews *et al*., (2014); Buchholz *et al.*, (2015); Birdsey *et al.* (2018)) which assign different levels of impact to different feedstock sources. The review report of Matthews *et al.* (2014) also provides more detailed discussion of factors that influence net biogenic carbon impacts.

5. Characterisation of scenarios

Following on from the detailed review of studies in Section 4, an attempt is made here to propose a provisional description of scenarios for forest management and feedstock use relevant to the supply of woody biomass for utilisation as an energy feedstock in the geographic regions of primary interest to this project, i.e. Europe, Canada and the USA. However, for reasons discussed in Section 4, notably Section 4.1.5, it is important to stress that it is very difficult to use the scenarios presented in published studies as a basis for specifying the most likely forest management activities and patterns of wood utilisation. Hence, the scenarios proposed below have been informed by published studies as far as possible, but also rely on the experience and judgement of the authors of this report.

Table 5.1 gives a summary description of the forest management activities and wood feedstocks involved in Europe for the three possible scenarios of:

1. "With bioenergy" - i.e. a scenario representing current practice with existing bioenergy policies
2. "Counterfactual" or "baseline" - likely practice in the absence of a demand, or reduced demand, for bioenergy
3. "Refined criteria" or "enhanced sustainability" – scenario(s) in which sustainability criteria attached to bioenergy sources are refined in accordance with management changes to try and reduce the risk of detrimental impacts on forest carbon stocks (e.g. as proposed in Matthews *et al*., 2018).

Tables 5.2 and 5.3 give similar descriptions for Canada and the USA respectively.

The tables give a list of forest management activities and wood feedstocks involved under the three scenarios. For the "with-bioenergy" scenario, qualitative assessments are also made of the likely impacts on forest carbon stocks and the importance of each activity and feedstock under current conditions, in terms of the likely prevalence of the activity and significance of the feedstock to bioenergy industries. The speculative nature of the assessments in Tables 5.1 to 5.3 must be stressed. To assist further with understanding of this point, a qualitative assessment of confidence is attached to each forest management activity and feedstock.

Further discussion is provided after Tables 5.1 to 5.3 to clarify the meaning of a number of terms referred to in the tables.

Table 5.1 Forest management activities and wood biomass feedstocks relevant in Europe

With-bioenergy scenario		Carbon stock impact	Importance	Confidence	Counterfactual scenario		Refined-criteria scenario	
Forest management	Wood feedstock				Forest management	Wood feedstock	Forest management	Wood feedstock
Thinning	Small roundwood	Reduction	High	High	Less thinning	Left to grow	Unchanged, slight disincentive	Unchanged, slight disincentive
Clearfelling	Small roundwood	Unchanged, possible reduction	High	High	Unchanged, slight disincentive	Alternative markets	Unchanged, slight disincentive	Unchanged, slight disincentive
Thinning or clearfelling	Sawmill residues	Unchanged	High	High	Unchanged	Alternative markets	Unchanged	Unchanged
Clearfelling	Forest residues	Reduction	Moderate	Moderate	Unchanged	Left in forest	Unchanged	Unchanged, slight disincentive
Forest enrichment	Small roundwood	Increase or unchanged	Moderate	Moderate	No enrichment	Less feedstock	Unchanged, slight incentive	Unchanged, slight incentive
Clearfelling	Small roundwood	Reduction	Moderate	Moderate	Less clearfelling	Left to grow	Unchanged	Unchanged
Clearfelling	Poor quality trees	Reduction	Moderate	Low	Clearfelling	Left in forest	Partial felling	Left to grow
Clearfelling	Poor quality trees	Reduction	Moderate	Low	Partial felling	Left to grow	Partial felling	Left to grow
Afforestation	Small roundwood	Increase	Low	High	Less afforestation	No feedstock	Unchanged, slight incentive	Unchanged, slight incentive

Table 5.2 Forest management activities and wood biomass feedstocks relevant in Canada and US Pacific West Coast

With-bioenergy scenario		Carbon stock impact	Importance	Confidence	Counterfactual scenario		Refined-criteria scenario	
Forest management	Wood feedstock				Forest management	Wood feedstock	Forest management	Wood feedstock
Clearfelling	Sawmill residues	Unchanged	High	High	Unchanged	Burnt to waste	Unchanged	Unchanged
Salvage logging	Small roundwood	Reduction	High	High	Less salvage logging	Left in forest	Unchanged	Unchanged
Clearfelling	Forest residues	Reduction	Moderate	Moderate	Unchanged	Left in forest	Unchanged	Unchanged
Salvage logging	Large poor quality roundwood	Reduction	Moderate	Low	Less salvage logging	Left in forest	Less salvage logging	Left in forest
Thinning	Small roundwood	Reduction	Moderate	Low	Less thinning	Left to grow	Unchanged	Unchanged
Clearfelling	Poor quality trees	Reduction	Low	Low	Partial felling	Left to grow	Partial felling	Left to grow

Table 5.3 Forest management activities and wood biomass feedstocks relevant in Southeast USA

With-bioenergy scenario		Carbon stock impact	Importance	Confidence	Counterfactual scenario		Refined-criteria scenario	
Forest management	Wood feedstock				Forest management	Wood feedstock	Forest management	Wood feedstock
Thinning	Small roundwood	Reduction	High	High	Unchanged	Left in forest	Unchanged	Unchanged
Thinning	Chip n' saw	Reduction	High	High	No thinning	Left to grow	Unchanged, slight disincentive	Unchanged, slight disincentive
Thinning	Chip n' saw	Unchanged	High	High	Unchanged	Alternative markets		
Clearfelling	Small roundwood	Reduction	High	High	Unchanged	Left in forest	Unchanged	Unchanged

Table 5.3 (continued) Forest management activities and wood biomass feedstocks relevant in Southeast USA

With-bioenergy scenario		Carbon stock impact	Importance	Confidence	Counterfactual scenario		Refined-criteria scenario	
Forest management	Wood feedstock				Forest management	Wood feedstock	Forest management	Wood feedstock
Clearfelling	Chip n' saw	Unchanged	High	High	Unchanged	Alternative markets	Unchanged	Unchanged
Clearfelling	Poor quality trees	Reduction	High	Moderate	Partial felling	Left to grow	Partial felling	Left to grow
Thinning or clearfelling	Sawmill residues	Unchanged	Moderate	Moderate	Unchanged	Burnt to waste	Unchanged	Unchanged, slight incentive
Convert regenerated pine to plantation	Small roundwood and chip n' saw	Unchanged	Low	Moderate	Regenerate pine	Less feedstock	Unchanged, slight incentive	Unchanged, slight incentive
Convert regenerated broadleaves to pine plantation	Small roundwood and chip n' saw	Unchanged?	Low	High	Regenerate broadleaves	Less feedstock	Regenerate broadleaves	Less feedstock
Afforestation	Small roundwood and chip n' saw	Increase	Low	Low	Less afforestation	No feedstock	Unchanged, slight incentive	Unchanged, slight incentive
Clearfelling	Small roundwood, chip n' saw and/or sawmill residues	Reduction	Low	Low	Clearfelling and land-use change	Less feedstock	Unchanged	Unchanged

Forest management activities

Most of the terms used to refer to forest management activities in Tables 5.1 to 5.3 have established meanings. However, the terms "forest enrichment", "partial felling", "convert regenerated pine/broadleaves to plantation" and "clearfelling and land-use change" require some clarification, which is provided in Table 5.4.

Table 5.4 Description of selected terms referring to forest management practices

Term	Description
Forest enrichment	Enrichment refers to a range of activities to maintain or improve the growing stock and productive potential of forest stands. Examples include improving the growing stock of degraded forest areas through tree planting or assisted regeneration and restocking productive forest stands with more productive tree species or genetically improved trees. Enrichment could also involve adjustments to silvicultural practice to maintain the growing stock whilst increasing wood production (see for example the series of related papers by Alam (2011); Pyörälä *et al.* (2012); Routa *et al.* (2012) and Baul *et al.* (2017)). Potentially, forest enrichment could include cases where new tree species are introduced into forest areas to increase resilience to climate change.
Partial felling	In the context of Tables 5.1 to 5.3, partial felling refers to a harvesting activity in a forest stand which is close to complete clearfelling but which leaves standing small numbers of trees, generally those regarded as of low value for timber utilisation.
Convert regenerated pine/broadleaves to plantation	These forest management activities may be relevant in the Southeast USA. Stands of regenerated trees, notably pine stands, may be replaced after clearfelling by planting genetically improved pine trees with a significantly higher growth rate. This could be regarded as a specific regional example of a forest enrichment activity. In principle, stands of regenerated broadleaves could be converted to pine plantations. The extent of this latter activity is uncertain and is likely to be constrained in situations where sustainability criteria apply to forest management.
Clearfelling and land-use change	This forest management activity may be relevant to the Southeast USA. It involves the clearfelling of forest stands (to produce timber) followed by conversion to a non-forest land use, such as agriculture, as a result of prevailing economic conditions.

Wood feedstocks

Most of the terms used to refer to wood feedstocks in Tables 5.1 to 5.3 have established meanings or their definitions have been discussed earlier in this report (see Sections 4.1.3 and 4.1.6) . However, the term "alternative markets" requires some clarification. This refers to situations, generally under a counterfactual scenario, in which a wood feedstock relevant to a "with-bioenergy" scenario would most likely find alternative markets for its use in the absence of a demand for forest bioenergy. Examples might include utilisation for paper or wood-based panels.

Carbon stock impact

The assessment of the carbon stock impact of a forest management activity and wood feedstock included as part of a "with-bioenergy" scenario in Tables 5.1 to 5.3 gives an indication of whether the activity and utilisation of the feedstock are likely to result in a reduction, increase, or no change in forest carbon stocks, compared with the specified counterfactual scenario. It is important to recognise that this assessment is qualitative and broadly defined. For example, the assessments do not indicate the magnitude of any carbon stock change or its duration (e.g. a few years, decades or centuries). The assessments are also made quite simplistically, generally by considering the likely carbon stocks in relevant forest areas under the "with-bioenergy" and counterfactual scenarios, without allowing for possible longer term consequences of forest management decisions, such as major disturbance events in unmanaged forest stands.

It must also be stressed that a reduction in forest carbon stocks related to a forest management activity and utilisation of a wood feedstock for energy does not necessarily imply net increases in GHG emissions as a result of the use of the bioenergy feedstock. This can only be assessed by a full life cycle assessment of the forest-energy system and its counterfactual. In contrast, unchanged or increased forest carbon stocks related to a forest management activity and utilisation of a wood feedstock for energy should normally imply net reductions in GHG emissions and possibly negative emissions as a result of the use of the bioenergy feedstock.

Importance

The assessment of the "importance" of a specific forest management activity and wood feedstock in Tables 5.1 to 5.3 gives an indication of whether the activity and utilisation of the feedstock are likely to represent a significant ("high"), limited ("low") or variable ("moderate") component of the "with-bioenergy" scenario. In particular, examples assessed as "moderate" may be more or less important in different localities or regions.

Confidence

The assessment of "confidence" in relation to a specific forest management activity and wood feedstock in Tables 5.1 to 5.3 gives a simple and strictly subjective indication of whether the authors of this report have "high", "moderate" or "low" confidence in their inclusion of the activity and feedstock as an element of the "with-bioenergy" scenario.

Refined criteria

Under the refined criteria, it is assumed that sustainability criteria similar to those proposed by Matthews *et al.* (2018) are applied to forest bioenergy sources. It should be noted that Matthews *et al.* (2018) made the presumption that such criteria would form a component of a wider sustainability framework, with further criteria addressing factors such as soil, water quality and biodiversity. In some cases, these wider criteria may constrain some of the forest management activities and types of wood feedstock utilised under the “with-bioenergy” scenario.

The characterisation of scenarios provided above illustrates how there are likely to be multiple forest management activities and wood feedstocks involved in supplying forest biomass as an energy source, and that responses within the forest sector to a demand for forest bioenergy are likely to be complicated. Furthermore, such responses to a change of scenario (e.g. counterfactual or revised criteria) are likely to be very complex and sensitive to wider surrounding circumstances (e.g. demands for wood from other markets). This may present difficulties to the reliable and clear development of scenarios representing the “with-bioenergy”, the counterfactual or any alternative scenario. However, the assessments in Tables 5.1 to 5.3 suggest a method for developing and documenting scenario assumptions that is reasonably clear and could be reviewed by stakeholders. The reductive approach also provides a basis for defining inputs to any model-based assessment and for presenting results so that the contributions of different forest management activities and wood feedstocks can be distinguished.

6. Methods for development and evaluation of scenarios

6.1. Development of scenarios

Based on the detailed literature review in Section 4.1, this section briefly considers the possible approaches to developing scenarios to describe:

- Current forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes
- Counterfactual forest management activities and utilisation of wood feedstocks in the absence of forest bioenergy supply chains
- Changed forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes, in response to refined biomass sustainability criteria.

Five main approaches to scenario development were identified in Section 4.1.5:

1 Simply making assumptions about the forest management activities and wood feedstocks involved in scenarios

2 Applying economic models in conjunction with large-scale forest sector models to simulate the forest management activities and wood feedstocks involved in scenarios

3 Referring to forestry sector information on the consumption of woody biomass for use as an energy feedstock, and inferring forest management practices from these

4 Undertaking case studies involving actual wood-processing facilities and investigating the use of wood feedstocks and the management of the forest areas involved

5 Consulting with stakeholders within a relevant region to try to establish the forest management practices and wood feedstocks most likely to be involved in scenarios.

Studies employing these approaches were discussed in Section 4.1.5 and a number of strengths and weaknesses were identified with regard to each approach. Table 6.1 presents a provisional assessment of the five approaches, drawing on the discussion in Section 4.1 and in particular Section 4.1.5.

Table 6.1 Provisional assessment of possible approaches for scenario development

Approach	Strengths	Weaknesses
Assumptions	• Quick • Transparent • Understandable • Can combine with sensitivity analysis	• Possibly difficult to justify • "Just another study" • No guarantee of reflecting actual scenario • Potentially highly uncertain
Economic modelling	• Systematic • Handles sector and land use dynamics • Comprehensive • Can combine with sensitivity analysis	• Not transparent • Difficult to understand • Still reliant on implicit assumptions • High uncertainty • Possibly difficult to justify
Data from sector	• Transparent • Clear basis in data • Understandable • Verifiable	• Data required may not always be available • Data will not exist for a hypothetical scenario, still reliant on assumptions • There could be data quality issues • Can be over-simplistic
Case study	• Clearly defined • Clear basis in actual system(s) • Understandable • Verifiable	• Reliant on co-operation and availability of information • Commercial constraints • May not represent the more general situation within a region
Stakeholder consultation	• Transparent • Inclusive • Clear link to authoritative stakeholders • Can still draw on data and make assumptions • Possibility for consensus building • Objective(s) and scope can be varied	• Reliant on co-operation • May be compromised by limited pool of stakeholders • Potentially constrained by consultation protocols • May not achieve consensus

Considering the assessment in Table 6.1, it would appear that none of the possible approaches stands out as being significantly better than the others in terms of the strengths and weaknesses identified. However, the weaknesses associated with some approaches seem to limit their applicability and possibly rule them out. Specifically:

- An approach involving the use of data from the sector has significant weaknesses that would make it impractical to apply in many situations. In reality, some of the data required for this approach will not exist, or will have significant quality issues. In particular, when considering a hypothetical scenario, e.g. the counterfactual, for which, by definition, there will be no meaningful data available
- Economic modelling approaches have a number of weaknesses which do not compromise them, but may limit their usefulness
- An approach based on simply making assumptions runs the risk of adding to the large body of existing studies without bringing any clarity to the question of which/whether scenario(s) reflect reality. This limits the potential usefulness of the approach
- The reliability of the results of an approach based on an actual case study may be limited to the particular case under consideration (e.g. a biomass facility or region of forests), which may or may not be important, depending on the scale and objectives of the study
- The approach of stakeholder consultation runs the risk of failing to make progress in achieving consensus and could potentially worsen cases where there are existing disputes amongst stakeholders.

The above provisional assessment suggests that, of the approaches identified, that of relying on sectoral data should be discounted. The other approaches each have some desirable strengths (e.g. systematic, transparent, verifiable, understandable, inclusive of stakeholders). There is a case for further detailed assessment of these approaches.

6.2. Methods for evaluation of scenarios

Based on the detailed literature review in Section 4.1, this section briefly considers the possible methods for evaluating the carbon impacts associated with scenarios for forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes.

Four methods for evaluating forest carbon stock impacts were identified in Section 4.1.9:

1. Application of modelling approaches
2. Analysis of national forest inventory (NFI) data
3. Presentation of results from formally designed field experiments
4. Interpretation of CO_2 flux data collected from a forest monitoring network.

Studies employing these methods were discussed in Section 4.1.9 and a number of strengths and weaknesses were identified with regard to each method. Table 6.2 presents a provisional assessment of the four methods, drawing on the discussion in Section 4.1 and in particular Section 4.1.9.

Considering the assessment in Table 6.2, the methods based on modelling stand out as having the most advantages, whilst there may be scope to mitigate weaknesses. All the other data-based methods involve some important weaknesses, not least the unsuitability of methods for estimating longer-term impacts (e.g. outside the timescales for which field measurements have been taken). Nevertheless, NFI data, field experiments and flux results have a role in providing input data for models and/or verifying the outputs of models, and there may be a case for further consideration of these contributions by data-based methods.

Amongst the model-based methods, those employing the application of forest sector carbon accounting models would seem most relevant to the type of study being considered in this project. Relevant models have been developed by a number of organisations and examples applicable in the geographic regions of interest to this current project include:

- CARBINE developed in the UK
- CO_2FIX originally developed in the Netherlands
- EFISCEN developed in Finland and the Netherlands
- CBM-CFS developed in Canada
- FORCARB2 developed in the USA, with regional variants
- FVS developed in the USA, with regional variants
- GLOBIOM in conjunction with G4M developed in Austria.

In principle, any of these models could be applied to assess forest carbon stocks and sequestration, and the potential impacts of forest management and wood utilisation to supply woody biomass for use as an energy feedstock. There may be a case for applying more than one such model within a full-scale study, as a way of cross-checking their results.

The essential features of these models are discussed, from the perspective of this project, in the Part B report for this project.

Table 6.2 Provisional assessment of possible methods for evaluating forest carbon stock impacts of scenarios

Approach	Strengths	Weaknesses
Modelling	• Relatively quick • Systematic • Can be adapted to work with available data • Straightforward to represent a range of forestry activities • Straightforward to represent hypothetical scenarios • Straightforward to project future impacts • Can combine with sensitivity analysis • Can be used as an educational tool, as well as for modelling scenarios • Relatively straightforward to transfer methods	• Dependent on robustness and accuracy of model implementation • Likely to be unreliable if applied outside the design specification (e.g. type of thinning not actually represented) • May need a lot of data processing and quality checks • May lack transparency, presenting obstacles to understanding how results have been produced
NFI data analysis	• Founded on actual data • Likely to be trusted by stakeholders, if results are clearly linked to data • Should provide a comprehensive assessment for the study region	• Dependent on a reliable NFI in the region • Short-term and retrospective results only, cannot project to future • Survey design may limit suitability of data for addressing certain questions • Assumptions need to be made to represent hypothetical situations in scenarios
Field experiments	• Founded on actual data • Likely to be trusted by stakeholders, if results are clearly linked to data • Systematic experimental treatments are represented	• Reliant on experiments existing, may need to set them up, then wait for results • Experimental treatments may not be relevant for addressing certain questions and may not represent relevant practices • Results limited to duration of experiment • Cannot project to future
Flux monitoring	• Founded on actual data • Likely to be trusted by stakeholders, if results are clearly linked to data	• Dependent on reliable flux monitoring network in the region • Flux results depend on implicit assumptions and modelling • Does not directly evaluate carbon stock impacts • Retrospective results only, cannot project to future • Assumptions need to be made to represent hypothetical situations in scenarios

7. Conclusions and recommendations

As explained in Section 3, the literature review for this project was specified to be systematic, but also concise and focussed on addressing the specified questions. However, it is impossible to avoid the fact that the body of literature on the subjects of interest is very large, particularly if papers dealing partially with closely relevant points are included in the scope of the review. An initial trawl through relevant literature sources produced a total of 352 documents (see Annex 1). Of these, 69 papers were selected for detailed review.

The detailed review revealed that published studies are very diverse:

- Various different geographic regions are covered in studies
- A variety of forest tree species groups are studied
- A very wide range of scenarios are constructed to represent “with-bioenergy” and counterfactual scenarios, even within the same geographic region
- Various woody biomass feedstocks are utilised for energy purposes
- Individual studies use widely varying approaches for the development of “with-bioenergy” and counterfactual scenarios, with many simply making assumptions
- Most studies apply modelling methods to evaluate impacts on forest carbon stocks and sequestration associated with forest management and wood utilisation to supply woody biomass for use as an energy feedstock
- Studies are variable in their representation of land use, land-use change and spatial scales
- The completeness with which carbon stocks associated with forests (tree biomass, litter, soil, harvested wood products) are represented in studies is variable
- Studies have assessed carbon impacts over different timescales and have reported these using various different metrics
- The majority of studies do not address the specific question posed for this project, i.e. impacts on forest carbon stocks associated with forest management and wood utilisation to supply woody biomass for use as an energy feedstock. Rather, most published studies present more integrated and comprehensive life cycle analysis results for woody biomass supply chains and their counterfactuals.

Perhaps unsurprisingly, given the variability in the objectives, scope and methods employed by studies, published results for the carbon impacts of utilising forest biomass as an energy feedstock suggest widely varying outcomes. However, the detailed analysis and categorization of methodologies and assumptions, discussed above, allows a number of more concrete, and valid, conclusions to be drawn. These have been discussed in Section 4.2 and the relevant points are not repeated here.

Following on from the detailed review of studies, an attempt has been made to propose a provisional description of scenarios for forest management and feedstock use relevant to the supply of woody biomass for utilisation as an energy feedstock in the geographic regions of primary interest to this project, i.e. Europe, Canada and the USA. However, for reasons discussed in the detailed literature review, it is important to stress that it is very difficult to use the scenarios presented in published studies as a basis for specifying the most likely forest management activities and patterns of wood utilisation. Hence, the scenarios proposed in this report have been informed by published studies as far as possible, but also rely on the experience and judgement of the authors of this report.

The scenarios are defined as a list of forest management activities and wood feedstocks involved. For the "with-bioenergy" scenario, qualitative assessments are also made of the likely impacts on forest carbon stocks and the importance of each activity and feedstock under current conditions, in terms of the likely prevalence of the activity and significance of the feedstock to bioenergy industries. The speculative nature of the details of the scenarios must be stressed.

The analysis of scenarios suggests there are likely to be multiple forest management activities and wood feedstocks involved in supplying forest biomass as an energy source, and that responses within the forest sector to a demand for forest bioenergy are likely to be complex. Furthermore, such responses to a change of scenario (e.g. counterfactual or revised criteria) are likely to be very complex and sensitive to wider surrounding circumstances (e.g. demands for wood from other markets). This may present difficulties to the reliable and clear development of scenarios representing the "with-bioenergy", the counterfactual or any alternative scenario. However, the approach adopted for constructing scenarios may serve as a method for developing and documenting scenario assumptions that is reasonably clear and could be reviewed by stakeholders. The reductive approach also provides a basis for defining inputs to any model-based assessment and for presenting results so that the contributions of different forest management activities and wood feedstocks can be distinguished.

This report has briefly considered the possible approaches to developing scenarios to describe:

- Current forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes
- Counterfactual forest management activities and utilisation of wood feedstocks in the absence of forest bioenergy supply chains
- Changed forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes, in response to refined biomass sustainability criteria.

Five main approaches to scenario development have been identified:

1. Simply making assumptions about the forest management activities and wood feedstocks involved in scenarios
2. Applying economic models in conjunction with large-scale forest sector models to simulate the forest management activities and wood feedstocks involved in scenarios

3 Referring to forestry sector information on the consumption of woody biomass for use as an energy feedstock, and inferring forest management practices from these

4 Undertaking case studies involving actual wood-processing facilities and investigating the use of wood feedstocks and the management of the forest areas involved

5 Consulting with stakeholders within a relevant region to try to establish the forest management practices and wood feedstocks most likely to be involved in scenarios.

The detailed literature review identified a number of strengths and weaknesses with regard to each approach. It would appear that none of the possible approaches stands out as being significantly better than the others in terms of the strengths and weaknesses identified. However, the weaknesses associated with some approaches seem to limit their applicability and possibly rule them out. In particular, it is recommended that the approach of relying on sectoral data should be discounted. The other approaches each have some desirable strengths (e.g. systematic, transparent, verifiable, understandable, inclusive of stakeholders). Further detailed assessment of these approaches is recommended.

An assessment has also been made of the possible methods for evaluating the carbon impacts associated with scenarios for forest management activities and wood feedstocks utilised to supply woody biomass for use for energy purposes.

Four methods for evaluating forest carbon stock impacts were identified:

1 Application of modelling approaches

2 Analysis of national forest inventory (NFI) data

3 Presentation of results from formally designed field experiments

4 Interpretation of CO_2 flux data collected from a forest monitoring network.

The detailed literature review identified a number of strengths and weaknesses with regard to each method.

The methods based on modelling stand out as having the most advantages, whilst there may be scope to mitigate weaknesses. Hence, it is recommended that these methods are focussed on for further consideration. All the other data-based methods involve some important weaknesses, not least the unsuitability of methods for estimating longer-term impacts (i.e. outside the timescales for which field measurements have been taken). Nevertheless, NFI data, field experiments and flux results have a role in providing input data for models and/or verifying the outputs of models, and there may be a case for further consideration of these contributions by data-based methods.

Amongst the model-based methods, those based on the application of forest sector carbon accounting models would seem most relevant to the type of study being considered in this project. Relevant models have been developed by a number of organisations, which are applicable in the geographic regions of interest to this current project. In principle, any of these models could be applied to assess forest carbon stocks and sequestration, and the potential impacts of forest management and wood utilisation to supply woody biomass for use as an energy feedstock. There may be a case for applying more than one such model within a full-scale study, as a way of cross-checking their results.

Drawing on the above discussion, in summary it is recommended that:

- Further assessment is made of approaches to the development of scenarios based on simple assumptions, economic modelling, case studies and stakeholder consultation, including the possibility of employing some combination of these approaches
- Consideration should be given to testing the provisional scenarios developed in this report through consultation with relevant experts
- Further assessment is made of modelling methods for the evaluation of the potential impacts on forest carbon stocks and sequestration arising from forest management and wood utilisation to supply woody biomass for use as an energy feedstock, under different scenarios
- The assessments recommended above should form the basis for developing and evaluating options for a full-scale study as envisaged in this project.
- The option of not proceeding with a full-scale study should be considered as part of further assessments, given the many uncertainties and technical difficulties identified in this review. It is important not to underestimate the complexity of the analysis implied in trying to establish impacts on forest carbon stocks occurring as a result of UK biomass policy, within the context of large forest areas and multiple forest management activities and markets for woody biomass within relevant regions.

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